Journal of Cleaner Production 180 (2018) 888–912

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Bullwhip effect mitigation of green supply chain optimization in electronics industry

Yuhuan Zhao [a, b], Ye Cao [a, *], Hao Li [a], Song Wang [a], Ya Liu [a], Yue Li [a], Yongfeng Zhang [a, c]

[a] School of Management and Economics, Beijing Institute of Technology, Beijing, 100081, China
[b] Sustainable Development Research Institute for Economy and Society of Beijing, Beijing, 100081, China
[c] School of Economics and Management, Yanan University, Yanan Shaanxi, 716000, China

ARTICLE INFO

Article history:
Received 27 May 2017
Received in revised form
15 October 2017
Accepted 17 January 2018
Available online 6 February 2018

Keywords:
Electronic products
Green supply chain
Recycling
System dynamics
Bullwhip effect

ABSTRACT

Technological advancement and rapid demand changes, lead to shorter life period and booming waste of electronic products. Recycling and reusing activities of electronic products has attracted much attention on the optimization of green supply chain (SC). This study employs system dynamics (SD) model to explore the effect of single strategy and combined scenarios on mitigating inventory amplification, i.e., bullwhip effect (BE) in three-echelon SC. Novel scenario simulation is designed to stimulate recovery activities of electronic waste, decrease solid material depletion and promote clean production. Main thread is as follows: establishing SD model in line with practical operation mechanism, testing the robustness of model, emulating the effect of single strategy and combined scenarios on mitigating BE and finally proposing optimal strategies on the optimization of green SC. Results show that positive recovery activities is an optimal solution in green SC among single strategies; simulated scenarios alleviate the BE largely especially the combination of higher recovery ratio and information transparency reinforcement. Initially, the emulated-mapping of this field helps graphically illustrate the potential optimized-directions and stimulate individual recovery behaviors in green SC.

1. Introduction

1.1. Green SC background

The successful integration of economic, environmental and social sustainability goals in green SC, has pushed green SC to be the forethought of leading supply chain and operation management. Implementing green SC becomes a strategic task of industrial development worldwide (Turrisi et al., 2013). Facing governmental regulations and green trade barriers, if enterprises want to win sustainable competitive advantage, a long-term choice is to take social-economic-environmental responsibility and provide green products (Pan et al., 2015).

Issued by China's SEPA (State Environmental Protection Administration) in 2007, environmental pollution regulation of electronic products refers to information technology products, communication products, office equipment, such as computer, printer, photocopier, telephone. Electronic waste refers to disused electronic products, electronic appliances, electronic equipment and its used parts and components, including daily-disused computer, phone etc. While rapid upgrading of electronic products has brought a substantial growth of electronic waste. According to a statistical report on electronic waste by European Union (EU) in 2011, electronic waste was surging at a rate of 16%–28% per 5 years, 3 times faster than total solid waste. Electronic waste grows fastest among all the solid waste. The cyclic utilization of electronic waste has aroused the attention in the field of green SC worldwide.

China, as the manufacture and consumption superpower, is confronted with inappropriate disposal and serious pollution of electronic waste. Derived from Academy of Social Sciences, electronic products in Beijing has approached a fastigium, with electronic waste rising to 15.83 million tons million tons (Abhishek and Jinhui, 2017). In views of the incapability of natural degradation of electronic products, overdue recovery processing particularly immediate landfill or combustion, surely incurs severe contamination (Carlsson and Fuller, 2000). In China, electronic waste is mainly disposed by three ways, namely refurbishment to secondary market, simple disassembly as parts manufacturing and dumping. This disordered reverse logistic system of China brings a great waste of

* Corresponding author.
E-mail address: 15733221284@163.com (Y. Cao).

https://doi.org/10.1016/j.jclepro.2018.01.134
0959-6526/

resources and heavy environmental pollution. Otherwise, electronic waste could be used as industrial product materials to generate social-economic-environmental value through adopting progressive technology.

Governments of many countries implement rules to regulate recycling and reusing of electronic waste, such as EU's enactment of VUEEE instruction in 2003 (Talaei et al., 2016). China has issued the first electronic waste recycling laws (Control measures for pollution control of electronic information products) in 2007. Developed countries have emphasized recycling and reusing of electronic waste and adopted many measures. Due to informal waste recycling channel and complicated operation process, reverse logistics of electronic waste in China needs to be improved. Especially, the regulatory enforcement of developed country has pushed China's export to a more severe situation. Higher technical costs and slow economic pay-back urge several brand enterprises to recycle waste and compel majorities of enterprises to focus on forward logistics.

Hence, green SC emerges largely from the appealing for both clean production and economic benefits. Green SC is an environmentally responsible system, including eco-management of both forward logistics and reverse logistics, especially the reverse logistics. As a typical application of green SC, the reverse SC extends the forward SC by including product return, recycling/recovery, remanufacturing and resale (He, 2015). Products are recycled by the original manufacturer or through indirect channels, and then resold in primary or secondary market after necessary disposition (Ashayeri et al., 2015; Turrisi et al., 2013). Among that, one of the most serious barriers is BE, a well-known but undesirable phenomenon to incur demand amplification from a downstream site to an upstream (Lee et al., 1997). Inventory amplification due to BE is described as two opposite trends, namely falling orders happens in decreasing demand and booming orders of down-stream sectors in growing demand. BE leads to tremendous supply chain inefficiencies such as excessive inventory investment, poor customer service, lost revenues, misguided capacity plans, ineffective transportation, and missed production schedules (Giri and Sharma, 2015).

1.2. Motivation

Majorities of literature reviews on green SC management have been completed over the past decade. Some of them have been comprehensively covered entire field (Seuring and Müller, 2008), whilst others have concentrated on detailed aspects like performance measurement (Taticchi et al., 2013), supplier selection in green SC (Igarashi et al., 2013) or calculation models (Ahi and Searcy, 2013). Over decades, general focus of numerous studies on SC mainly pours on evaluating their effective performance on economical sustainability, environmental sustainability, and operational performance (Georgiadis and Besiou, 2008; Paksoy, et al., 2011; Jayaram and Avittathur, 2015; Zhou and Piramuthu, 2013). In the contrast, few works attempt to probe the SC dynamics in inventory and order amplification, let alone from the side of detailed industry. Recycling and reusing activities of waste might impact the dynamics of members' inventories and order (Adenso-Díaz et al., 2012; Turrisi et al., 2013), and also amplify or moderate detrimental time-varying phenomena, especially BE and inventory instability (Disney and Towill, 2003).

Forrester (1958) describes BE for the first time and believes that BE causes time delay, and larger demand information fluctuations. Lee et al. (2000) summarizes the causes of the BE, such as demand forecasting, supply stock, lead time and price volatility. Through simulation methods, Towill (1997) reveals that the demand information doubles its volatility from distributor to manufacturer. Zhang (2004) considers the impact of forecasting methods on BE for a simple replenishment system, describes the customer demand and an order-up-to inventory policy characterizes the replenishment decision. Chatfield and Pritchard (2013) adopts a (simulation model)">simulation model to examine the effects of stochastic lead times and information sharing on SC. They demonstrate that lead-time variability exacerbates variance amplification in a SC and information sharing is highly significant. Jaksic and Rusjan (2008) examine the influence of different replenishment policies on the occurrence of the BE. They demonstrate that certain replenishment policies could induce BE while others inherently decrease demand variability. The main causes of demand information amplification are future demand expectations that leads to over-exaggerated responses to demand changes.

Very few studies discuss the effect of the reverse logistics on BE which are quite contrasting and incomparable (e.g., Huang and Wang, 2007; Ding and Gan, 2009; Adenso-Díaz et al., 2012; Turrisi et al., 2013; Corum et al., 2014). The reasons might lie in distinguished configurations and modeling assumptions of SC. For another issue, crucial impact factors of the inventory management in SC (i.e., remanufacturing lead time, recovery ratio, SC tiers etc.) are not highlighted thoroughly. Still, non-common agreement about how different remission strategies may change SC social-economic-environmental performance is reached (e.g. Lee et al, 2000; Disney and Towill, 2003; Zhang, 2004; Agrawal et al., 2009; Jaksic and Rusjan, 2008). BE has generated attention among researchers and practitioners alike, companies have not yet succeeded incompletely taming it.

Motivated by these contrasting results and realistic significance, we list two main objectives. (1) This paper is devoted to contributing to the existing literature on reverse logistics and green SC by comparing three main BE-mitigation methods (i.e., increasing recovery ratio, information transparency reinforcement and forecast time reduction) and the combined scenarios. (2)We attempt to analyze the impact of reverse logistics on inventory fluctuation in electronic industry, to propose optimal strategies for dampening such amplification and then to decrease material consumption as well as solid waste pollution reduction.

Our final research make original contributions in two important ways. (1) It is helpful to optimize green supply chain (SC). This study proposes combined scenarios of inventory fluctuations mitigation, decreases material consumption, reduce solid waste pollution and optimize green SC. Based on clean production and green SC optimization, this study proposes BE-reducing scenarios and provides reference for green electronic industry improvement. (2) This study provides practical implications on realistic reverse logistics. The authors propose an empirical closed-loop system that accurately emulates the upstream and downstream flows in green SC and be consistent with realistic operation. Hence, the results are beneficial in motivating many firms to implement reverse logistics suitable tools for the proper management of the information and material flow in the green SC. (3) The reinforcement of foreign electronic products legislation in international trade has made the export of China's electronic products more difficult. Hence, exploration on reverse SC management of China's electronic products is critical to break green trade barriers and smoothly participate in international market competition.

The exposition is organized as bellow. An overview of SD modeling including application, modeling boundary, variables description and casual-loop diagram is described in Section 2. Section 3 introduces data source and model test. Bullwhip effect analysis in closed-loop SC is presented in Section 4. Section 5 discusses the comparison analysis of green SC optimization scenarios. Concluding remarks and further research are presented in the final section.

2. Methodology

2.1. SD model

As a prominent phenomenon in SC management, BE refers to a demand amplification phenomenon that all members make supply decisions based on the downstream demand information. This study employs SD model and Vensim software to establish a green SC and emulate the combined scenarios of reducing BE.

Originated in 1956 by Professor Forrester J.W., SD model is appropriate for analyzing the dynamic variation of system internal structure and dynamic external environment. It is operated by cause-and-effect feedback and computer simulation. SD model has a lower data sensitivity due to its basis (i.e, feedback loop). As long as parameter estimation is reasonable and falls in limited range, SD simulation show the consistent variation trend with realistic operation. SD employs given equation, parameter and initial conditions to quantify most variables and eliminate ambiguity. Reverse SC in electronic industry shows complicated, uncounted and changing. Pure mathematics methods fail to express the dynamic variation and relevant system risk. SD model was appropriate for handling bullwhip effect (BE) mitigation of green SC optimization.

A systemactic literature review on BE-mitigating methods is illustrated in Table 1. SD model has been widely adopted to alleviate BE issues and reveals obvious advantages, such as investigating the influence of reverse activities on dynamic performance, approaching realistic operation, lower data sensitivity, handling complicated situation etc. Furthermore, works about application of SD model to mitigate BE appears early. Towill utilizes SD model to study the expanded phenomenon of demand information. He reveals that, the longer SC leads to more serious BE. The magnitude of amplification even reaches 8 times than the original demand. Anderson et al., 2000 employs SD model to explore demand fluctuation in machine tool industry, and finds that accelerating investment leads to productivity improvement and serious demand augment.

2.2. Modeling boundary and variables description

This paper establishes a three-echelon SC and involves in manufacturers, distributors and retailers in top-down terms. SD model simulation is achieved by causality loop, which involves in four variables (state variable, rate variable, auxiliary variable and constant variable) and five types of parameters (initial value, rate, constant, table function and auxiliary variable). Detailed type of variables is shown in Appendix B. Besides, Specific description of equations and parameters about the three-echelon SC and recycling links is shown in Appendix C. Variables description is presented by main equations (Tate et al., 2010). Among that, state variables refer to summation of current value and variation; rate variables reflect input or output rate; auxiliary variables are computed by other variables and independent to past or future record; auxiliary variable is interpreted as affecting any variables of SC, some of the set equations can also be regarded as auxiliary variables; safety stock and stock accommodation time are set as constant variables, while stock supplement depends mainly on the upstream (Appendix A).

Four types of state variables are described as follows:

(1) Manufacturer component stock is influenced by component reproducing amount, directly used-component amount, component production rate and product production rate. Component stock goes up as component production rate increases, while component stock inclines with growing production rate in manufacturer. In other words, there is a positive correlation between component stock and component production rate, while a negative correlation between component stock and manufacturer production rate. A higher component production rate directly increases the quantity of manufacturer component stock; while growing manufacturer production rate will increase the utilization of parts and components thus reducing original component stock.

(2) Available stock of manufacturer product (MS) is related to product reproduced amount, manufacturer delivery ratio and manufacturer production rate. It is equal to product reproduced amount plus manufacturer production rate minus manufacturer delivery ratio integration. In views of time delay in production, delay happens in the conversion of materials to component, i.e., component production time.

(3) Variation of distributor stock (DS) is caused by the decreasing rate (manufacturer delivery ratio) and increasing rate (distributor delivery ratio). Distributor delivery ratio, refers to the smaller value between initial stock of distributor next cycle plus present delivery ratio of manufacturer and retailer

Table 1
Systematic literature review on BE-mitigating methods.

Typology	Author (Year)	Methodology	Main contribution	Limitations
Journal	Zanoni et al. (2006)	Simulation	Four inventory policies comparison about economic consequences and BE formalization in hybrid inventory system	
Conference	Huang and Liu (2008)	SD	Effect of remanufacture, remanufacturing lead-time; Return rate on the inventory variance and BE	
Journal	Guo and Xu (2008)	Control theory	Presentation of an Hinfinity control strategy to reduce BE	Lack of specific insights on the influence of reverse logistics factors on dynamic behavior
Conference	Ding and Gan (2009)	SD	Closed SC model under APIOBPCS; Effect of remanufacture and turn ratio on BE;	
Conference	Xiong et al. (2010)	Mathematical model	Comparison of the BE between forward logistics and the SC; An exacerbated BE in reverse logistics	Lack of dynamic features
Journal	Pati et al. (2010)	Statistical analysis	Insights on BE in a six- echelon SC for recycling; Impact of segregation degree on BE	
Conference	Tejeida et al. (2010)	Fractal analysis	BE in an after-sales spare part SC intelecom firms	Lack of specific insights on the influence of reverse logistics factors on dynamic behavior
Journal	Adenso-Díaz et al. (2012)	Simulation technique	Impact of 12 factors significant about BE both in forward and reverse SC	
Journal	Le and Yi (2014)	SD	Dynamics modeling of BE in remanufacturing closed SC	

order rate. The smaller value is consistent with actual situation of SC, namely delay between distribution amount and retailer delivery ratio. Initial stock of distributor in next cycle is derived from present stock delay value of distributor.

(4) Retailer stock (RS) equals to distributor delivery rate minus retailer sales integration and is affected by retailer sales rate and distributor delivery rate. Distributor delivery rate is the increasing rate of retailer product stock and retailer sales rate is the decreasing rate of retailer product stock.

In views of transportation delay, initial retailer stock (RS) in next cycle is the delay value of present retailer stock (RS). Distributor stock (DS) is influenced by manufacturer delivery rate and distributor delivery rate (Forrester et al., 1976). Assuming no implement of information sharing during the whole SC, distributor order is predicted by supply information to the downstream. A cycle delay appears. Distributor stock (DS) adjustment rate, refers to the error of setting safe stock and actual stock dividing own stock adjustment time. After the sales process, indirectly used reproduced-product is split and flows into components. The split components are decomposed into three sorts: directly used component flowing into finished-product stock, indirectly used component flowing into component stock by secondary assemble and check, disused component recovery raw material flowing into raw material stock.

2.3. Casual-loop diagram

Closed-loop SC (both the forward and the reverse SC), employs casual loop diagram to express the qualitative relationships of variables. Feedback arrows depict action direction of one variable towards another; addition and subtraction symbols respectively indicate the reinforcing and counteracting loops, namely + noting the codirectional function while - meaning the counteracting function; manufacture and transport delays exist by marking the sign of//(Dill, 1997).

2.4. Casual-loop diagram in forward SC

Forward casual-loop diagram runs as follows and is illustrated in Fig. 1. The following are three main casual-loop feedback:

First feedback loop: Component stock of manufacturer→+Manufacturer product productivity→+Manufacturer stock→+Component stock of manufacturer.

Second feedback loop: Manufacturer product productivity→+Manufacturer stock→+Manufacturer delivery ratio→+Distributor stock→-Manufacturer order→+Component stock of manufacturer→+ Manufacturer product productivity.

Third feedback loop: Manufacturer product productivity→+ Manufacturer stock→+Manufacturer delivery ratio→+Distributor stock→+Distributor delivery ratio→+ Retailer stock→-Distributor order→+Manufacturer order→+Component stock of manufacturer→+ Manufacturer product productivity.

Forward feedback loop starts and ends at market demand, which sends order information through retailer order, distributor order, eventually to manufacturer order. The symbol + denotes the codirectional function, namely growing market demand generates ascending retailer order, then transfers to increasing distributor order, eventually leads to a manufacturer order, and vice versa. As the direct receipt, retailer receives the original market demand and transfers to the superior (distributor). Distributor faces two conditions; videlicet adequate distributor stock generates direct supply while insufficient distributor stock leads to a new distributor order. Similarly, two conditions happen in manufacturer stock. In other words, adequate manufacturer stock generates direct supply while insufficient manufacturer stock leads to a new manufacturer order towards manufacturer component stock. Eventually manufacturer organizes various materials and component to conduct production and satisfy order demand.

Among the main variables, a dynamic relation exist. Component stock of manufacturer is mainly affected by manufacturer order and manufacturer stock. With the expanding of manufacturer order, manufacturer stock ascends while component stock of manufacturer descends. Manufacturer order is determined by distributor order and distributor stock, videlicet growing distributor order will generate increasing manufacturer order and decreasing distributor stock. Distributor order relies on retailer order and retailer stock, namely rising retailer order brings growing distributor order and reducing distributor stock. Eventually, increasing retailer order is derived from increasing demand market and vice versa. An ascending manufacturer productivity evokes a growing manufacturer stock. Similarly, increasing manufacturer delivery ratio and distributor delivery ratio, severally cause the augment of distributor stock and retailer stock. Component stock of manufacturer further produces a higher manufacturer productivity; more manufacturer stock generates a higher manufacturer delivery ratio; larger distributor stock incurs a higher distributor delivery ratio. Hence, the casual-loop diagram appears dynamic.

2.4.1. Casual-loop diagram in reverse SC

Previously, more priority of SC management has been put into manufacture efficiency rather than recovery. On account of economic-environmental value, many electronic enterprises attempt to recycle waste and maximize product value. Recovery products are constrained to three ways, adoptive ones flow into recycled and reproduced products and induce closed-loop SC; recovery products are offered for sale in flea market and shape an open-loop SC (Stefan and Martin, 2008); crappy products are disposed directly. In this paper, primary object incorporates manufacturers, distributors, retailers and relevant recycler.

Unlike forward casual-loop diagram, reverse SC begins with sales of electronic waste after life cycle. In line with research purpose, non-recyclable products are ignored. After rigid screening, reproducing used-products enter into reproducing stock thus bringing its augment and declined stock. Green-reproducing

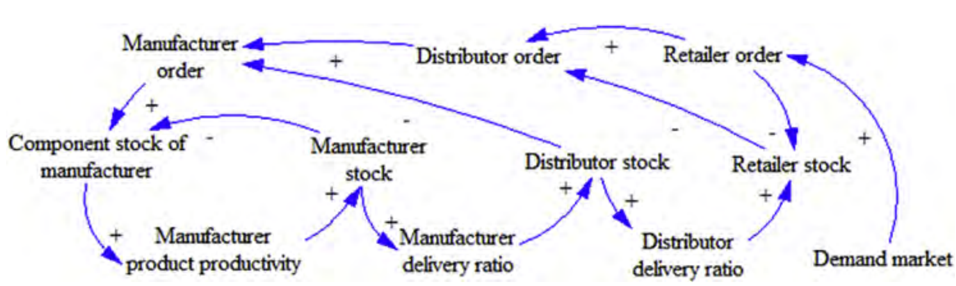

Fig. 1. Casual-loop diagram in forward SC.

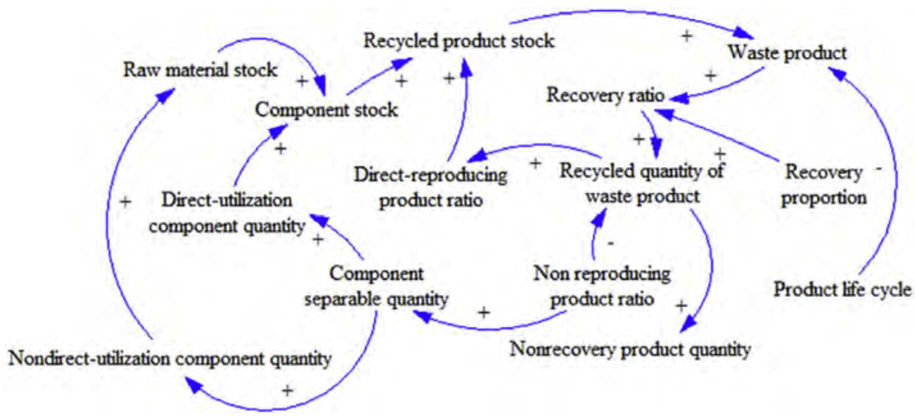

Fig. 2. Casual-loop diagram in reverse SC.

capability determines reproducing rate of enterprises (Fig. 2). Main feedback loop is shown as follows:

Recycled product stock→+waste product→+Recovery ratio→+Recycled quantity of waste product→+Direct-reproducing product ratio→+Recycled product stock.

Raw material stock is affected by nondirect-utilization component quantity. A more nondirect-utilization component quantity leads to a larger raw material stock. Component stock goes up with raw material stock increment and direct-utilization component quantity. Recycled product stock ascends as component stock and direct-reproducing product ratio increases. Waste products, influenced by recycled product stock and product life cycle, increases with the former ascending and the latter life cycle shorten. Recovery ratio could also expands with the augment of waste product and recovery proportion. Recycled quantity of waste product, affected by recovery ratio and non-reproducing product ratio, rises with recovery ratio's increment and the reduction of non-reproducing product ratio. Besides, recycled quantity of electronic waste generates an opposite effect on direct-reproducing product ratio and non-recovery product quantity. An increasing non-reproducing product ratio brings an augmented component. Component increasing contributes to the ascending of direct-utilization component quantity and nondirect-utilization component quantity.

2.4.2. Flow diagram of green SC

Based on the set equations and parameters, system flow diagram is capable of providing casual relationships in quantitative terms. Superior to casual-loop diagram, system flow diagram describes the distinction and correlativity of various variables (Appendix C). System flow diagram integrates with two process and runs as follows:

In forward SC, retailer stock is codetermined by sales rate and manufacturer delivery rate; distributor stock depends on distributor productivity (i.e., manufacturer delivery rate and recycled waste reproducing rate) and delivery rate; manufacturer stock is related to component productivity (i.e., new raw material productivity and recycled component reproducing rate) and manufacturer delivery rate. The order demand from retailer to distributor and from distributor to manufacturer, as well as manufacturer production demand and distributor component demand, are attributed to each sales forecast, each stock adjustment time and each stock adjustment quantity.

After the product life cycle, reverse SC recycles waste and screens out the reproducing type and not. All the recycled products are resold in primary or secondary market after necessary disposition. The reproducing waste increases manufacturer stock. However, the non-reproducing components are distributed to component stock or material stock, then flows into manufacturer stock. Eventually all the recycled products and components flow back to the market (i.e., customer) through forward logistics function.

3. Data source and model test

3.1. Data source and model consumption

All electronic data is derived from Internet Data Center (IDC) China Data Center, Wind database, Electronics Information Industry Statistics Society and National Bureau of Statistics. SD model has a lower data sensitivity due to its basis, i.e, feedback loop. As long as parameter estimation is reasonable and falls in limited range, simulation results show the same variation trend. SD employs given equation, parameter and initial conditions to quantify variables and eliminate ambiguity.

The assumption in three-echelon SC is as follows:

(1) Product life cycle, supplier productivity, manufacturer productivity, productivity of remanufacturing products and productivity of remanufacturing components are limited;
(2) There is no difference in reproduced products and new products, videlicet the recycling and reproducing process cannot affect market demand;
(3) The inventory strategies of this SC is classic order-up-to-stock, namely production assignment is on the basis of demand and actual stock then satisfy order demand;
(4) Recycled cost is lower than new production, thus pushing a priority selection of adopting recycled waste to organize product and component production;
(5) Customer does not discriminate the reproducing products and reproduced parts; customer has the same demand for new products and remanufactured products (parts).

This simulation is based on the following settings:

(1) Market demand is shown in the following equation. Market demand rate of former 4 weeks is set at 1000 piece per week, random fluctuation happens from 5th week with fluctuation range at 200, mean at 0, volatility at 100 times and random factor at 4. In order to emulate actual-environment operation, market demand is assumed to scatter randomly. It is well known that, BE refers to market demand amplification

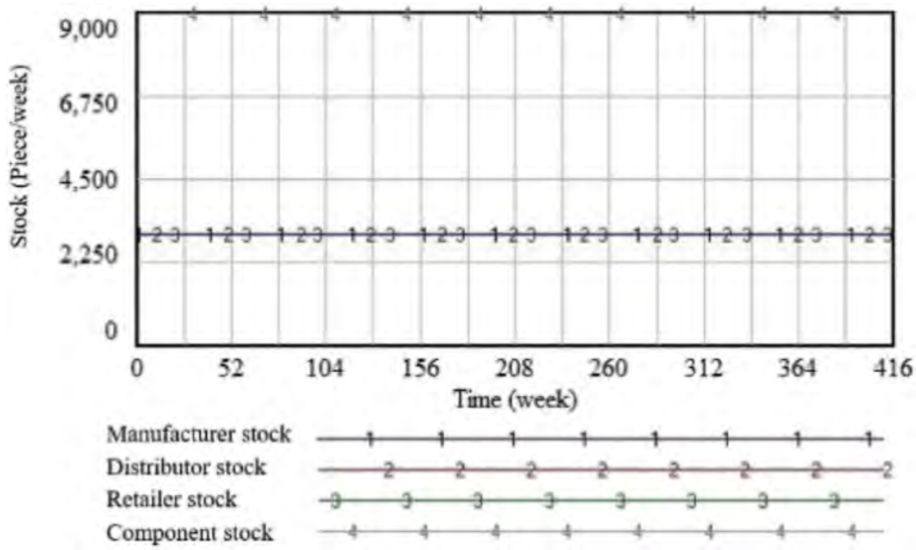

Fig. 3. Consistency test of extreme condition with market demand at 0 level.

issues with its bottom-up transferring. Stochastic demand universally is easily to perform successful simulation; Market demand[1] quantity = 1000 + IF THEN ELSE (Time>4, RANDOM NORMAL (−200, 200, 0, 100, 4), 0)

(2) Initial inventory and expected inventory of each node are all 3000 pieces with 3 weeks duration of expected inventory, stock adjustment time at 4 weeks, moving average time at 5 weeks, delay time in manufacture and transportation are all 3 weeks without ordering delay;
(3) INITIAL TIME = 0, FINAL TIME = 416, SAVEPER = TIME STEP. Simulation cycle is with a duration of 416 weeks, namely 8 years from 2007-2014.[2] In order to demonstrate variation trend and identify variation sources of market demand, emulated-step size is set as week;
(4) Expected inventory is equal to product of duration time of expected inventory and sales forecasting of each node; products spent 52 weeks to transform into waste ones with initial recovery rate at 65%.

3.2. Model test

3.2.1. Consistency test of variable dimension

Consistency test of variable dimension is employed to calculate unit conversions and maintains dimension uniformity (Sterman, J.D., 1989) by Vensim software. Variable dimension proves consistent by automatic checking.

3.2.2. Consistency test of uniformity in model and actual system (extreme condition test)

Extreme condition test is widely adopted to test the consistency with realistic operation.

Supposing market demand at 0 level, stock operation of various links in SC is compared in Fig. 3. Judged from Fig. 3, component stock, manufacturer stock, distributor stock and retailer stock all present the situation of being initial value level (i.e., 3000 pieces severally). Briefly, constant market demand leads to unchanged stock situation. Likewise, order level of retailer, available stock of distributor and components stock of manufacture turns out to be 0 level, namely unchanged situation (Fig. 4). It shows that, market demand at 0 level has pushed three-echelon unchanged. Extreme condition test proves the model effectiveness, constructed closed-loop SC is closer to actual operation of electronic industry.

3.2.3. Consistency test of uniformity between model and actual system (Behavior recreation test)

Behavior recreation is applied to trace dynamic behaviors when a sudden drop or increase in market demand happens at some point breaks. Simulation is performed through great leaps or bounds of market demand. Market demand = 1000 + IF THEN ELSE (Time>4, RANDOM NORMAL (−200, 200, 0, 100, 4), 0) +STEP (500, 110). Namely, market demand uprushes from 1000 piece per week to 1500 piece per week in week 110.

After a while of vibration, unchanged market demand still maintains a steady stock situation; at the 110_{th} week, an uprush in component stock, manufacturer stock, distributor stock and retailer stock appears. It is consistent with market demand mutation. All links require to satisfy down-stream demand by ordering from up-stream supplement. It stimulates the ordering ratio increment and satisfies product demand increment thus reaching a new steady state.

Through consistency test, nothing in dynamics behaviors is incompatible with actual environment. Almost variables variation is attributed to actual-environment causes. Hence, established SD model in green SC is a faithful representation of reality(see: Figs. 5–8).

4. Bullwhip effect analysis

In forward supply chain, waste-product recovery ratio is assumed at 65%; in the closed-loop supply chain, waste-product recovery ratio is set at 30%, 60% and 90% respectively (Maiti and Giri, 2017).

[1] The base for market demand evaluation is derived from two aspects. In views of literature reviews, Le Ma et al. and Salvatore et al. have proved the effectiveness of setting this kind of market demand (Le and Yi, 2014; Salvatore et al., 2016). As for actual conditions, especially data range in electronic industry and its realistic operation situation, the set market demand illustrates electronic industry operation conditions.

[2] 2008 is the initial year of Circular Economy Promotion Law enactment in China. Here we select the starting year of 2007 to provide general situation of China's electronic industry without waste product regulation enforcement. The whole period covering 2007–2014, facilitates comprehending waste product variation and the consequent stock fluctuation before and after legal supervision.

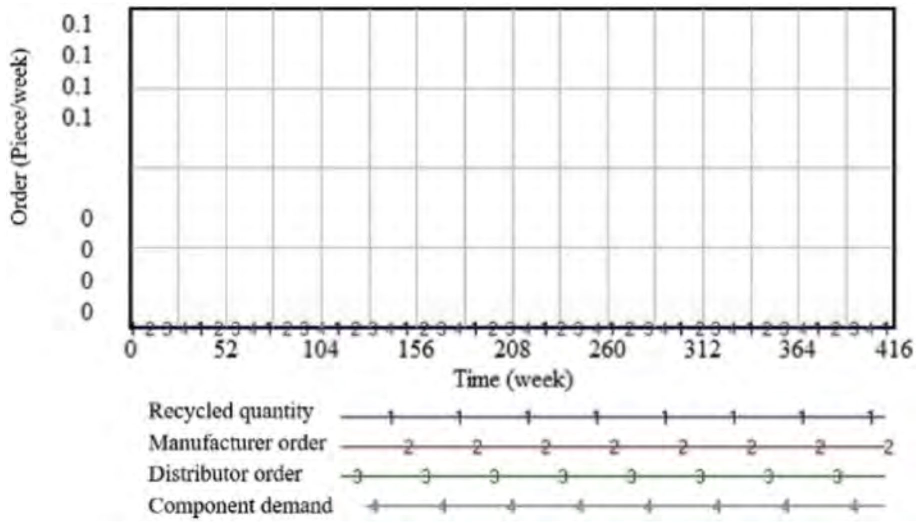

Fig. 4. Consistency test of extreme conditionwith order at 0 level.

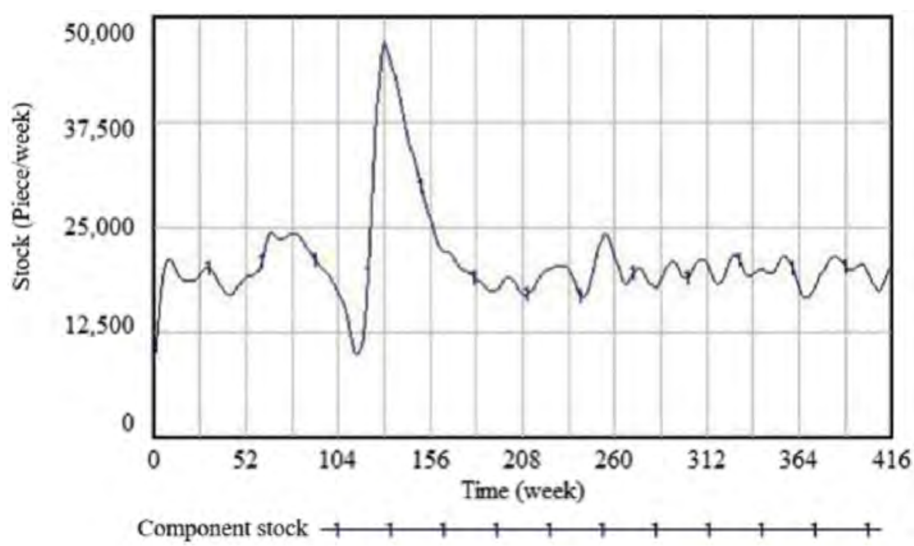

Fig. 5. Simulated-variation of component stock.

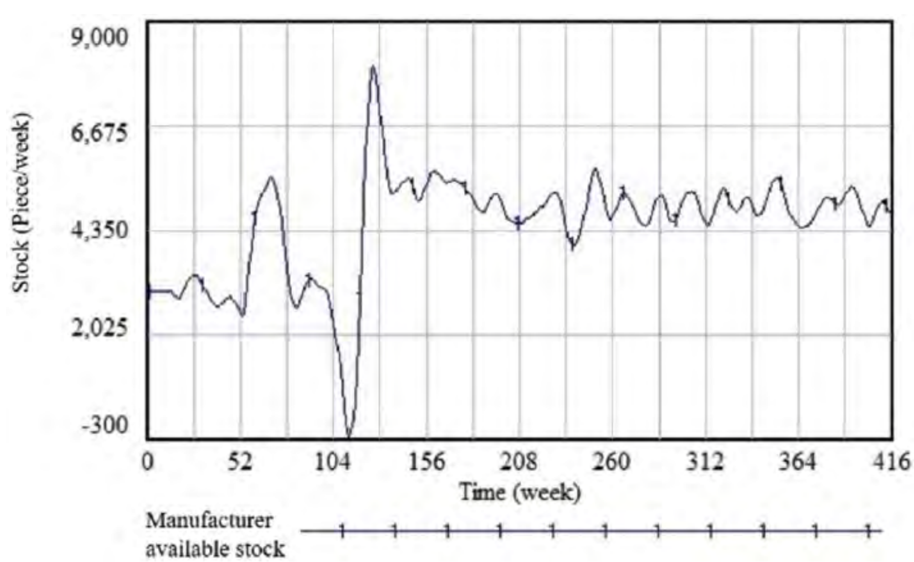

Fig. 6. Simulated-variation of available stock.

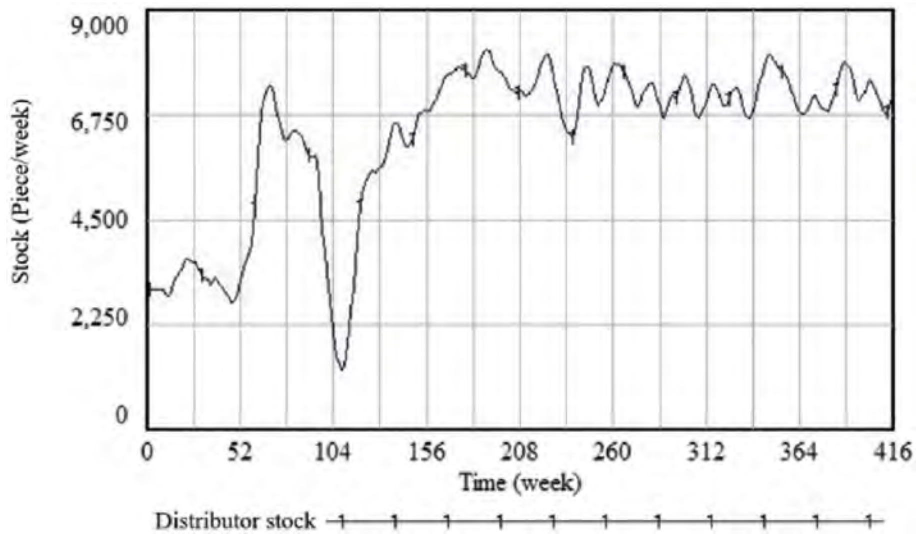

Fig. 7. Simulated-variation of distributor stock.

4.1. BE analysis in forward SC

Integral assessment index is involved in component stock of manufacturer, available stock of manufacturer, distributor stock and retailer stock (Figs. 9–12). In forward SC, the three-echelon shows huge fluctuation. Variation range of retailer stock is in 2500–3500, variation range of distributor stock is in 2000–4300, variation range of manufacturer stock is in 2000–4250 and variation range of component stock is in 7500–22500. Serious BE appears in forward SC. In detail. inventory amplification (i.e., BE) is sorted in a descending order, namely manufacturer component stock, manufacturer stock, distributor stock and retailer stock. The upstream ranking member shows more amplifications over the downstream.

Closest to market demand, retailer tends to send order information to distributor; if stock shortage appears in distributor, order information turns to manufacturer. Each SC link is likely to possess a certain amount of stock for demand satisfaction and competitiveness improvement rapidly. However, exaggerated product demand is in conflict with economic-environmental benefit, which emphasizes the significance of mitigating BE.

4.2. BE analysis in reverse SC

4.2.1. Original reverse SC

In Original reverse SC, recovery ratio is set in 65%. Emulated-results are shown in Figs. 13–14. Variation of both inventory and order demand in manufacturer component, appears the most fluctuated, with order changing during 0–4000 and stock changing covering 7500–30000. However, stock and order variations of distributor and retailer, respectively show a small volatility. Findings illustrates that BE appears particularly in more echelons. BE in component stock of manufacturer proves the most obvious. Sorting in a descending order as fluctuation range, variation of order and stock in manufacturer occupies the first, followed by distributor and retailer.

In comparison with open SC, introduction of reverse SC, has obviously alleviated the fluctuation range of stock and order, especially for retailer and distributor.

4.2.2. Reverse SC under various recovery ratio

Now that reverse SC can relieve BE largely, there is a necessity to explore the impact of various recycling ratio on the mitigation of

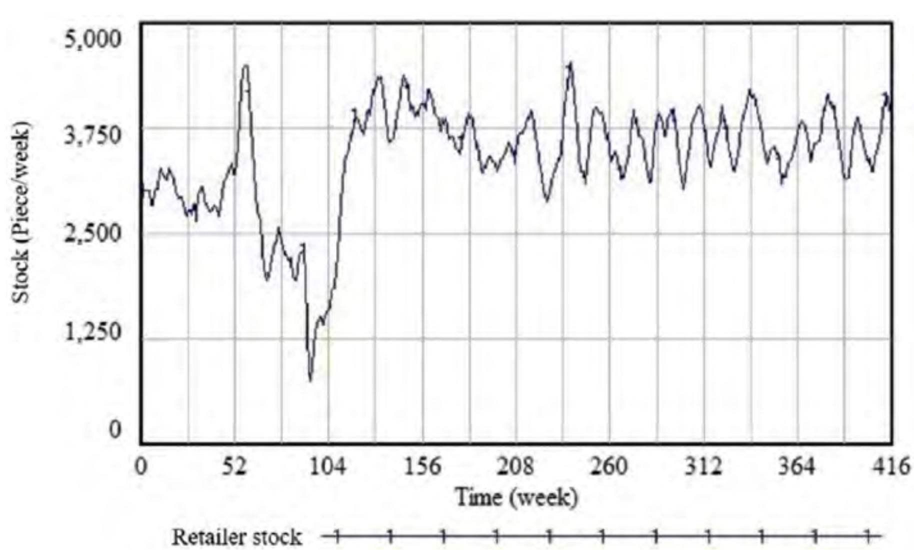

Fig. 8. Simulated-variation of retailer stock.

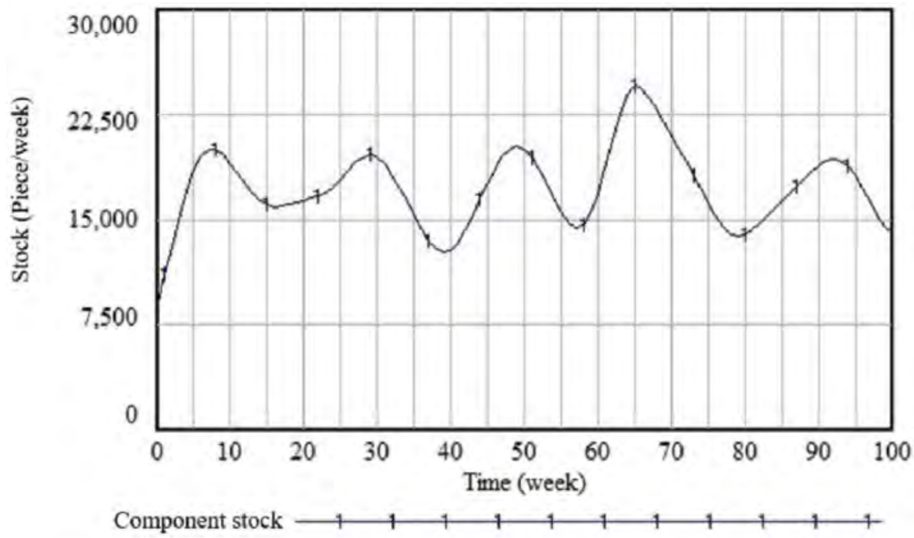

Fig. 9. Component stock variation.

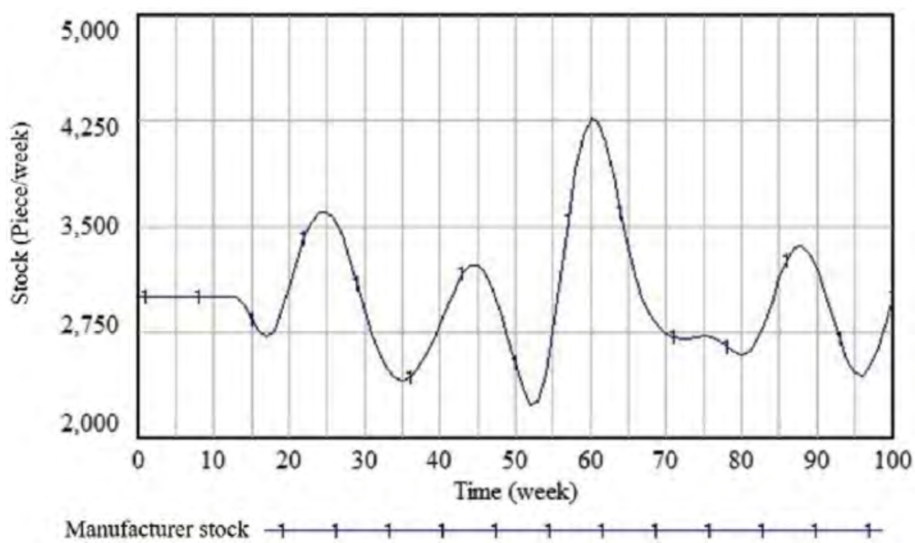

Fig. 10. Manufacturer stock variation.

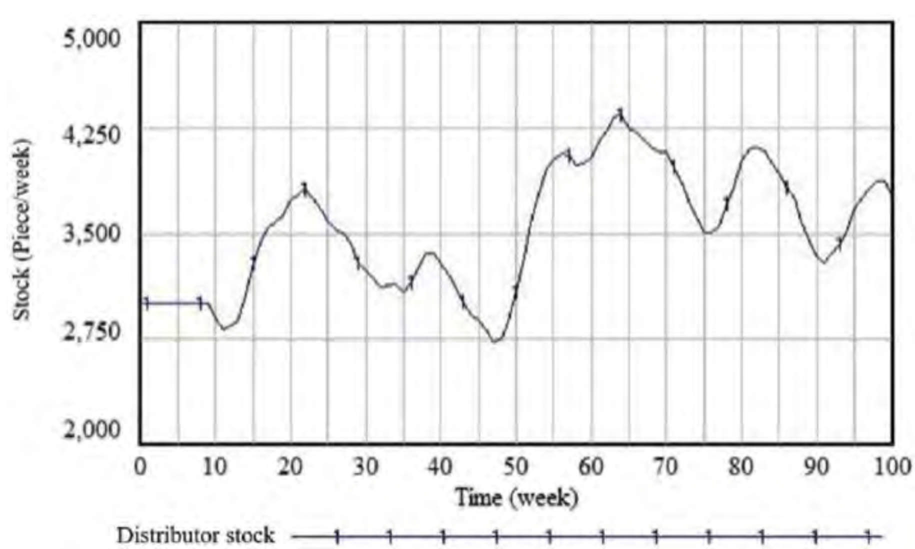

Fig. 11. Distributor stock variation.

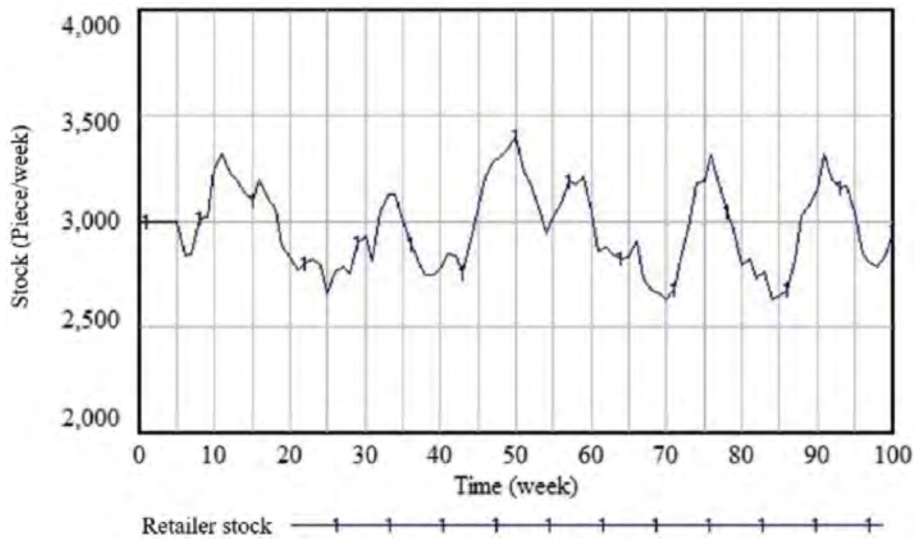

Fig. 12. Retailer stock variation.

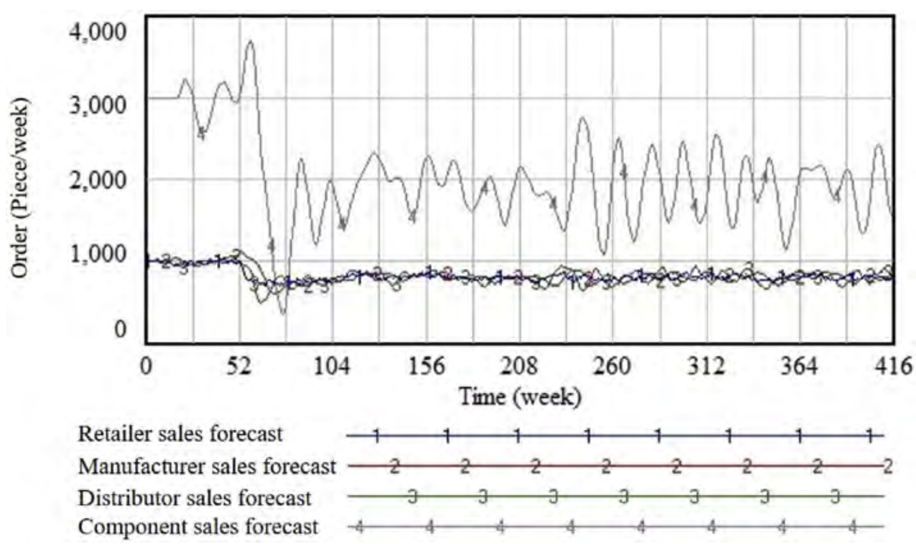

Fig. 13. Demand forecasting variation.

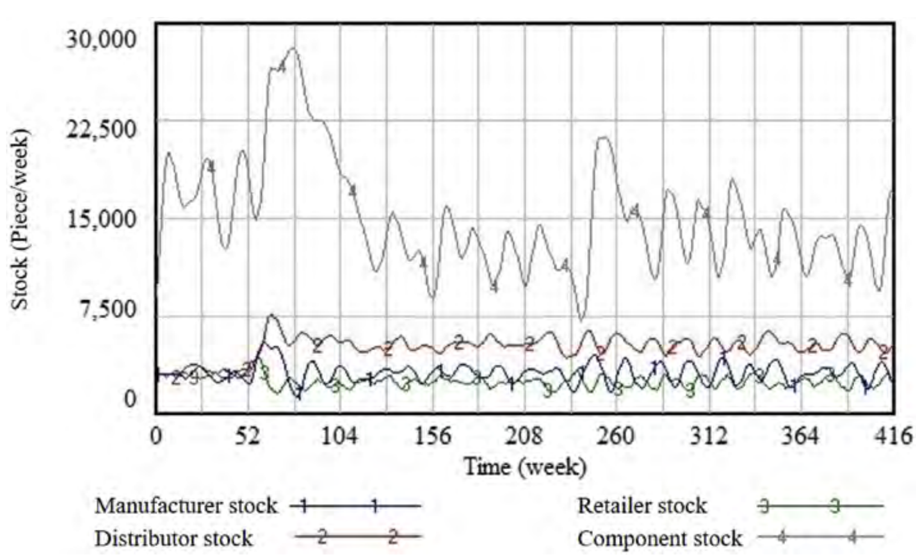

Fig. 14. Stock variation.

Table 2
Comparative BE calculation.

Recovery ratio		Market demand	Retailer order	Distributor order	Manufacturer order
30%	Variance	822.91	1682.31	2755.32	4478.89
	BE		2.04	3.35	5.44
60%	Variance	1183.12	1987.65	3125.65	4966.54
	BE		1.68	2.64	4.20
90%	Variance	2098.35	2788.78	3912.53	5800.98
	BE		1.33	1.86	2.76

Note: BE is represented by the ratio of ordering variance ratio to market demand variance (Chen and Lee, 2012).

BE. In brief, if the positive recovery activities are capable of influencing the typical stock amplification in forward SC? Recycling ratios of waste products are respectively set at 30%, 60% and 90%.

Generally, recovery ratio is related to retailer market sales, electronic waste amount, actual recovery capability of firms, national policy and so on. Due to previous contrasting statements about the impact of recovery ratio on the SC (Salvatore et al., 2016; Turrisi et al., 2013; Huang and Liu, 2008; Le and Yi, 2014), we adopt three levels of recovery ratio, i.e., 30%, 60%, 90%. In 2011, State Council of China releases the document of Suggestions to establish a complete and advanced recycling system. This regulation pointes out clearly that China pledges to establish a normative product reverse logistics before 2015 and increases the recovery ratio of main waste to 70%. In this regard, this recovery ratio (30%, 60% and 90%) allows us to compare distinguished recovery behaviors in a green SC reasonably.

From Table 2, BE of retailer is 2.04, 1.68 and 1.33 respectively at 30%, 60% and 90%; likewise, BE of distributor is 3.35, 2.64 and 1.86 severally; BE of manufacturer is 5.44, 4.20 and 2.76. Besides, with recovery ratio increasing from 30% to 90%, order level shows a gradually decline. Under random fluctuation of market demand, ordering demand of SC at all levels has magnified from downstream to upstream, while BE tends to descend with recovery ratio increasing. In brief, positive recovery activities alleviate the BE efficiently and largely.

Relevant BE variation is delineated as Figs. 15–18. Recovery ratio augment is critical in decreasing BE and the upstream shows more stock amplification. It is in accordance with detailed BE computation.

5. Scenarios comparison analysis of green SC optimization

Non-common agreement about how different BE-mitigating strategies may affects SC social-economic-environmental performance, is reached (e.g. Lee et al., 1997; Zhang, 2004; Agrawal et al., 2009). We comply with Disney's seminal work in mitigating BE, namely intensifying information sharing and reducing forecast time.

5.1. Information sharing reinforcement-based strategy

Generally, there is six types of information including sales, product, process, inventory, plans and resources. Information sharing reinforcement-based strategy is represented by sharing sales information from retailer. If all members fail to share sales information, the upstream would be constrained to their production by historical data or contracts. The downstream reaches a dilemma, namely cost optimization and surplus inventory backlog. Closest to market demand, retailer is capable of collecting accuracy sales information and distributing valuable information. Centralized management towards sales information, reduction in uncertainty of information and obtainment time as well as deep trench excavation, are valid for information sharing (Moyaux et al., 2007).

Primarily, ordering ratio of all links is determined by retailer sales information and its own stock. Figs. 19–22 emulate stock variation of optimized SD model, which shows information sharing reinforcement. Fluctuation of ordering demand and inventory in information sharing context, is much lower than current situation (without information sharing). It is obvious in three-echelon chain.

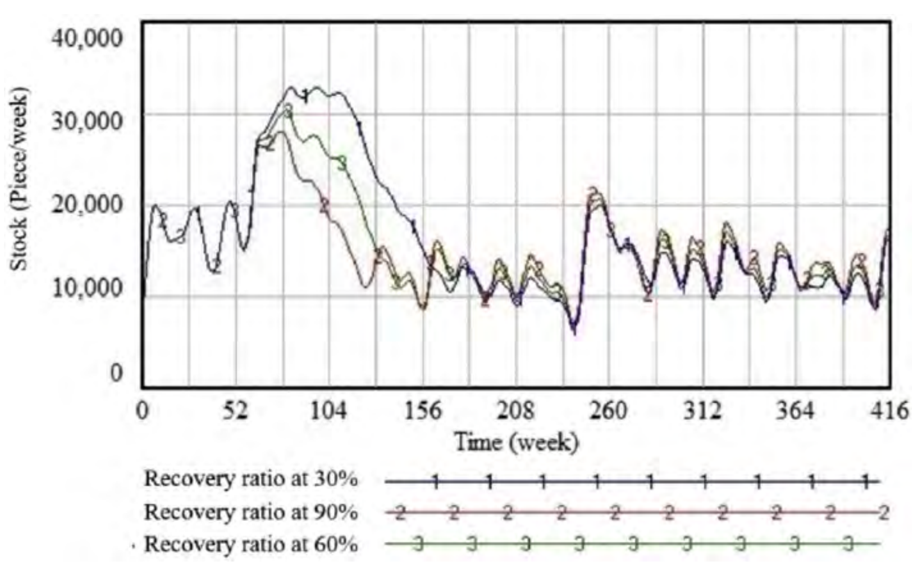

Fig. 15. Retailer stock variation.

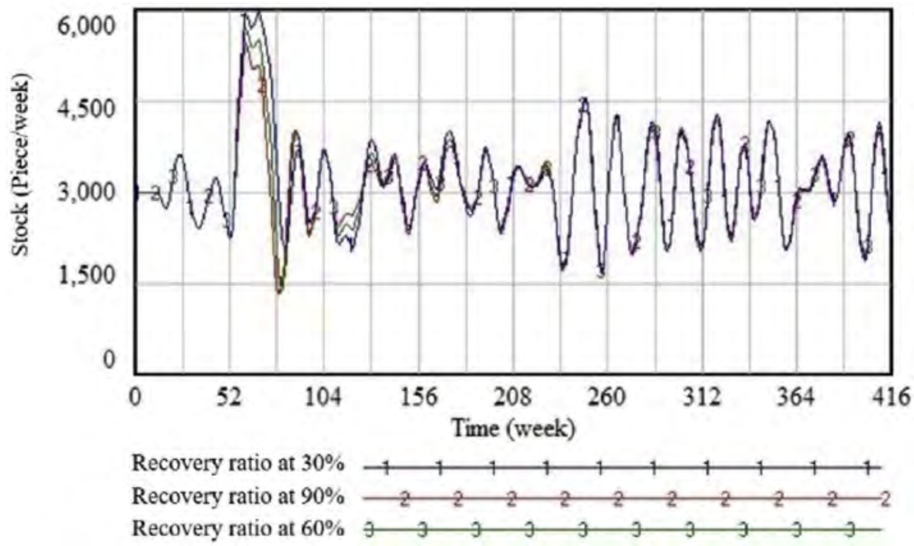

Fig. 16. Available stock variation.

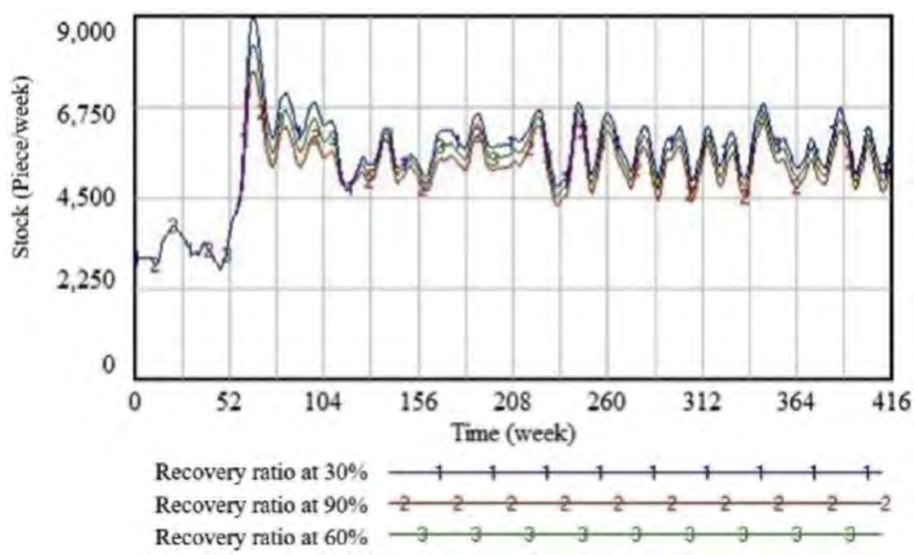

Fig. 17. Distributor stock variation.

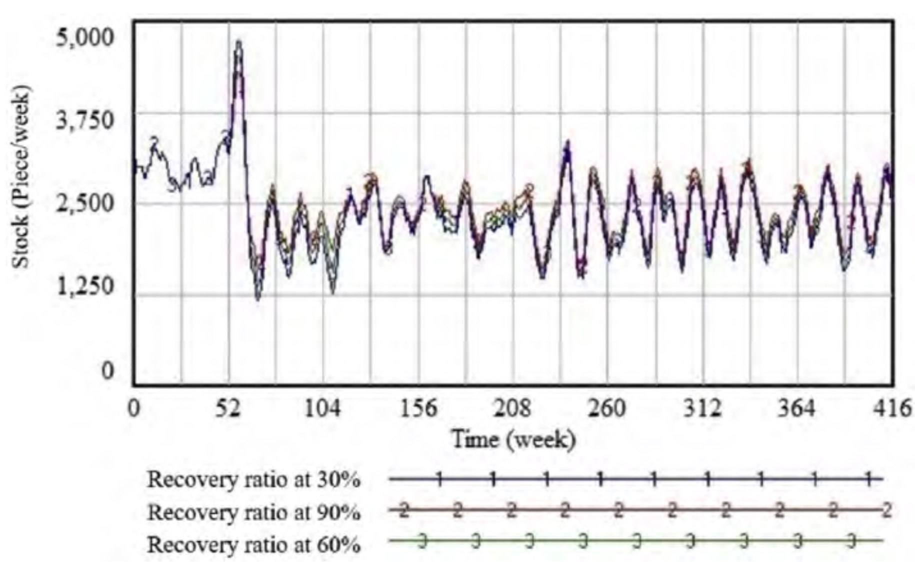

Fig. 18. Retailer stock variation.

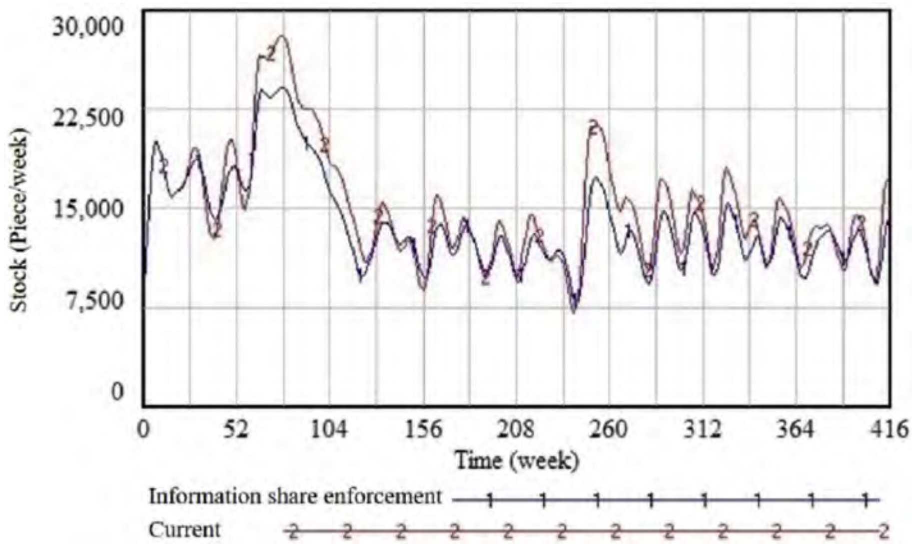

Fig. 19. Emulated-variation of component stock.

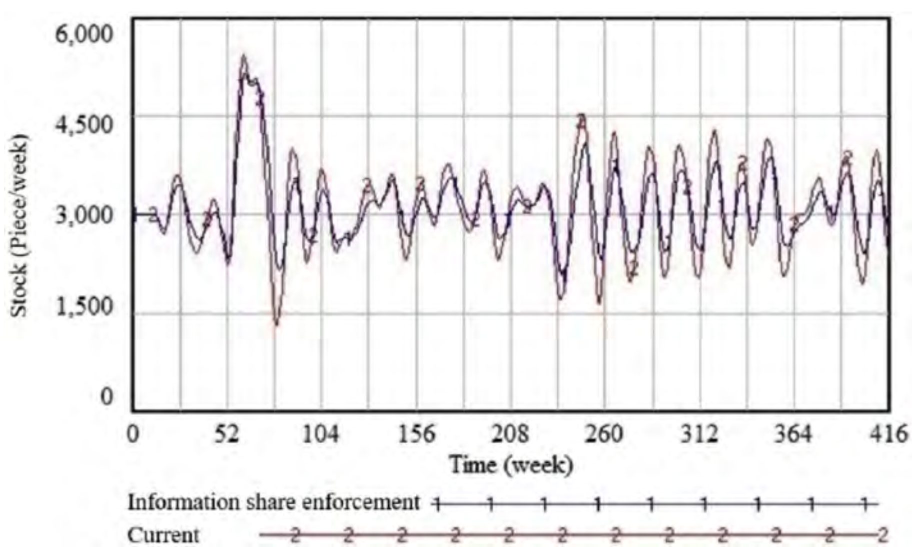

Fig. 20. Emulated variation of available stock.

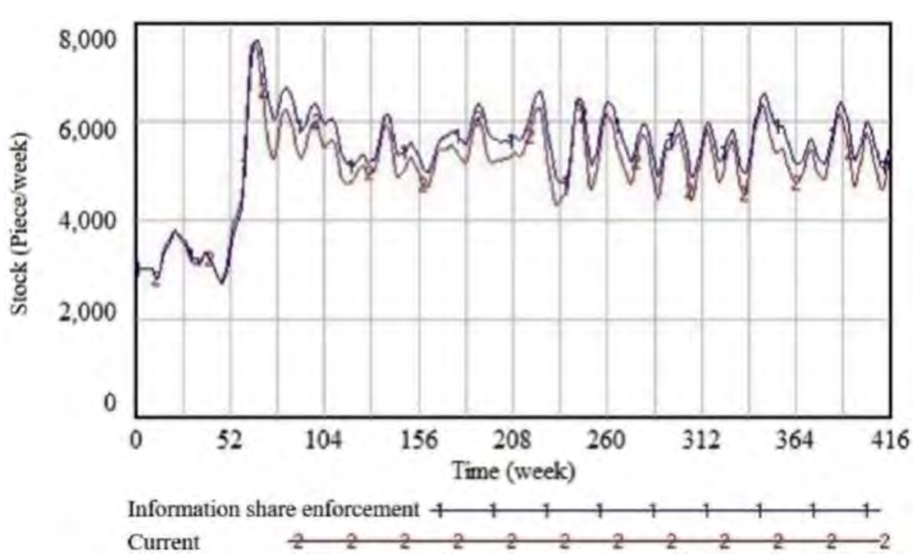

Fig. 21. Emulated-variation of distributor stock.

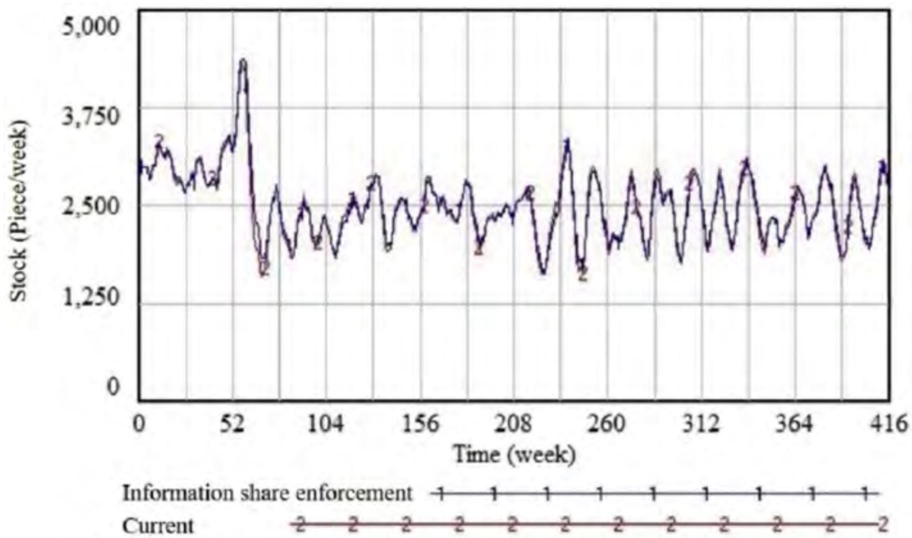

Fig. 22. Emulated-variation of retailer stock.

Table 3 demonstrates detailed response data of comparative existence effect of information sharing. Without sales information sharing, all links in SC displays a magnifying trend over market demand, with magnification of retailer demand at 1.22 times, magnification of distributor ordering demand at 1.63 times, magnification of manufacturer ordering demand at 2.07 times. With sales information sharing, all levels of SC still reveal a magnifying trend over market demand, with magnification of retailer demand at 1.11 times, magnification of distributor ordering demand at 1.31 times, magnification of manufacturer ordering demand at 1.62 times. Hence, information sharing is an effective method to mitigate rather than to remove BE, and remission efficiency with information sharing proves to be more obvious.

5.2. Lead/forecast time reduction-based strategy

Lead time is usually composed with two parts, namely order lead time and information lead time. They respectively refer to product manufacture-transport time and order processing time. Reduction of lead time is contributed to connecting intermediate links and easing BE from entirety. Besides, lead time in order processing is easy to regulate via electronic data interchange, while reduction of product manufacture-transport time appears tough extremely. In this regard, much more consideration has been put to shrink order processing lead time.

Figs. 23–26 describe the emulated results whether lead time reduction exists by modifying relevant parameters and decreasing forecasting time. Apparently, forecast time reduction helps decrease inventory volatility of distributor and manufacturer. Based on shrinking lead time, ordering demand changes in smaller ranges than the source model, so does ordering fluctuations and stock alterations of retailer. Table 4 explains comparative effect of lead time. Without decreased lead time, all levels display an expanded trend, with magnification of retailer demand at 1.22 times, distributor ordering demand at 1.63 times, manufacturer ordering demand at 2.07 times. With shrinking prediction time, all links still reveals a magnifying trend over market demand, with magnification of retailer demand at 1.07 times, magnification of distributor ordering demand at 1.35 times, magnification of manufacturer ordering demand at 1.45 times. Thus, reduction of lead time is effective to mitigate BE particularly obviously in the upstream. Nevertheless, reduction of lead time is an effective method to mitigate rather than to eliminate.

5.3. Scenario comparison analysis

Based on previous study, utilization of increasing recovery ratio, enforcing information sharing and decreasing lead time, are key strategies of reducing BE. It is necessary to discuss the effect of combined strategies on green SC. Herewith six simulated scenario are provided in Table 5.

5.3.1. Simulated comparison of Scenario 1, Scenario 2 and Scenario 3

Scenario 1, Scenario 2 and Scenario 3 delineates the emulated effect of lead time reduction and distinct recovery ratio simultaneously. From Figs. 27–30, three scenarios are valid for the reduction of inventory fluctuation in three-echelon SC compared with Figs. 23–26; BE in Scenario 3 is the lowest. Hence, Scenario 3 outperforms to mitigate BE compared with Scenario 1and Scenario 2.

Table 3
Comparative existence effect of information sharing.

Without information sharing		Market demand	Retailer order	Distributor order	Manufacturer order
	Variance	2429.05	2965.32	3966.21	5024.89
	BE		1.22	1.63	2.07
Information sharing		Market demand	Retailer order	Distributor order	Manufacturer order
	Variance	2391.53	2656.85	3125.65	3866.54
	BE		1.11	1.31	1.62

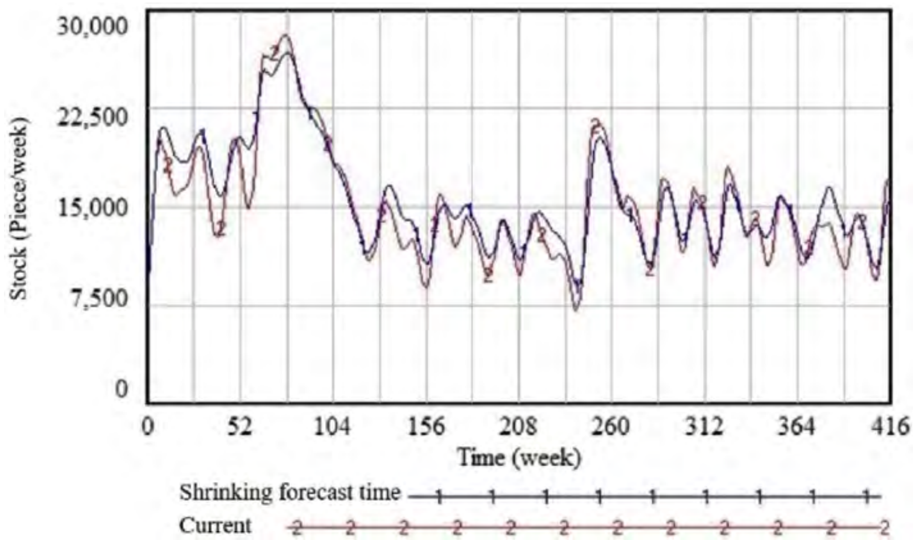

Fig. 23. Emulated-variation of component stock.

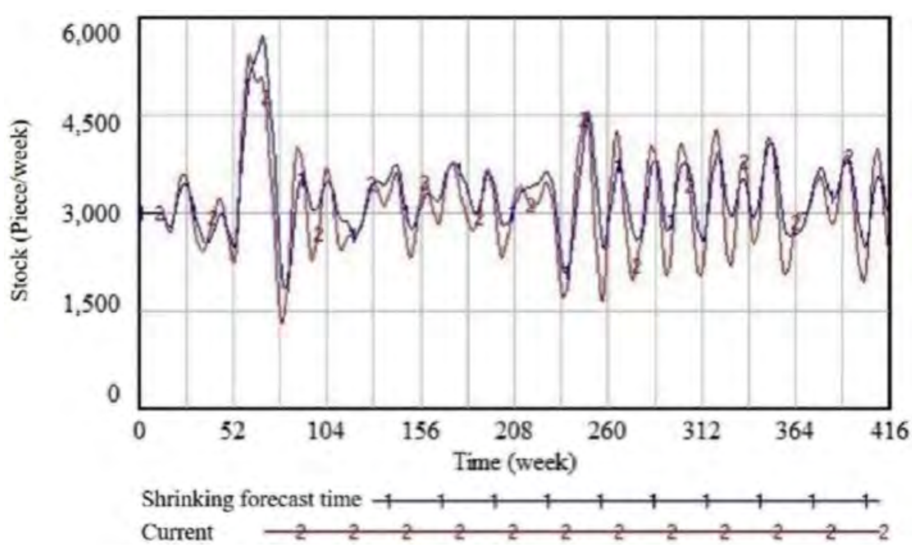

Fig. 24. Emulated variation of available stock.

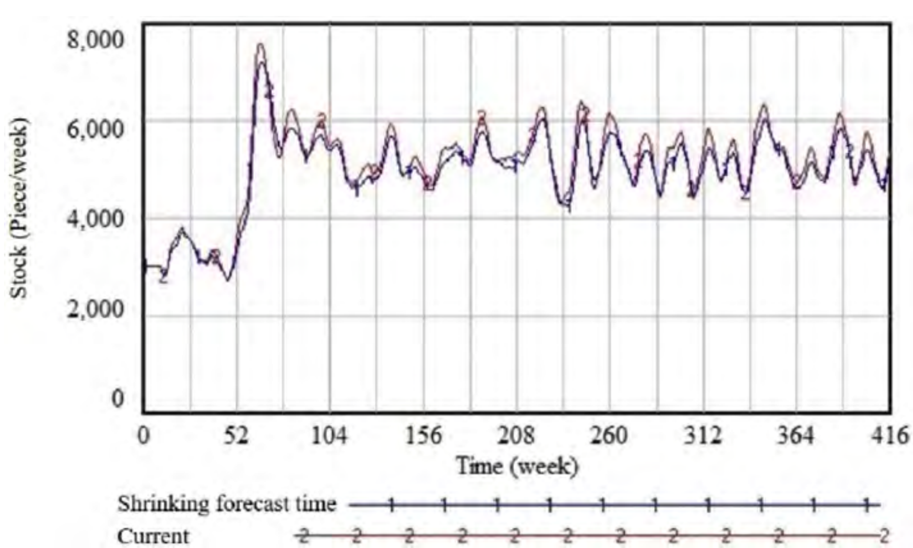

Fig. 25. Emulated-variation of distributor stock.

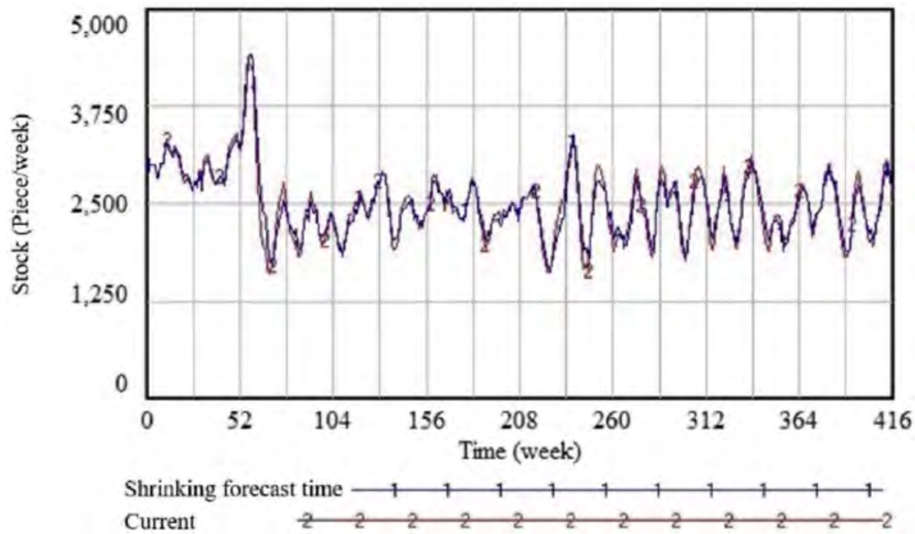

Fig. 26. Emulated-variation of retailer stock.

Table 4
Comparative alternation effect of forecasting time.

Constant lead time		Market demand	Retailer order	Distributor order	Manufacturer order
	Variance	2429.05	2965.32	3966.21	5024.89
	BE		1.22	1.63	2.07
Reduced lead time		Market demand	Retailer order	Distributor order	Manufacturer order
	Variance	2384.53	2556.85	3225.65	3466.54
	BE		1.07	1.35	1.45

5.3.2. Simulated comparison of Scenario 2, Scenario 4 and Scenario 5

Comparison of Scenario 4 and Scenario 5, denotes the scenario of different lead time with same recovery ratio (60%). Comparison of Scenario 2 with Scenario 5, emphasizes information sharing disparity with same recovery ratio (60%) and reducing lead time. From Figs. 31–34, three scenarios display greater mitigation effect on BE. Scenario 4, i.e., lead time reduction and high recovery ratio, proves superior. BE in Scenario 4 is being the lowest.

5.3.3. Simulated comparison of Scenario 3, Scenario 4 and Scenario 6

In views of above-mentioned comparison results, there is a necessity to compare the BE-mitigating results of Scenario 3, Scenario 4 and Scenario 6. From Figs. 35–38, three scenarios appear beneficial to alleviate BE. Among that, different nodes of green SC should adopt strategies respectively. Scenario 4, which represents the recovery ratio at moderate level (60%), emphasizes information sharing technology without reducing lead time, and tends susceptible by component stock and available stock of manufacturer, as well as retailer stock. However, distributor stock inclines to Scenario 3, which reducing lead time at recovery ratio of 90% without information sharing technology. The reason is mostly attributed to complicated impact factors of BE and different nodes in green SC.

Table 5
Scenario parameters.

Scenario	Recovery ratio	Information sharing	Reducing prediction time
Scenario 1	30%	No	5->4
Scenario 2	60%	No	5->4
Scenario 3	90%	No	5->4
Scenario 4	60%	Yes	5
Scenario 5	60%	Yes	5->4
Scenario 6	30%	Yes	5->4

5.3.4. Discussions on green SC optimization

Green SC is an environmentally-friendly system and pays much attention to the reverse SC. This study aims at proposing a new combination of strategies for dampening inventory amplification, stimulating recycling of electronic waste, decreasing material consumption and optimizing green SC.

(1) Discussions on combined strategies

For the combined strategies (proposed scenarios), Scenario 4 (higher recovery ratio and information sharing) proves to be more effective in green SC.

Combined strategies of high recovery ratio and information sharing, could not only enhance the recycling and reusing of overall electronic waste but also provide accurate demand information from the source. This scenario is more appropriate for manufacturer and retailer. However, distributer prefers the combined strategies of higher recovery ratio and reducing prediction time because of higher response efficiency.

(2) Discussions on single strategy

For single strategy, higher recovery ratio is an optimal solution in term of green SC because of the recycling of electronic waste and reduction of solid material depletion.

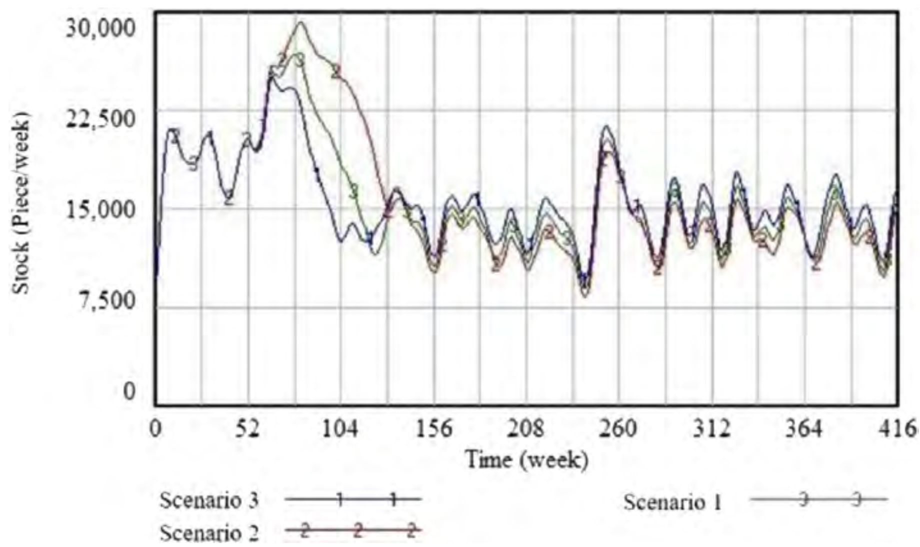

Fig. 27. Emulated-variation of component stock.

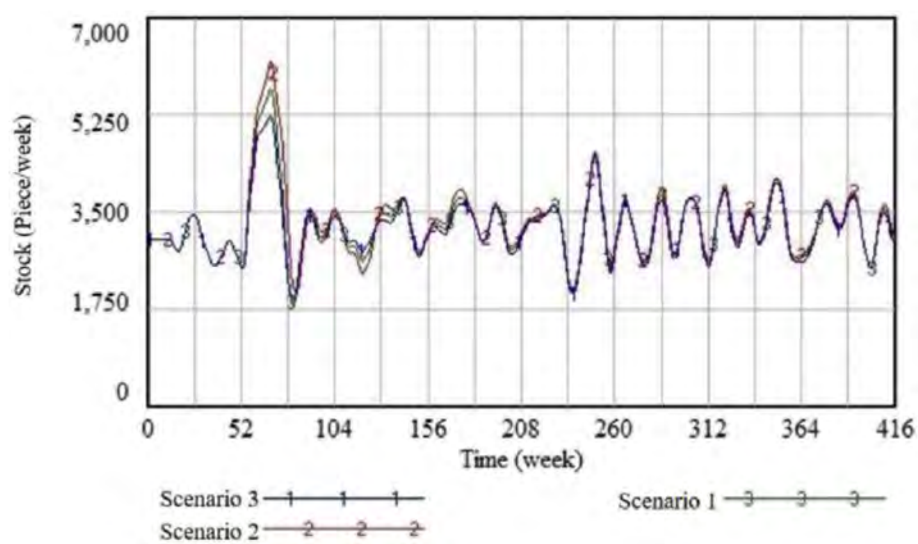

Fig. 28. Emulated variation of available stock.

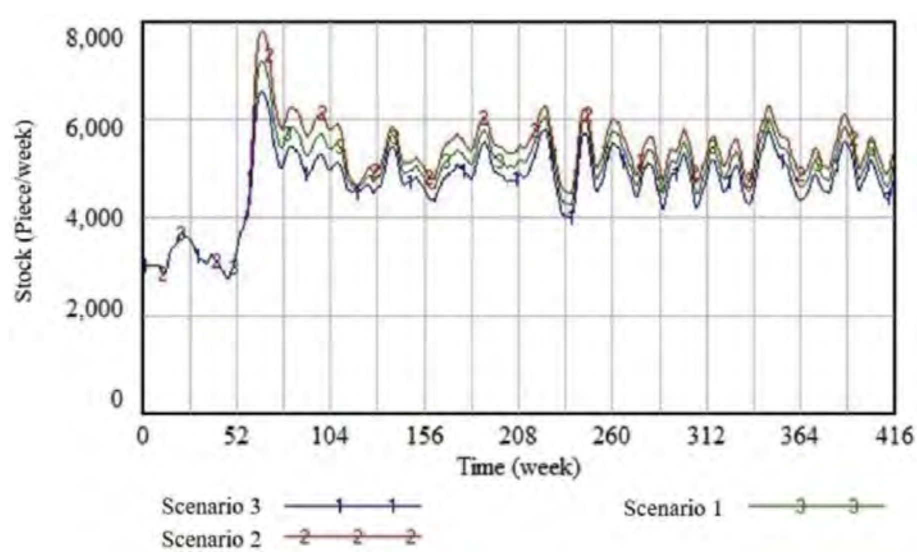

Fig. 29. Emulated-variation of distributor stock.

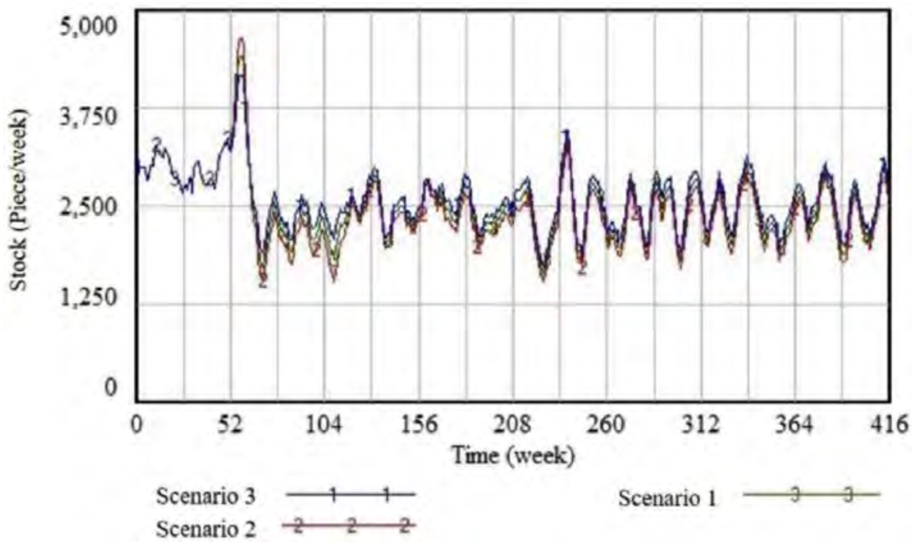

Fig. 30. Emulated-variation of retailer stock.

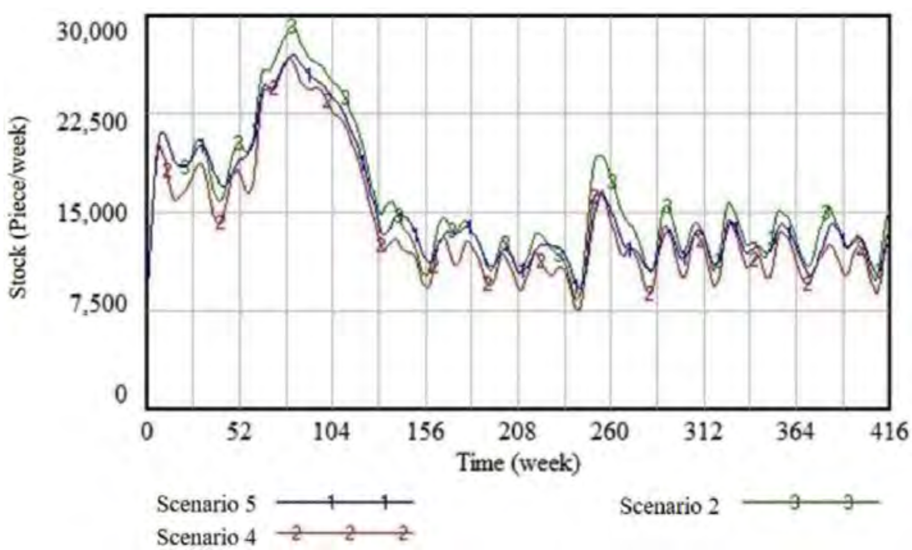

Fig. 31. Emulated-variation of component stock.

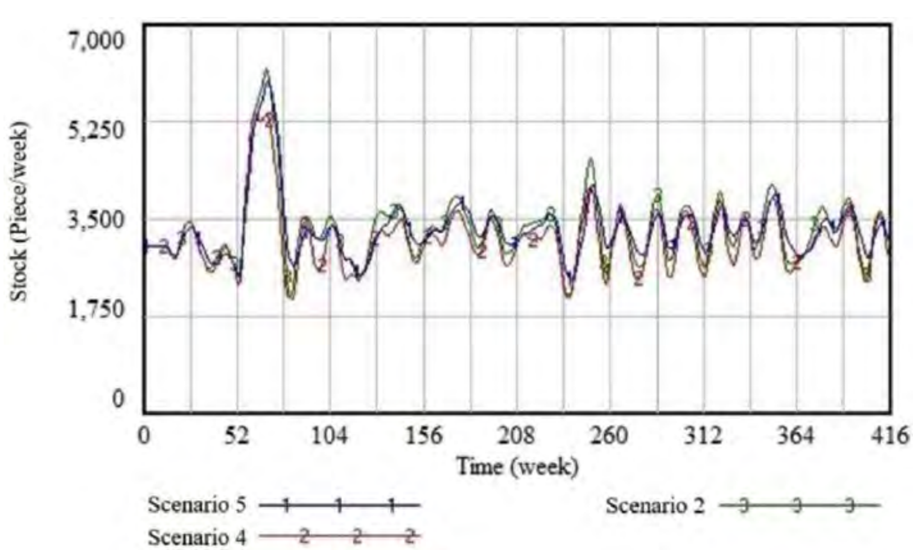

Fig. 32. Emulated variation of available stock.

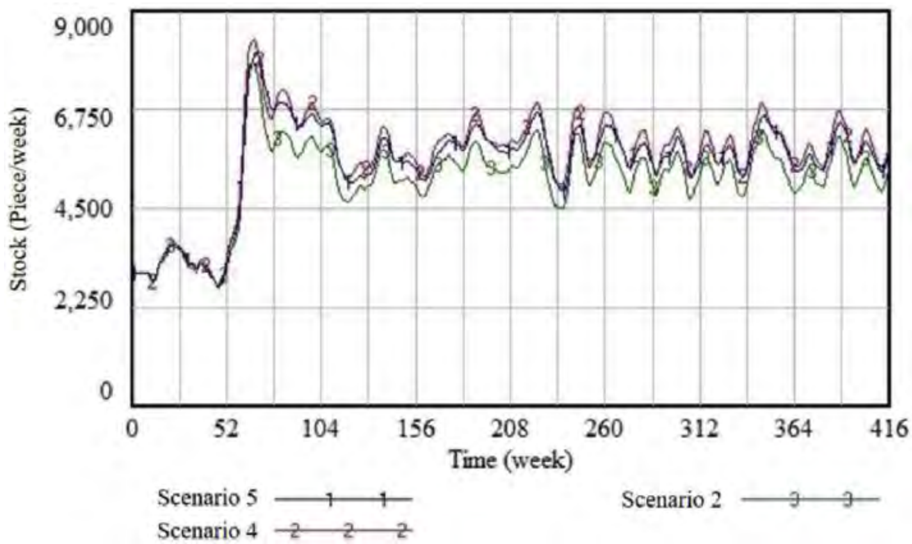

Fig. 33. Emulated-variation of distributor stock.

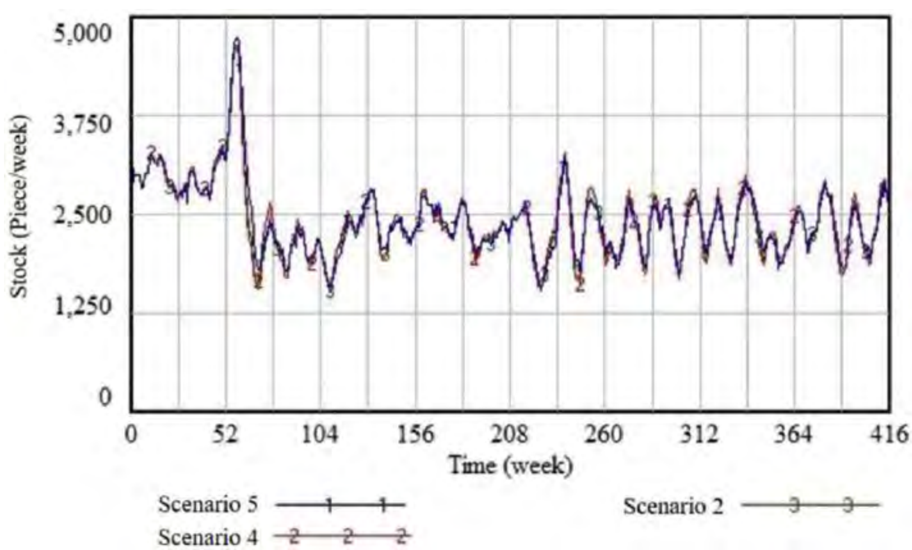

Fig. 34. Emulated-variation of retailer stock.

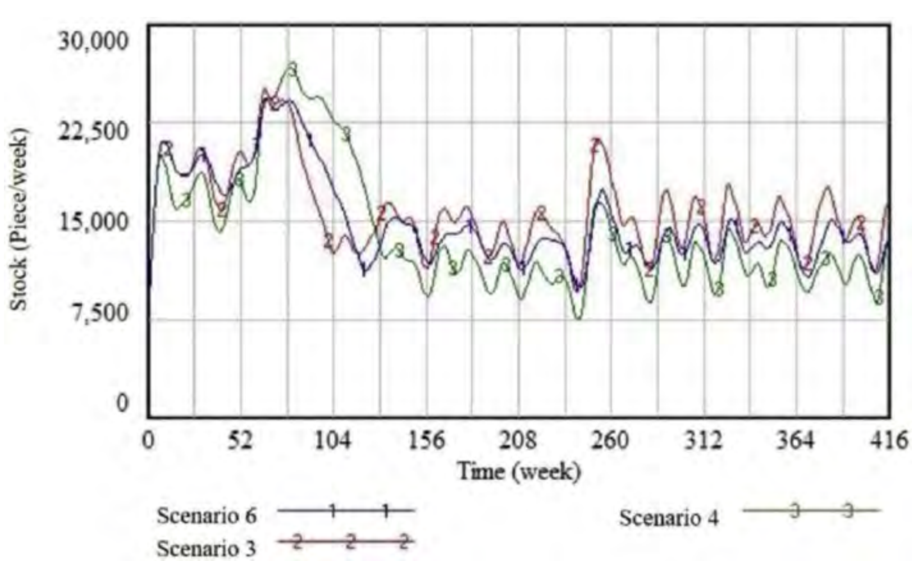

Fig. 35. Emulated-variation of component stock.

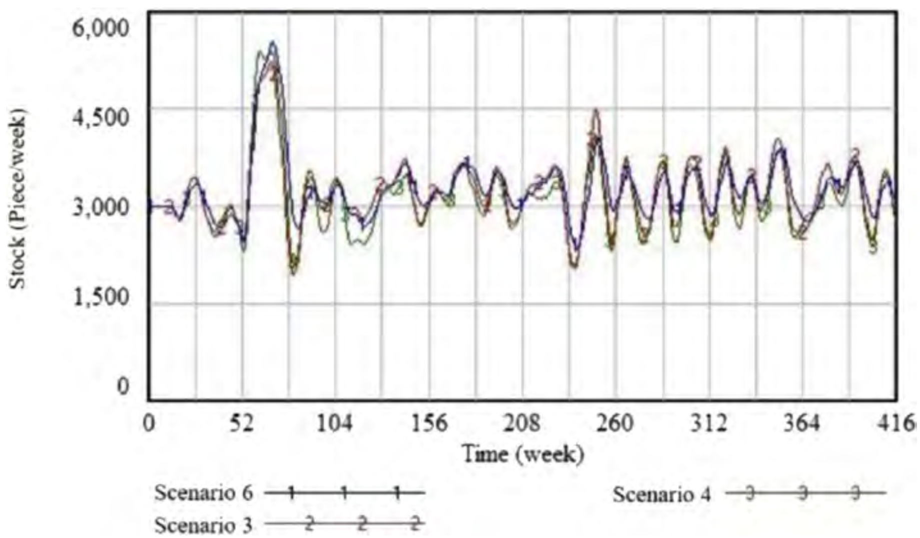

Fig. 36. Emulated variation of manuscript stock.

1) Recovery ratio increment

Introduction of reverse logistics has alleviated the BE in forward logistics (seen from Table 1) and enhanced the overall robustness of green SC. Reverse behaviors of electronic waste is more preferable in improving the performance of green SC. Higher recovery ratio, especially at 90% level, brings a large reduction both in BE and inventory instability. Regarding this, this study provides support in what kind of recovery ratio is more preferable for material depletion mitigation, waste product decline, solid pollution reduction and green effect improvement.

Moreover, this study encourages firms to develop reverse flows. Although the investment payback is delayed, recovery behaviors bring huge economic benefit and enormous environmental efficiency in the long run. As a self-reliant measure, reverse flow could be used to be supplement when exogenous methods occur any accidents. In brief, recovery ratio increment outperforms other single strategies including information sharing, echelons reduction and forecast time saving.

2) Information transparency reinforcement

Information sharing has a greater impact on the decline in inventory, and as the variance increases, the impact would gradually diminish. Nevertheless, decline in inventory would be significant as the variance rises. The reasons lie in that, retailer can accurately forecast the market demand when the demand fluctuates in a small range, and then share the information with the suppliers. Suppliers can reduce the unnecessary inventory. When the demand variance increases, retailer can still forecast the market demand but with relatively less accuracy (Cannella, 2014). Suppliers obtains the less accurate information and would not

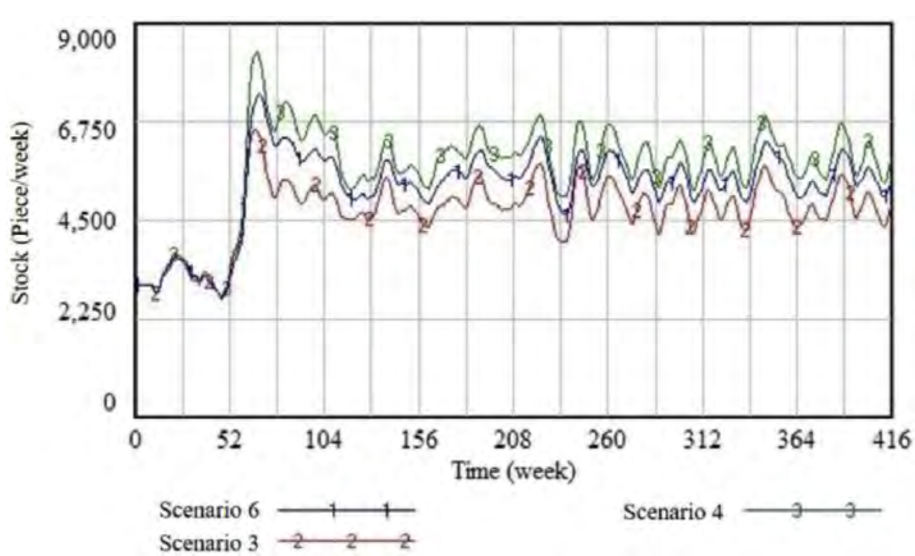

Fig. 37. Emulated-variation of distributor stock.

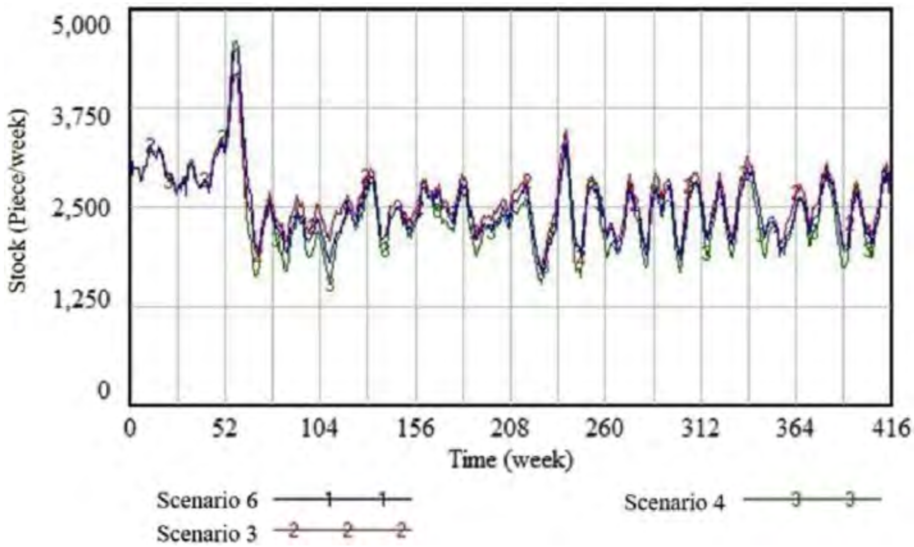

Fig. 38. Emulated-variation of retailer stock.

decrease inventory. Shown from the scenario simulation results in Table 5, information sharing technology tends to be susceptive by manufacturer and retailer.

Hence, information transparency reinforcement is essential, since it can enhance the performance of the SC and intensify the competition among members. While this strategy shows lower green effect than higher recovery ratio because of indirect function multiply.

3) Forecast time reduction

Lead times of manufacturing and distribution are recognized among the operational variables that largely impact the effectiveness of operations in SC (Ciancimino et al., 2012; Chatfield and Pritchard, 2013). Hence, the reduction of lead times has been recognized as a direct driver of business improvement (Towill, 1997). In this study, the reduction of lead times is critical to mitigate BE, while not the best measure for green SC optimization (Seen from Table 3). Shown from the scenario simulation results in Table 5, distributor inclines to the reduction of lead times.

In order to improve SC dynamics, the manufacturer has to invest in recycling technology and reduce recycling process time. Furthermore, managers may focus on production and operations approaches which improves the technological level of remanufacturing process.

6. Conclusions

This study implements SD model to perform scenario simulation and explore optimal BE-mitigating strategies in the optimization of green SC. A series of validity tests convince the robustness of established SD model. Relevant results are shown as follow:

Firstly, green SC refers to eco-management of both forward logistics and reverse logistics, especially the reverse logistics. As a typical phenomenon in green SC, BE leads to enormous inefficiencies such as excessive inventory investment, misguided capacity plans, ineffective transportation, invalid production schedules and so on. Through the mitigation of BE, we could mitigate inventory amplification, reduce the solid material depletion, optimize the whole green SC and obtain economic-environmental value.

Secondly, for single strategy, positive recovery activity is an optimal solution in green SC because of the recycling of electronic waste and reduction of solid material depletion; for the combined strategies (proposed scenarios), the combination of higher recovery ratio and transparency reinforcement proves to be more effective in alleviating the BE largely. Besides, the emulated-mapping of this field helps graphically illustrate the potential optimized-directions and stimulate individual recovery behaviors in green SC. Due to complication of SC structure, joint regulation is an effective method to mitigate rather than to remove BE, and remission efficiency in the superior proves to be more visible.

Thirdly, SD model has been widely adopted to alleviate BE issues and reveals obvious advantages, such as investigating the influence of reverse activities on dynamic performance, approaching realistic operation, lower data sensitivity, handling complicated situation etc. The emulated results testify the robustness of SD model in the mitigation of inventory amplification.

To summarize all the research content mentioned above and indicate the problems with lucubrate direction, future work can be extended to other aspects and systems. Take the following suggestion as reference.

This paper employs system dynamic model (SD) to emulate realistic operation of electronic industry. Consistent with practical operation mechanism, the results are critical in dampening such amplification, stimulating positive recovery activities, decreasing material consumption and improving social-economic-environmental value. Future researches should evaluate the impact of the proposed SD model and combined scenarios on other industries, such as the reverse logistics of China's typical high-consumption industry. Considering the facts that the power sector is and would always be the largest energy consumer in China, it is obvious that this sector should be treated as a priority for cleaner production (Lisha and Lin, 2016). As the largest industry of energy consumption in China, power industry showed serious materials waste (e.g. coal cinder) in production side. By adopting different recovery ratio (over 60%) in all workshops, power industry could be able to maximize the waste and save materials. The social-economic-environment value would be improved. Besides, considering the reduction of lead time from demand side, final product (i.e., electricity) could be purchased and consumed with less time delay. Recycling technology and reduce recycling process time could be stimulated.

Acknowledgements

This study was financially supported by the National Natural Sciences Foundation of China (No. 71774008), Beijing Natural Science Foundation (No. 9172015), Beijing Social Science Foundation (No.17JDYJB010) and Joint Development Program of Beijing Municipal Commission of Education.

Appendix A

Table A1
Variables type

Variable tape	Content
State variable	Retailer stock (RS)
	Distributor stock (DS)
	Manufacturer stock (MS)
	Component stock (CS)
	Recycler stock (Recycler S)
Rate variable	Retailer selling rate (R selling rate)
	Manufacturer delivery rate (MDR)
	Distributor delivery rate (DDR)
	Component productivity (CPR)
	Recovery product rate (Rec overy P rate)
	Recovery reproducing product rate (Recovery reproducing P rate)
	Recovery reproducing components rate (Recovery reproducing C rate)
Auxiliary variable	Distributor order (D order)
	Distributor product demand rate (DP demand rate)
	Distributor expected stock (D expected S)
	Distributor selling forecast (D selling forecast)
	Manufacturer order (M order)
	Manufacturer product demand rate (M P demand rate)
	Manufacturer selling forecast (M selling forecast)
	Retailer order(R order)
	Retailer product demand rate (R P demand rate)
	Retailer expected stock (R expected S)
	Retailer selling forecast (R selling forecast)
Constant variable	Product recovery rate (P recovery rate)
	Distributor delivery delay (D delivery delay)
	Distributor production delay (D delivery delay)
	Recycled product stock adjustment time (Recycled P S adjustment time)
	Recycled product reproducing ratio (Recycled P reproducing ratio)
	Recycled product reproducing delay (Recycled P reproducing delay)
	Recycled component reproducing ratio (Recycled C reproducing ratio)
	Recycled component reproducing delay (Recycled C reproducing delay)
	Stock adjustment time (S adjustment time)
	Sustainable time of expected stock (Sustainable time of expected S)
	Moving average period
	Manufacturer delivery delay (M delivery delay)
	Manufacturer production delay (M production delay)
	Transportation delay
	Recycled product (Recycled P)
	Product life cycle (P life cycle)
	Distributor production capacity (D production capacity)
	Manufacturer production capacity (M production capacity)
	Remanufacturing product capacity (Remanufacturing P capacity)
	Production capacity of remanufacturing component (Production capacity of remanufacturing C)

Appendix B. Variables description

(1) M CS

Relevant equations about M CS are shown as below. The unit of manufacturer delivery rate, manufacturer production order, manufacturer production demand rate and manufacturer sales forecast, is piece/week. Stock unit is piece.

1) C amount forecast = P C amount*Smooth (M PR, 7)
2) Expected CS = Expected CS cover time*C amount forecast
3) Expected CS cover time = 3
4) C production time = 3
5) C production time = Delay 3 (C demand, C production time)
6) C demand = Max (0,C amount forecast + CS error/CS adjustment time)
7) C reproduce percentage = 0.65
8) C reproduce amount = Indirectly used C*C reproduce percentage/Secondary produce time

9) CS=Integ (Directly used C capacity + C reproduce amount + C Production rate-M Production rate, 9000)
10) CS error = Expected CS-CS
11) CS adjustment time = 5

Relevant equations about available S of M P are shown as below.

1) P reproduced percentage = 0.65
2) P reproduced amount = Directly used reproduced P/Reproduced time
3) P C amount = 3
4) Available S= Integ (P reproduce amount + MPR− MPR, 3000)
5) Available S gap = M expected S−Available S
6) Available S adjustment time = 5
7) M delivery rate = Delay3 (D order, Time in transporting to D)
8) M expected S = M expected S cover time* M selling forecast
9) M expected S cover time = 3
10) MPR = Delay3 (M order, M production time)
11) M order = Max (0, M selling forecast + Available S error/Available S adjustment time)
12) M selling forecast = Smooth (M delivery rate, 7)

(2) DS

Relevant variables about DS are described as follows. The unit of distributor delivery rate, distributor order, distributor production demand rate and manufacturer sales forecast, is piece/week. Stock unit is piece.

1) D delivery rate = Delay3 (R order, time in transporting to R)
2) DS = Integ (M delivery rate−D delivery rate, 3000)
3) DS error = Max (D expected S−DS, 0)
4) DSA time = 5
5) Expected D S = D selling forecast*D expected S cover time
6) Expected D S cover time = 3
7) D order = Max (0,D selling forecast + D S error/DSA time)
8) D selling forecast = Smooth (D delivery rate, 7)
9) Time in transportation to D = 3

(3) RS

Relevant variables about R S are described as follows. The unit of retailer order and retailer sales forecast, is piece/week. Stock unit is piece.

1) Time in transporting to R = 3
2) Sales = If then else (RS-actual demand>=0, Actual demand, RS)
3) RS = Integ (D delivery rate-sales, 3000)
4) RS error = Expected RS- RS
5) Available S adjustment time = 5
6) Expected RS = Expected R S cover time*Expected demand
7) Expected RS cover time = 3
8) R order = Max (0, Expected demand + RS error/RSA time)
9) Expected demand = Smooth (Sales, 7)
10) Actual demand = S demand- Coefficient* (P recovery ratio* WP)
11) S demand = 1000 + If then else (Time>4, Random normal (−200,200,0,100, 4),0)

(4) Reverse logistics

Relevant equations about reverse logistics are listed as below. Similarly, unit of amount and stock is piece.

1) Final time = 416
2) Initial time = 0
3) Time step = 1 week
4) Secondary produce time = 2
5) Reproduce time = 1.2
6) Reproduced C=Integ (C reproduced amount, 0)
7) Initial check time = 1
8) RM = Integ (Disused C RM Recovery amount−CPR, 1e+012)
9) Available P percentage = 0.65
10) Available recovery amount = Waste P*Available P percentage*P recovery ratio
11) Available C percentage = 0.35
12) Directly reproduced P capacity = P reproduced percentage*Recovery waste P/Initial check time
13) Directly used C= Integ (Directly used C capacity, 0)
14) Directly used C capacity = CS of indirectly reproduced P *Available C percentage/Assemble and check time
15) Directly used reproduced P = Integ (Directly reproduced P capacity−P reproduced amount, 0)
16) Recovery RM = Integ (Indirectly used C RM RA, 0)
17) Recovery waste P = Integ (Available recovery amount-Directly reproduced P capacity−Indirectly reproduce unacceptable−P, 0)
18) Abandoned amount = Waste P−Available recovery amount
19) Disused C RM recovery amount = Indirectly used C*(1− C reproduced percentage)/Secondary produce time
20) Indirectly reproduce unacceptable-P=(1−P reproduce percentage)*Recovery waste P/Initial check time
21) C of indirectly reproduce P=P C amount*Indirectly reproduce unacceptable-P* CS of indirectly reproduced P= Integ (C of indirectly reproduced P−Directly used C capacity- Indirectly used unacceptable-C,0)
22) Indirectly reproduced P =Integ (Indirectly reproduce unacceptable-P, 0)
23) Indirectly used C=Integ (Indirectly used unacceptable−C−Indirectly used C RM recovery amount−C reproduce amount, 0)
24) Indirectly used unacceptable−C=CS of indirectly reproduce P*(1−Available C percentage)/Assemble and check time
25) Waste P = DELAY FIXED (Sales, 52, 0)
26) Waste P abandoned amount = Integ (Abandoned amount, 0)
27) Coefficient = 0.5
28) Assemble and check time = 1

Appendix C

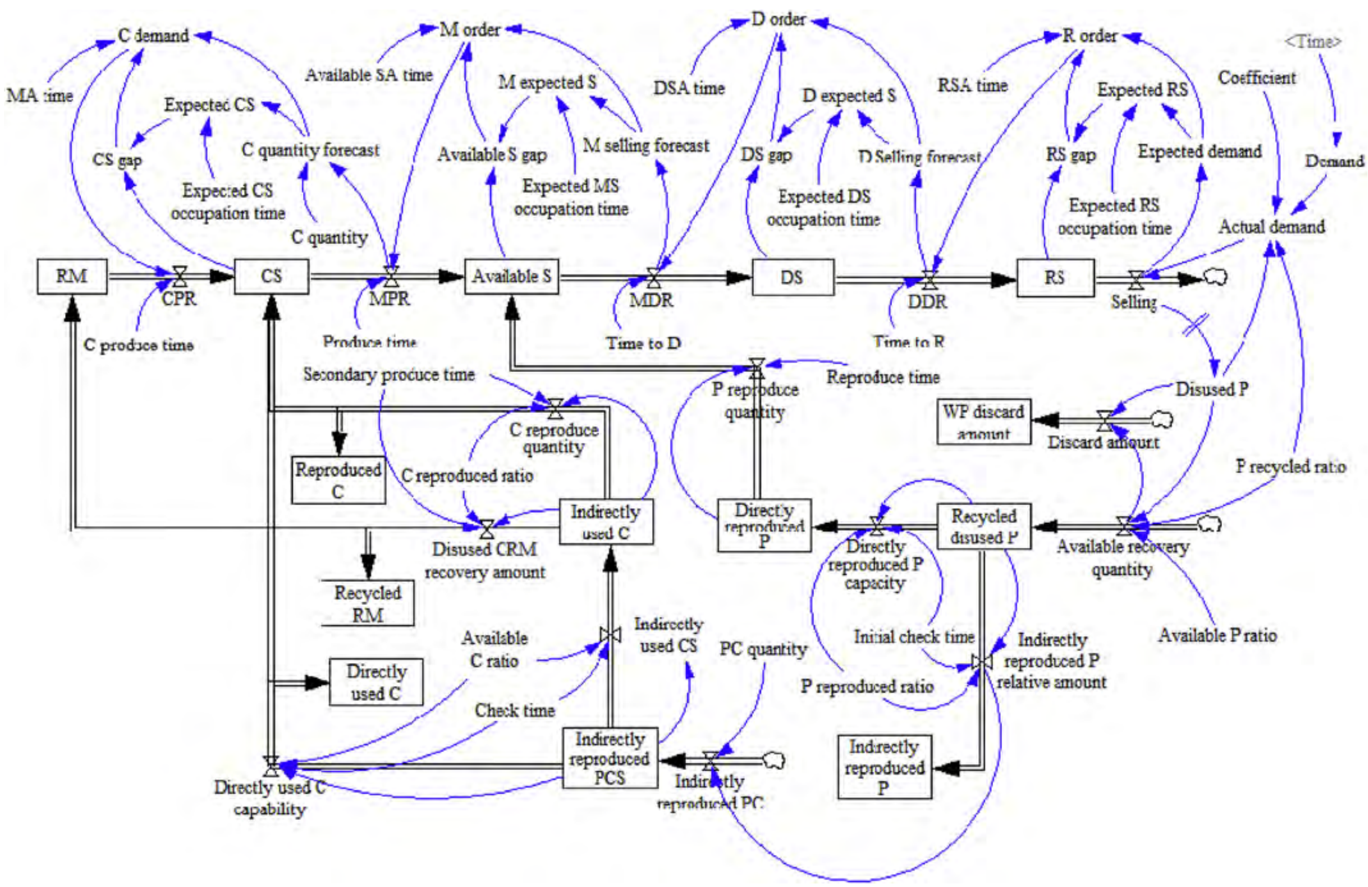

Fig. A1. Flow diagram of green supply chain.

Abbreviations Main variables in Appendix A, Appendix B and Appendix C are expressed in abbreviation.

Component = C
Manufacturer = M
Distributor = D
Retailer = R
Product = P
Stock = S
Order = O
Component stock = CS
Manufacturer stock = MS
Distributor stock = DS
Retailer stock = RS
Waste product = WP
Raw material = RM
Distributor stock adjustment = DSA
Retailer stock adjustment = RSA
Component production rate = CPR
Manufacturer productivity = MPR
Manufacturer delivery rate = MDR
Distributor delivery rate = DDR
Component raw material = CMR
Product component stock = PCS

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