Research Article

A System Dynamic Model of Closed-Loop Supply Chain considering Recovery Strengthening and Product Differentiation

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1. Introduction

The development of technology and information has made the renewal cycle of products highly reduced. Although it has brought convenience to consumers, the number of waste products has sharply increased, and even the phenomenon of “garbage siege” has become rather serious. At present, two-thirds of large and medium-sized cities in China are surrounded by garbage. The output of urban garbage exceeds 400 million tons per year, and it is increasing at an annual rate of 9–10%, which not only causes huge garbage disposal costs and environmental problems but also discards a large number of reusable resources. Since recycling and remanufacturing of used products could provide a new opportunity to prevent the impact of waste on the environment [1] and bring huge economic values, they have gotten increased attention. Data shows that remanufacturing of waste tires, electronic products, and automobile engines can effectively save raw materials by over thirty percent and reduce energy consumption by up to 15% [2]. Extensive research studies on recycling and remanufacturing with various research methods have been drawn. Among them, factors which are involved in the practice of recycling and remanufacturing are mostly conducted from single or double aspects. Comprehensive studies are obviously rare. In addition, few literatures considered the impact of recycling on demand and the relationship between remanufactured products and new products. With the development of the closed-loop supply chain (CLSC) and the improvement of environmental awareness of consumers, the effect of recycling and remanufacturing on demand can not be ignored, which not only brings greater uncertainty to the closed-loop supply chain but also becomes an opportunity for supply chain expansion. The relationship between remanufactured products and new products will also become an important issue in CLSC when there are more remanufactured products. Therefore, it is necessary to explore the effects of recycling on demand and even on the whole CLSC. For these reasons, a comprehensive multifactor closed-loop supply chain system dynamics model with the strengthening effect of the recovery on the demand and the relationship between remanufactured products and new products is established.
2. Literature Review

This section reviews the research on recycling and remanufacturing to analyze the factors of the CLSC and derives the value of this article.

2.1. The Overview of the Quality and Classification of Returned Products. There are great differences in the qualities of returned products due to factors such as using conditions and times which seriously affect the costs and benefits of recycling and remanufacturing. Therefore, some researchers considered the quality of recycled products in their research. Masoudipour et al. [3] gave returned products different quality scores according to their characteristics and qualities to classify them. Miao et al. [4] established three e-waste classification methods based on the different qualities of returned products. Jia [5] analyzed the impact of the qualities of returned products on the CLSC in terms of uncertainty.

2.2. The Overview of Recycling Incentives and Recycling Efforts. Great cognitive differences among consumers lead to incentives and efforts for returning of used products. To facilitate product recycling, incentives for recycling efforts were taken. Wang et al. [6] incorporated the cost of efforts such as advertising investment into the model. Wang et al. [7] considered the investment costs of recycling and found that there was a threshold for the incentives of governments. Only when the incentive was greater than the threshold, the mechanism could be effective. Taleizadeh et al. [8] pointed out that in order to increase the amount of returned products, both the third parties and retailers chose to invest in collection efforts. De Giovanni [9] believed that companies sponsored the recycling of products in different ways for different motives. Besides the natural recovery rate, this paper introduces a recovery rate which is related to recycling incentives and efforts. The natural recovery rate is defined as the spontaneous return rate of consumers.

2.3. The Overview of the Effect of Recycling on Demand. Considering recovery rate as a part of the demand was the majority assumption in the public research. Hosoda and Disney [10] believed that the recovery rate was related to the demand, but the opposite was not true. However, few literatures discussed the impact of recycling on the market demand. Ma and Hu [11] considered that recycling could expand demand by improving the recovery rate. Ma and Hu [12] gave another reason for the increased demands by recovery rate. When people chose to return waste products, they need to buy new products to meet the continuous demands. De Giovanni [13] regarded recycling as a marketing lever and believed that the demand was a function of the retail price and the recovery rate. Hosoda et al. [14] believed that the market demand and recovery rate were random and interrelated. From the above, it is necessary to consider the strengthening effect of recycling on the market demand in CLSC and explore the impacts from different intensities.

2.4. The Overview of the Relationship between Remanufactured and New Products. The relationship between remanufactured products and new products is an important issue to CLSC: how do consumers treat remanufactured products and new products, the same or having preferences? Whether the remanufactured products have impacts on demand for products in the forward supply chain? And, the impact is positive or negative? Most papers assumed that remanufactured products were “as good as new” [15, 16]. Some studies believed that there were differences between new products and remanufactured products [17–19]. Among them, there were two views: one was that both were the function of their own and relative prices; the other was that the needs of the two were independent [20, 21]. This paper holds that there are differences between remanufactured products and new products, and consumers can distinguish them. Since this paper focuses on simulation, it only assumes that the demands of the both are independent.

2.5. The Overview of Recycling Channels. In the existing studies, recycling channels were uncertain: single, double, and multiple channels were all possible. Chen et al. [22] established four closed-loop supply chain models of dual selling and recycling channels and analyzed the profits of CLSC members. Shi et al. [23] studied the impact of reward and punishment mechanisms on the cooperation strategies of manufacturers in CLSC with double recycling channels between the manufacturer and the third party. Jalali et al. [24] discussed the optimal configuration of the CLSC with complementary products recycled by the manufacturer and the retailer, respectively, and jointly. Taleizadeh et al. [8] studied channel choices and coordinations between the retailer and the third party. With the promotion of recycling activities, recycling channels will be diversified and channel competitions will become an inevitable factor in CLSC. This paper extends the single-channel model to a dual-channel model to discuss the impact of channel competitions.

2.6. The Overview of Research Methods. There were three kinds of methods used in the research on the CLSC: game theory, and almost all pricing and coordination problems were established by GT [25]; the second was the mathematical programming method [1], mainly used for network planning, design, and optimization. The last was the system dynamics (SD), which was used to solve multifactor and complex problems. Li et al. [26] used SD to study the impact of the service radius of the recovery center. Miao et al. [4] constructed an SD model of online-disposal and offline-transaction. Da et al. [27] analyzed behaviors of the CLSC using SD. In this paper, the system dynamics method and Vensim 7.3.5 are used.
From the literature review, the impact of recycling on the demand and the relationship between remanufactured products and new products are rarely considered simultaneously. This paper integrates the impact of recycling on the demand and the relationship between remanufactured products and new products for the first time and comprehensively considers a variety of factors in CLSC to explore the influences of recycling and remanufacturing on the CLSC.

3. Parameter Definition and Equations

3.1. Model Description. The forward supply chain considered in this study consists of a supplier, a manufacturer, a retailer, and a collector. The supplier provides the parts required by the manufacturer. The manufacturer is responsible for the production of new products and the remanufacturing of recycled products. The retailer sells products to meet the market demand. All of them have the ability to predict demands from the downstream and hold expected inventories. In the reverse activities, driven by government policies, social benefits, and economic values, the recycler adopts a variety of strategies, such as old for new, advertising, and recycling price subsidies to promote recycling activities. The recovery rate is divided into two parts: the natural recovery rate and the recovery effort effect, which is affected by policies. The qualities of used products have great differences, and testing and classifying are taken to distinguish them. Returned products with better quality that can be directly remanufactured and can be reused after disassembly as available parts are stored as inventories. The unavailable parts are processed in a controllable manner. Recycled products and parts are only used in remanufactured products. In addition, remanufactured products can use new parts but conversely is not feasible. Remanufactured products are sold by the retailer at different prices. The conceptual diagram of the system is shown in Figure 1.

3.2. Model Assumptions. The following assumptions are made for the CLSC:

Hypothesis 1: both new products and those with potential remanufacturable value could be recycled and remanufactured
Hypothesis 2: remanufactured products and new products have their own demands, and the price of remanufactured products is lower than that of new products
Hypothesis 3: consumers are price-sensitive, remanufactured products could be sold completely and have a negative impact on the demands for new products
Hypothesis 4: the retailer, the manufacturer, and the supplier all adopt the order-up-to inventory replenishment strategy
Hypothesis 5: there is no limit on the production capacity and inventory capacity
Hypothesis 6: the system has no backlog orders

3.3. Model Formulations

3.3.1. Causality Diagram. In order to establish the SD model that clearly and accurately reflects the actual relationship in CLSC, it is necessary to sort out the relationships between the main activities of the system. The causality diagram is an effective representation, and the causality diagram of the model is shown in Figure 2.

3.3.2. Stock Flow Diagram. Different types of elements are involved in the model. The elements are mainly divided into two categories: stock and flow. The stocks are determined by the integration of flows. And, the flows include both inflows and outflows. The stock flow diagram that captures the relationships between variables is shown in Figure 3.

3.3.3. The Equations of Simulation

(1) The Equations of the Supplier. The supplier sets up production activities for the demand of parts with the expected inventory. The expected inventory is equal to the demand forecast multiplied by the inventory coverage time. The exponential smoothing method is used for forecasting. The parts produced by the supplier can be supplied to the manufacturer as available inventories after the production lead time and the delivery delay. The equations are as follows:

\[ \text{supplier productivity} = \text{supplier demand forecast} + \text{manufacturer inventory adjustment/supplier inventory adjustment cycle} \]
\[ \text{supplier inventory adjustment} = \max(0, \text{supplier expected inventory - supplier inventory}) \]
\[ \text{supplier expected inventory} = \text{supplier demand forecast} * \text{supplier inventory sustainability time} \]
\[ \text{supplier demand forecast} = \text{SMOOTH} \left( \text{manufacturer order rate} + \text{remanufactured parts order rate}, \text{supplier forecast moving average cycle} \right) \]
\[ \text{supplier inventory} = \text{INTEG} \left( \text{DELAY}(\text{supplier productivity}, \text{supplier production lead time}) + \text{supplier delivery rate} - \text{supplier remanufacturing parts delivery rate} \right) \]
\[ \text{supplier delivery rate} = \text{SMOOTH} \left( \text{manufacturer order rate}, 1 \right) \]
\[ \text{supplier remanufacturing parts delivery rate} = \text{SMOOTH} \left( \text{remanufactured parts order rate}, 1 \right) \]

(2) The Equations of the Manufacturer. In the hybrid system, production activities and remanufacturing activities of the manufacturer are affected by production conversion. Therefore, the lead time of production is extended, and the degree of extension is determined by the production conversion coefficient. The equations of the manufacturer are as follows:

\[ \text{manufacturer order rate} = \text{manufacturer demand forecast} + \text{manufacturer inventory adjustment/supplier inventory adjustment cycle} \]
\[ \text{manufacturer productivity} = \text{manufacturer demand forecast} + \text{manufacturer inventory adjustment/supplier inventory adjustment cycle} \]
manufacturer inventory adjustment = MAX (0, manufacturer expected inventory - manufacturer inventory)

manufacturer expected inventory = manufacturer demand forecast * manufacturer inventory sustainability time

manufacturer demand forecast = SMOOTH (retailer order rate, manufacturer forecast moving average cycle)

manufacturer inventory = INTEG(DELAY1 (manufacturer productivity, manufacturer production lead time) - manufacturer delivery rate)

manufacturer delivery rate = SMOOTH (retailer order rate, 1)

manufacturer production lead time = 2/production conversion coefficient

(3) The Equations of the Retailer. At the initial stage of the system, the market is only dominated by the demand for new products. After the recycling and remanufacturing activities start, the market is faced with the demands for new products and remanufactured products at the same time. The equations of the retailer are as follows:

retailer order rate = retailer demand forecast + retailer inventory adjustment

retailer delivery rate = SMOOTH (new products demand rate, retailer forecast moving average time)

retailer inventory adjustment = MAX (0, retailer expected inventory - retailer inventory)

retailer expected inventory = retailer demand forecast * retailer inventory sustainability time

Figure 1: The system conceptual diagram of the CLSC. Note. The solid lines are the forward supply chain material flow; the dashed lines are the reverse flow.

Figure 2: The causality diagram of the CLSC.
The demand for new products is equal to the total market demand minus the demand for remanufactured products. At
the same time, this paper considers that recycling and remanufacturing will increase the total market demand. The equations of demand are as follows:

\[
\text{new products demand rate} = \text{total market demand rate - remanufactured products demand rate.}
\]

\[
\text{remanufactured parts order rate} = \text{MAX (0, remanufacturable products inventory/recycling delay time-available remanufactured parts inventory/parts recovery delay time)}
\]

\[
\text{remanufacturing lead time} = 1/\text{production conversion coefficient}
\]

4. Analysis of Simulation Results

4.1. Simulation Parameters. Relevant parameter values are listed in Table 1.

4.2. Discussions

4.2.1. The Traditional Model. Set the recycling and remanufacturing parameters as 0 and the production conversion coefficient as 1 to simulate the model as the traditional supply chain. The results are shown in Table 2.

4.2.2. The Single Recovery Model. The impact of factors on the CLSC is generally expressed through amplification of order and inventory. Since the demand is divided into two parts, in addition to analyzing the amplification of order and inventory, the demand for remanufactured products and for new products are especially analyzed in the study. The order and inventory amplification are measured using the ratios as order variance amplification (OVrA) and the inventory variance amplification (IVrA).

\[
\text{OVrA} = \frac{\sigma_i^2/\mu_o}{\sigma_o^2/\mu_i}
\]

\[
\text{IVrA} = \frac{\sigma^2/\mu_i}{\sigma^2/\mu_o}
\]

(1) Discussion on Impacts of “Policy Effect Coefficient.” The policy effect coefficient is set as 1, 1.3, and 1.6, respectively. The results are as follows.

As shown in Figures 4(a) and 4(b), after the remanufacturing starts, the remanufactured products meet parts of the market need and demands of the forward supply chain decrease. And, the higher the policy effect coefficient is, the greater the influence is on both. This is because the policy effect coefficient reflects the enthusiasm for policies. A high coefficient represents a positive response, and the quantity and quality of recycled products will be high, thus the quantity of remanufactured products increases. In the long run, rates of the demand for remanufactured products and new products tend to be stable. The reason is that the response to policies does not increase continuously but has a peak. The stability of recycling leads to the stability of returned products and stabilizes the demands for remanufactured products and new products.

As can be seen from Figures 4(c) and 4(d), no matter what the policy effect coefficient is, the order and inventory of the retailer and the manufacturer amplify, but both are lower than those of the traditional supply chain, which is consistent with the conclusion of many studies that reverse
Table 1: Simulation parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supplier production lead time</td>
<td>2 week</td>
<td>Natural recovery rate</td>
<td>0.2</td>
</tr>
<tr>
<td>Supplier inventory sustainability time</td>
<td>3 week</td>
<td>Recovery price effect</td>
<td>0.05</td>
</tr>
<tr>
<td>Manufacturer inventory sustainability time</td>
<td>3 week</td>
<td>Old for new effect</td>
<td>0.05</td>
</tr>
<tr>
<td>Retailer inventory sustainability time</td>
<td>2 week</td>
<td>Advertising effect</td>
<td>0.05</td>
</tr>
<tr>
<td>Delivery delay</td>
<td>1 week</td>
<td>Classification accuracy rate</td>
<td>0.95</td>
</tr>
<tr>
<td>Forecast moving average cycle</td>
<td>2 week</td>
<td>Standard coefficient 1</td>
<td>0.3</td>
</tr>
<tr>
<td>Inventory adjustment cycle</td>
<td>4 week</td>
<td>Standard coefficient 2</td>
<td>0.35</td>
</tr>
<tr>
<td>Remanufactured products retail inventory</td>
<td>4 week</td>
<td>Policy effect coefficient</td>
<td>1.3/setting during simulation</td>
</tr>
<tr>
<td>sustainability time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recovery delay time</td>
<td>12 week/setting during simulation</td>
<td>Recovery strengthening coefficient</td>
<td>1.2/setting during simulation</td>
</tr>
<tr>
<td>Parts recovery delay time</td>
<td>12.5 week/setting during simulation</td>
<td>Production conversion coefficient</td>
<td>0.95/setting during simulation</td>
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</tbody>
</table>

Table 2: Simulation results of the traditional model.

<table>
<thead>
<tr>
<th>Supplier IVrA</th>
<th>Manufacturer IVrA</th>
<th>Retailer IVrA</th>
<th>Manufacturer OVrA</th>
<th>Retailer order OVrA</th>
</tr>
</thead>
<tbody>
<tr>
<td>9924.98</td>
<td>199.87</td>
<td>146.80</td>
<td>106.31</td>
<td>9.11</td>
</tr>
</tbody>
</table>

Figure 4: Continued.
supply chain has a positive effect on the CLSC [19, 28]. In addition, with the increasing of policy effect coefficient, the order amplification and inventory amplification are weakening, and the weakening degree of upstream is more dramatic, which is more obvious when the policy effect coefficient is lower.

Some management implications can be drawn: policies can strengthen the recycling and remanufacturing activities so that the order and inventory amplifications weaken. CLSCs could focus on government policies related to recycling and remanufacturing and respond to policies. Moreover, the response to policies needs to be agreed upon across the CLSC to facilitate the sharing and allocation of costs and benefits.

(2) Discussion on Impacts of “Recovery Delay Time.” Keep other parameters unchanged, take recovery delay time and component recovery delay time as 10 and 10.5, 12 and 12.5, and 14 and 14.5, respectively.

Figures 5(a) and 5(b) show that in the early stage, a higher recovery delay time leads to a lower demand rate for remanufactured products and a higher demand rate for new products. At the later stage, demand rates of remanufactured products and demand rates of new products tend to be equal at different recovery delay times. The reason is that the recovery delay time affects the remanufacturing yield and the remanufactured retail inventory through remanufacturable products and available recycled parts in the early stage. Therefore, higher recovery delay times make the remanufactured product yield and the remanufactured retail inventory lower than those of low recovery delay times, resulting in the result of high recovery delay times to low demand rates of remanufactured products. In the later stage, the number of returned product stabilizes. Therefore, the demand rate of remanufactured products and the demand rate of new products tend to be equal at different recovery delay times.

Figures 5(c) and 5(d) indicate that recovery delay time has a positive impact on the order amplification and inventory amplification in the forward supply chain, and high recovery delay times make the amplification low. Relative to the policy effect coefficient, the recovery delay time has a relatively stable impact on the order and inventory amplification.

In terms of the stability of the CLSC, short recovery delay time brings great amplification. Therefore, it is necessary to appropriately improve the time for products to be held by consumers (such as improving product quality). For products with fast renewal and short recovery delay time, the CLSC needs to adopt more flexible strategies to deal with the amplification.

(3) Discussion on Impacts of “Recovery Strengthening Coefficient.” Keep other parameters unchanged, the recovery strengthening coefficient is set as 1, 1.2, and 1.4.

According to Figures 6(a) and 6(b), the impact of the recovery strengthening on the demand rate of new products starts from the initial stage, while on the demand rate of remanufactured products starts after the start of recycling and remanufacturing. The recovery strengthening coefficient expresses the positive promotion degree of recycled products on the whole demand. It can be seen that the higher the recovery strengthening coefficient is, the higher the demand rate of the remanufactured products and the demand rate of the new products will be. This is exactly the significance of recycling and remanufacturing. As shown in Figures 6(c) and 6(d), with the increasing of the recovery strengthening coefficient, the order amplification and inventory amplification also increase, which are still better than those of the traditional supply chain.
Some management enlightenments can be obtained. Recycling can indeed promote consumption. CLSCs can leverage recycling in boosting the demand and make recycling an effective way to expand the market. However, uncertainties of amplifications increase. Therefore, in addition to expanding the market, CLSCs should pay attention to identifying those uncertainties and improving prediction accuracy to cope with the uncertainties.

(4) Analysis of Variance. Three scenarios are set and the Minitab statistical software is used for the variance analysis. According to the results, which are shown in Table 3, Figures 7 and 8, all factors are significant to the order amplification and inventory amplification, and the interactions between factors are also significant. The results prove that it is necessary to pay attention to the influence of a single factor and also consider the influence of interactions between factors.

4.2.3. The Dual-Channel Model. In the dual-channel model, the relative investment recovery rate can be interpreted as the recovery rate brought by investments in recovery activities. Due to competitions, the recovery of one party is also affected by the investment of the other.
Figure 6: (a) Demand rates of new products with different recovery strengthening coefficients. (b) Demand rates of remanufactured products with different recovery strengthening coefficients. (c) OVrA with different recovery strengthening coefficients. (d) IVrA with different recovery strengthening coefficients.

Table 3: Results of analysis of variance.

<table>
<thead>
<tr>
<th>Indexes factors</th>
<th>Policy effect coefficient</th>
<th>Recovery delay time</th>
<th>Recovery strengthening coefficient</th>
<th>Policy effect coefficient * recovery delay time</th>
<th>Policy effect coefficient * recovery strengthening coefficient</th>
<th>Recovery delay time * recovery strengthening coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>OVrA</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Retailer</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>OVrA</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Supplier</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>IVrA</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturer</td>
<td>0.001</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>IVrA</td>
<td></td>
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</tr>
<tr>
<td>Retailer</td>
<td>0.000</td>
<td>0.000</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>IVrA</td>
<td></td>
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</table>

* p value < 0.05
The competition coefficient is used to describe the degree of competitions between channels. The dual-channel model is shown in Figure 9.

The equations of the dual-channel recycling model are as follows:

- **Total recovery rate**: \( \text{recovery rate} 1 + \text{recovery rate} 2 \)
- **Recovery rate 1**: \( \text{IF THEN ELSE (Time} \geq \text{recovery delay time, DELAY1 (relative investment recovery rate 1-competition coefficient} \ast \text{relative investment recovery rate 2, recovery delay time), 0) } \)
- **Recovery rate 2**: \( \text{IF THEN ELSE (Time} \geq \text{recovery delay time, DELAY1 (relative investment recovery rate 2-competition coefficient} \ast \text{relative investment recovery rate 1, recovery delay time), 0)} \)

Keep other parameters unchanged, set the relative investment recovery rate 1 as 0.2, the relative investment recovery rate 2 as 0.25, and the competition coefficients to be 0.1, 0.2, and 0.3, respectively.

Figures 10(a)–10(d) show that the high competition coefficient makes the demand rate for remanufactured products low and the demand rate for new products high. In addition, high competition coefficients cause high order and inventory amplifications. Compared with the results of the above-given models, the impact of the competition
Figure 8: (a) Interaction plots for manufacturer OVrA. (b) Interaction plots for retailer OVrA. (c) Interaction plots for supplier IVrA. (d) Interaction plots for manufacturer IVrA. (e) Interaction plots for retailer IVrA.

Figure 9: The dual-channel model.
coefficient on the inventory is higher than that on order. CLSCs with dual recovery channels should pay more attention to inventory management.

5. Conclusion

Considering the strengthening effect of the recovery on demand and the relationship between remanufactured products and new products, under the hybrid manufacturing/remanufacturing system in which the manufacturer produces new products and remanufactured products at the same time, a single-channel multifactor CLSC model is constructed and is extended to the dual-channel. Then, the models are simulated using Vensim7.3.5, and the following conclusions are drawn:

(1) Consistent with the conclusions of many studies, this study concludes that recycling and remanufacturing weaken the bullwhip effect of the forward supply chain.

(2) Recycling policies reduce the bullwhip effect of the CLSC by increasing recovery rates. And, the more significant the policy effect is, the more obvious the effect will be. In terms of the conclusion, CLSCs need
to establish unified awareness and construct actions on policies in order to achieve the maximum benefit of the CLSC.

(3) Recovery delay times have an inverse relationship with the bullwhip effect of the forward supply chain, and the impact on upstream is more significant. Therefore, CLSCs can take measures to make recovery delay times flexible.

(4) Recycling has an impact on the market demand, CLSCs can use it as a way to expand the market. On the other hand, it is necessary to improve the flexibility to deal with the increased uncertainties.

(5) When there are dual or more recycling channels, the competition between recycling channels will increase the bullwhip effect. Therefore, recycling channels should be set reasonably to avoid fierce competitions.

The research has some limitations. The model assumes that the production capacity and storage capacity are unlimited without backlogs, while the capacities of production and storage in practice are limited. And, factors affecting the recovery rate are simply considered, but the mechanisms and degrees of their influences on the CLSC can be studied in depth. Moreover, discussions are based on the amplification of order and inventory, further research studies can be done to analyze the costs and profits of the CLSC.

**Data Availability**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Conflicts of Interest**

The authors declare that there are no conflicts of interest regarding the publication of this article.

**References**


Mathematical Problems in Engineering


