

Research Article

O2O Recycling Closed-Loop Supply Chain Modeling Based on Classification Process considering Environmental Index

Shidi Miao , Di Liu, and Junfeng Ma

School of Computer Science and Technology, Harbin University of Science and Technology, Harbin 150080, China

Correspondence should be addressed to Shidi Miao; msdking@126.com

Received 3 August 2019; Revised 25 February 2020; Accepted 16 March 2020; Published 20 April 2020

Academic Editor: Aura Reggiani

Copyright © 2020 Shidi Miao et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

“O2O” (online to offline) classification recycling is a new recycling mode. It is premised on the double lines of online service platform and offline recycling service system, thus forming a pattern of online disposal and offline trading. This mode is capable of integrating upstream and downstream resources on the network platform, creating a recycling and processing mode for the entire industry chain of waste sorting, and developing a circular development mode featuring “resources-products-waste-renewable resources” to realize the recycling of resources. In this paper, the abovementioned recycling mode is constructed using the dynamic method. Taking the recycling of electronic waste (e-waste) as an example, on the basis of the original recycling, an online recycling mode is added and the e-waste is reprocessed by means of classification. Besides, the final process of manufacturing is put into the market for new products. By comparing the efficiency of different classification processing channels and the efficiency of O2O recycling, it was found out that the higher the product quality, the higher the recycling efficiency, and the efficiency of online recycling was concluded due to offline recycling. The system effect is evaluated according to the environmental index. In addition, this paper demonstrates the applicability of the mode by introducing Gree Corp. The results of this research are believed as contributory to improving the efficiency of recycling and remanufacturing at corporate level. It also provides a valuable reference for the improvement of e-waste management work for governments both in China and other countries.

1. Introduction

Waste is an important issue closely related to urban life around the world [1]. The rapid growth of electronic production has resulted in the fast-paced rise in the amount of e-waste [2]. According to the relevant reports, the world produces between 30 and 40 million tons of e-waste annually, at a growth rate of 6% per year, which is six times higher than that of total waste. It was expected that, by 2017, global e-waste would increase significantly from 49.7 million tons per year to 65.4 million tons, a rise of 33% [3], while it was estimated that 75% to 80% of global e-waste production is exported to various developing countries in Asia and Africa. Therefore, it is imperative to achieve the effective recycling of e-waste, which is regarded as the main challenge facing society nowadays [4].

At present, many governments around the world have drawn attention to the recycling and effective use of e-waste.

There are plenty of countries having adopted legislation to enforce the relevant policies to regulate and promote the recycling of e-waste. For example, at the forefront of the world in the management of e-waste recycling, Germany has put in place its e-waste collection system which covers the collection points established by public waste management agencies, commercial collection points, and the collection points intended for manufacturers. The state government has set up the Waste Electronic Product Registration Foundation to manage the e-waste processing industry fund [5].

In China, the e-waste recycling process usually involves four outlets [6], which are flow through individual recyclers, waste collection stations, product repair points, or idle through certain channels. Individual scrap buyers could purchase old appliances on the streets and then resale them to low-income users in towns or rural areas. When the electronics in second-hand market or owned rural

consumers are no longer usable, they will be sent to the repair points for disassembling. For those nonreusable parts, the contained precious metal is usually extracted in a simple way, with the rest left discarded as garbage [7]. The details are shown in Figure 1.

2. Method

The issues related to e-waste recycling and sustainable development have attracted increasing attention worldwide [8]. Over the past 10 years, different waste collection systems and recycling processes have been trialed globally. Among them, the recycling system in the major cities of Pakistan [9] for the disposal of e-waste is carried out in a rough manner without considering environmental safety, and it is necessary to effectively monitor the management of e-waste. Giorgia et al. [10] took Denmark as the research object and studied the waste with a classified treatment method and finally concluded that the waste material composition is important for waste recycling. Although Brazil [11] has established a recycling system for e-waste, its recycling is still in its early stages, and it is necessary to organize effective recycling management. Rodrigues et al. [12] proposed a new waste collection system classification based on the case of the Greater Lisbon area of Portugal. Mazon et al. [13] studied the applicability of the concept of sustainable innovation systems in developing countries, explored environmental regulations related to e-waste, and proposed a legislative analysis study based on e-waste recycling. There are also various recycling treatment modes for domestic e-waste. In Hangzhou [14], a new “2 + T” classification method was implemented to classify waste into biodegradable waste, other wastes, and toxic wastes. Regarding the study of the system dynamics of waste recycling methods, Xu [15] and Yu [16], respectively, studied the recycling of e-waste according to the type and channel of waste. The comparison shows that the above methods can improve recycling efficiency and reduce environmental pollution in conclusion. The above-mentioned literature is invariably aimed at the research and analysis of foreign recycling systems. The recycling methods proposed by Giorgia and Susana in their research are similar to ours suggested in this papers. Additionally, they all adopt the classification and recycling mode. However, they are mainly classified by the materials contained in the waste. The variety of waste materials is difficult to distinguish, and the process of separation is time consuming to ensure recycling efficiency. Although the relevant research to waste recycling classification has been conducted using the system dynamics model method, they are still restricted to the classification by product categories, which fails to improve the efficiency of waste treatment. In this paper, depending on the degree of waste disposal, different treatments are carried out to suit the different degrees of damage by applying the system dynamics model. In doing so, the classification time can be reduced and the recycling cost can be lowered.

Consumers as the major source of waste recycling are a significant influencing factor in the recycling of e-waste. Bai et al. [17] found that information security is the primary factor affecting the positive discovery of consumer recycling.

Jenni et al. [18] found that consumers have a high awareness of the importance and existence of waste recycling system, but awareness has not been translated into recycling behavior. Pilar and Adenso-Díaz [19] proposed that the collection point distance has a certain influence on the collection of waste by citizens. Regarding the study of this factor in system dynamics, Kautish et al. [20] studied the impact of environmental awareness and recycling intent on green purchasing behavior (GPB) in emerging economies, in addition to other external factors (such as expanding the collection range), also has an important impact on the recycling behavior of recyclers [21]. In the abovementioned studies, the factor of consumer recycling behavior has been introduced into the system dynamics model, and its impact on the recycling system has been investigated. In the research of this paper, the effect of consumers on recycling efficiency is already taken into consideration. Apart from that, in order to make the study more rigorous, other influencing factors, such as the recycling point coverage rate, are also taken into account.

Research on mixed recycling modes: Jena and Sarmah [22] studied the competition and cooperation modes of different recyclers, established corresponding mathematical models for different remanufacturing configurations, and reached equilibrium decisions under each configuration. Under the dual-channel CLSC [23], revenue sharing, the cost sharing mechanism can increase retailers' efforts in repair and recycling. Abbey et al. [24] studied the complex situation of manufacturers recycling and remanufacturing to the mixed recycling of manufacturers and third parties and analyzed the optimal pricing under different conditions. Panda et al. [25] studied the channel coordination problem in the socially responsible manufacturer-retailer closed-loop supply chain. The mixed recycling problems as studied in the aforementioned literature are all based on the system dynamics model of competing decision-making between different recyclers. By contrast, this article presents a study of O2O hybrid recycling models. The distribution ratio of O2O recycling is determined by the change in influencing factors, and an allocation mechanism is developed to optimize the recycling efficiency.

In many cases, material recycling could create greater environmental benefits than heat treatment or landfill [26]. Among them, Tang et al. [27] proposed that recycling rate is a key factor affecting socioeconomic environment. Sandin et al. [28] proposed that waste recycling would bring greater environmental benefits than recycling. Guilhem et al. [29] and Neto et al. [30] proposed the use of life cycle assessment (LCA) and reverse logistics methods for recycling, which can reduce the impact on the environment and establish related system dynamics models, verifying the feasibility of the method. Marconi et al. [31] proposed a reuse scheme of electronic components based on the web platform, which improved manufacturers' related benefits in terms of environmental impact and economic savings. In addition, they also studied the reuse of cable plastics and concluded that, in the WEEE field, the implementation of the industrial symbiosis model can bring a win-win situation to relevant stakeholders [32]. The above are the improvements made to

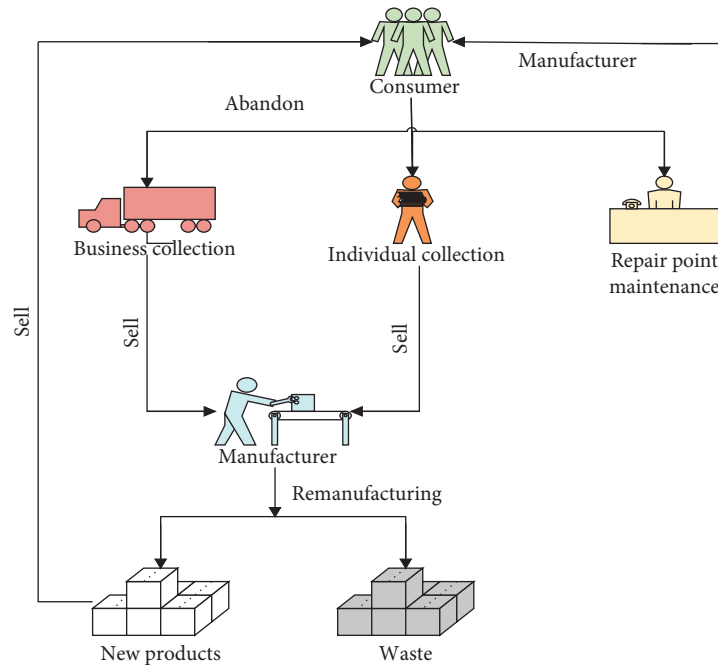


FIGURE 1: E-waste recycling flow chart.

the recycling method for the reduction of environmental pollution. The system dynamics simulation is conducted to compare the models before and after the improvement, so as to validate the effectiveness of the improved method. In spite of this, the primary objective of this article is to optimize the processing link to improve the reuse of resources while reducing pollution.

Research on recycling efficiency in recycling systems: Park [33] and Trulli [34] pointed out that economic incentives and waste pretreatment can lead to higher recycling efficiency. In addition, government subsidies to support recycling [35] and pricing of waste disposal [36] are also important to improve the efficiency of e-waste recycling. Wang et al. [37] used evolutionary game theory to establish a system dynamics model consisting of government, manufacturer, and consumer, which improved the recycling efficiency in the waste recycling process. Peng and Wang [38] used system dynamics to establish an e-waste recycling inventory flow chart and simulated government environmental protection publicity investment, the number of regular operators, and service levels. It was found that the amount of recycled waste increased significantly. Long et al. [39] studied the actual end-of-life (EoL) treatment process, including the remanufacturing, refurbishment, repair, recycling, reuse, and disposal of e-waste, and provided guidance for adjusting EU WEEE management to increase component recycling. The above is premised on system dynamics and research into the influencing factors in recycling efficiency. In this article, a description is made of a new recycling method purposed for online recycling. The combination of multiple recycling methods is effective in improving recycling efficiency and making the system more efficient.

3. Case Study

3.1. Case. Currently, the recycling of e-waste is heavily reliant on the offline recycling method, that is, recycling station. Due to the limited coverage of recycling bins and the negative impact of unprofessional personnel, the slack results of e-waste classification work lag far behind the target, which makes it necessary to exercise such high-tech means as “Internet +” [40] to promote the transformation and upgrading of the entire waste sorting industry and improve the recycling level of renewable resources, thus achieving the ultimate goal of coordinated economic and environmental development.

Based on this, Gree proposed a “four-in-one” green recycling system [41]. The company’s self-built recycling personnel system + on-site service mode shared economic mode of the entire category “O2O waste recycling platform.” Consumers log in to the recycling platform by signing up and complete the online submission recycling process by following the operation guide. Gree recyclers receive instructions from the Gree dispatch system, make contact with the consumer for an appointment of collection, and deliver on the recycling willingness to complete the recycling. The discarded household appliances are transferred to the green recycling station, where the waste electronics are dismantled before sorting and recycling. In doing so, the raw materials are regenerated, thus completing the ecological cycle of the home appliance industry chain, while creating a huge amount of economic, environmental, and social benefits. The whole process is detailed in Figure 2. With reference made to the abovementioned Gree online recycling and classification processing methods, this paper proposes the system dynamics model constructed for the following

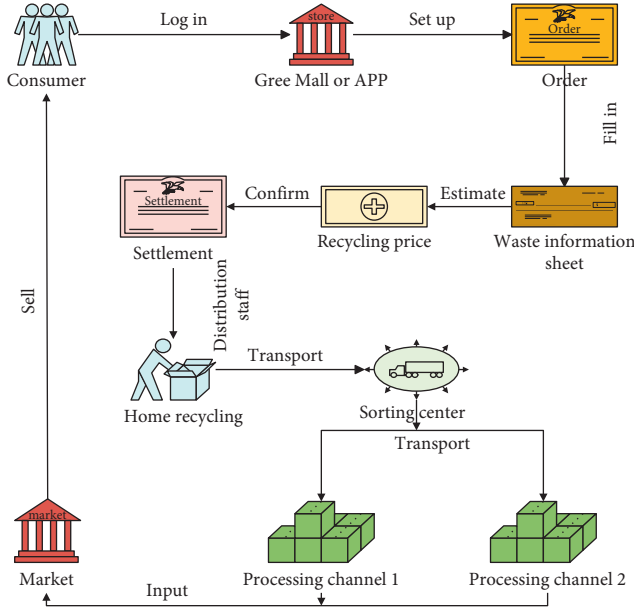


FIGURE 2: Flow chart of Gree's new recycling mechanism.

classification processing, as well as O2O recycling. Moreover, research and analysis are conducted.

3.2. System Dynamics Modeling Based on Classification Processing. From Figure 3, it can be seen that there are three paths to e-waste recycling process. Among them, the first loop will reprocess the damaged e-waste to generate new materials. The second loop will be disassembled by the e-waste that can be directly reused to obtain the parts that can be utilized straightaway. The recycled materials as obtained from the abovementioned two circuits are transferred to the manufacturer's production line for remanufacturing of the products. The third loop deals with e-waste, which is less damaged, and shifts its maintenance to the market for secondary sales. The dynamic equation established using the system is as follows:

$$C(t) = T_1(t) + T_2(t), \quad (1)$$

where $C(t)$ represents the collection rate of e-waste at time t , which is the sum of the online recycling rate $T_1(t)$ and the offline recycling rate $T_2(t)$ at time t .

$$D(t) = f(Q) \left\{ \left(\begin{array}{l} [(0, 0) - (10, 1)], \\ (0.2, 0.96), (0.3, 0.92), (0.4, 0.87), (0.5, 0.78), (0.6, 0.67), (0.7, 0.53), (0.8, 0.48), (0.9, 0.46) \end{array} \right) \right\}, \quad (2)$$

where Q stands for product quality. Since the product damage rate $D(t)$ varies according to Q , different Q s are set here to correspond to different $D(t)$.

$$d_1 = I(t) \times \frac{V_1}{T_f}, \quad (3)$$

where d_1 represents the sorting rate of the first processing channel. In the sorting center $I(t)$, the e-waste ratio of each recycling is V_i , where $i = 1, 2, 3$; since the recycling path is 1, the distribution ratio is V_1 . The total number of recovered e-wastes is obtained by finding the product of the two, and the ratio of the total number of e-waste to the sorting time T_f is d_1 .

$$I_s(t) = \int_{t_0}^t (d_1(t) - V_t(t))dt + I_s(t_0), \quad (4)$$

where $I_s(t_0)$ and $I_s(t)$ represent the damage of severely damaged stock at t_0 and t , respectively, which is the accumulation of the difference between the sorting rate d_1 and the transport rate V_t from time t_0 to time t .

$$V_t(t) = \frac{I_s(t)}{T_{t2}}. \quad (5)$$

The transport rate $V_t(t)$ is the transport rate at time t , which is the ratio of the inventory $I_s(t)$ that is severely damaged at time t to the transport time T_{t2} .

$$I_c(t) = \int_{t_0}^t (V_t(t) - \beta_1(t) - V_c(t))dt + I_c(t_0), \quad (6)$$

where $I_c(t)$ represents the inventory of the processing center at time t , which is the accumulation of the difference between the transport rate V_t and the discard rate β_1 from the time t_0 to the time t , and the regenerative processing rate V_c , wherein the discard rate is

$$\beta_1 = I_c(t) \times \frac{\alpha}{T_q} \times V_r \times (1 - \alpha). \quad (7)$$

$V_c(t)$ represents the reproducible processing rate at time t , where α is the discard index and C_s is the reproducible ability. The product of the two is the total available material, and the ratio of the obtained result to the regeneration processing time T_s is $V_c(t)$.

$$w_1 = \frac{V_c(t) \times C_z / T_z}{1 + C_z / T_z}, \quad (8)$$

where w_1 is the remanufacturability rate 1, which is the ratio of recyclable materials to manufacturing time. We use C_z for remanufacturing ability and T_z for remanufacturing time 1.

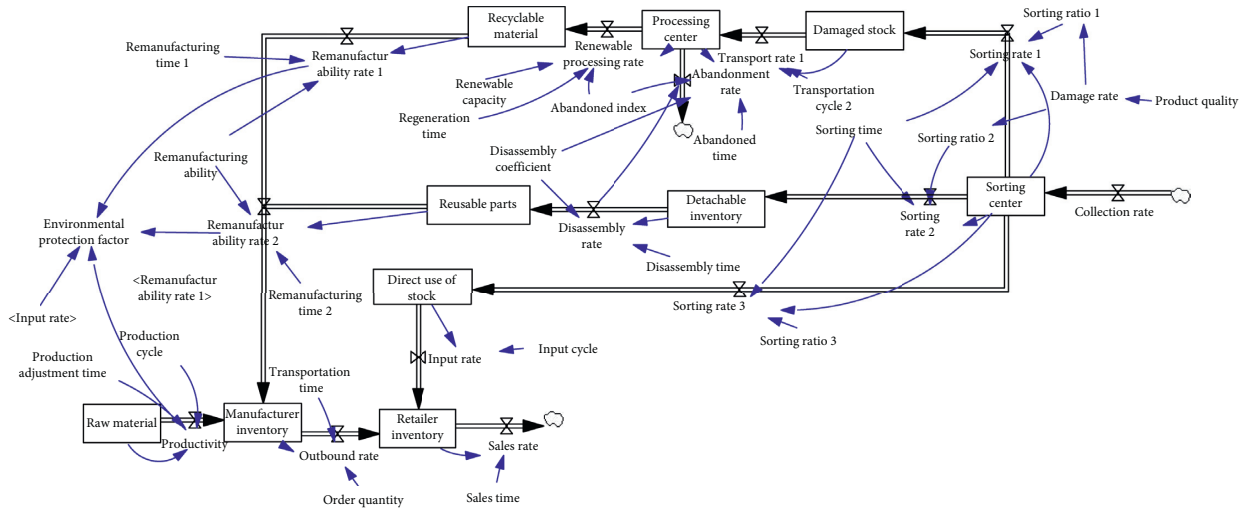


FIGURE 3: Classification processing system dynamics mode.

Among them, the usable material can be obtained by simplification of the above formula, thereby obtaining the abovementioned manufacturing rate of $1 w_1$. Through the above formula simplification method, the remanufacturability rate w_2 is obtained, and the input rate w_3 is

$$w_2 = \frac{[r \times I(t) \times V_2/T_f / (1 + (r/T_r)) \times (c_z/t_{z2})]}{(1 + (c_z/t_{z2}))}, \quad (9)$$

$$w_3 = \frac{[I(t) \times (V_3/T_f)]}{(1 + T_t)},$$

where r is the disassembly coefficient, t_{z2} is the disassembly time, and T_t is the input period.

$$e = \frac{(w_1 + w_2 + w_3)}{V_p(t)}, \quad (10)$$

where e is the environmental index. Since the environmental index is positively correlated with the reusability w and negatively correlated with the productivity V_p , the value is defined as the ratio of w to V_p .

3.3. System Dynamics Modeling Based on Online Recycling.

The system dynamics model recovered from the O2O lines shown in Figure 4 demonstrates that the product is recycled by the manufacturer, sold by the retailers, used and disposed of by the consumers, and finally enters into the market for recycling. The recycling system consists primarily of two parts: online and offline recycling (O2O recycling). Online recycling is affected by service quality and the time of order completion. Offline recycling is affected by the enthusiasm of the recycler and the coverage of the recycling point. The total amount of O2O recycling is always the total amount of e-waste recycled. Therefore, the total amount of recycling is 1, and the proportion is determined by the O2O recycling

factors to obtain the recycling distribution law. The dynamic equation established using the system is as follows:

$$V_p(t) = \text{Max} \left(\text{Min} \left(C_s, \text{Min} \left(\left(\frac{I}{T_{s1}} \right), \text{Min} \left(O(t), \frac{J_1(t)}{T_{s2}} \right) \right) \right), 0 \right), \quad (11)$$

where $V_p(t)$ represents the productivity of the manufacturer at time t , which is affected by the production capacity C_s , the unit raw material consumption I , the expected order rate $O(t)$, and the manufacturer's unit inventory adjustment capability $J_1(t)$; In addition, T_{s1} is the production cycle and T_{s2} is the production regulation time.

$$f(t) = \int_{t_0}^t [f_i(t) - R_v(t) - \beta_2(t)] dt + f(t_0), \quad (12)$$

where $f(t)$ denotes the e-waste stock at time t , and its value is the increase rate $f_i(t)$ of e-waste at time t , minus the recovery rate $R_v(t)$ and the direct rejection rate $\beta_2(t)$, plus stock $f(t_0)$ at time e-waste.

$$R_v(t) = R_n(t) + R_f(t). \quad (13)$$

where $R_v(t)$ represents the recycling rate at time t , which is the sum of the online recycling ratio $R_n(t)$ at time t and the offline recycling rate $R_f(t)$.

$$\beta_2(t) = (1 - \varepsilon) \times \frac{f(t)}{t_f}. \quad (14)$$

The recycling rate $R_n(t)$ at time t is the product of the online recycling ratio r_n and the recycling coefficient, the total amount of e-waste at time $t(t)$, and the ratio of the obtained result to the online recycling time t_n , where the recycling coefficient ε and recycling price P_r are as follows:

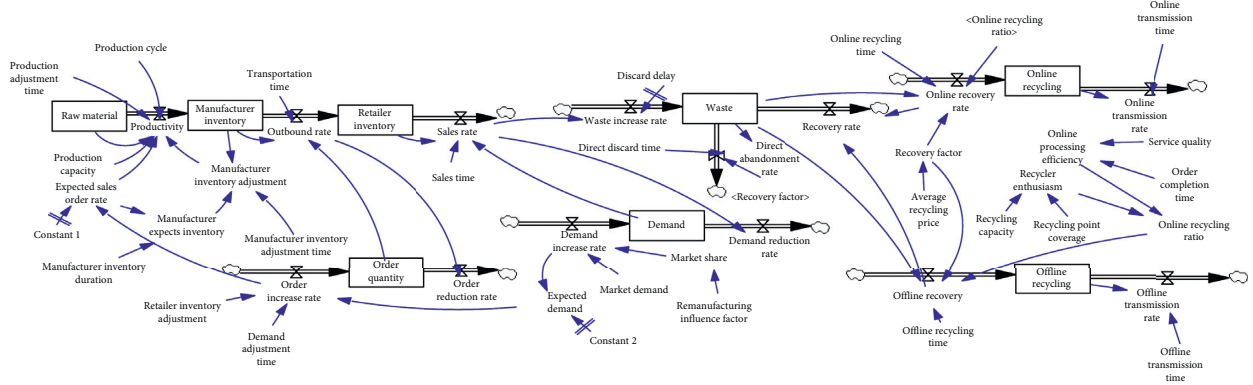


FIGURE 4: System dynamics mode for O2O recycling.

$$\varepsilon = f(P_r)\{(20, 0.03), (25, 0.07), (30, 0.1), (35, 0.18),$$

$$(40, 0.27), (45, 0.38), (50, 0.52), (55, 0.68),$$

$$(60, 0.86), (65, 0.93), (70, 0.96)\},$$

$$R_f(t) = r_f \times f(t) \times \frac{\varepsilon}{t_f}, \quad (15)$$

The recycling rate $R_f(t)$ at time t is the product of the online recycling ratio r_f and the recycling coefficient, the total amount of e-waste at time $t(t)$, and the ratio of the obtained result to the online recycling time t_f .

4. Discussions

In this article, the system dynamics approach is taken to characterize Gree's new recycling framework, which achieves an improvement and optimization based on the original recycling framework. Therefore, in order to validate the performance of the improved model, it is necessary to perform a simulation comparison test on the model before and after the improvement. The improved model has been described in detail above, and the original recycling and remanufacturing model is shown in Figure 5. The product is first produced by the manufacturer and then is sold to the consumers by the retailer. After the product is discarded, it is recycled by the manufacturer through a recycling center. After recycling, the waste is sorted in a sorting center, where the waste product is disassembled into two parts. One includes those nonreusable components to be directly destroyed and the other is made up of recyclable components. After the waste is processed, new materials are synthesized and processed into new products as raw materials for the purpose of resource conservation.

As the model in this article is mainly intended for the recycling of waste, the recovery and remanufacturing rates are regarded as the key factors in the effectiveness of model improvement. Under this circumstance, the recycling efficiency of the two models is compared first, and the comparison result is shown in Figure 6.

As can be seen from Figure 6, the recycling efficiency of the original model is about 0.075, while the recycling efficiency of the improved model is roughly 0.14. It thus can be seen that the improved recycling efficiency is significantly higher compared to the original model because the improved model combines online recycling and offline retail store recycling. Compared to the traditional single-path recycling mode, the scope of recycling is widened, as a result of which the total amount of waste recovered per unit time is higher, as is the collection rate.

Secondly, the comparison results of remanufacturing rates are presented in Figure 7.

As revealed by Figure 7, the remanufacturing rate of the improved model reaches 0.09, which is significantly higher than 0.016 under the original model. This is because in the remanufacturing process, the improved model is transformed from a single processing mode into a multichannel processing mode, which reduces the severity of the damage caused to the waste. In addition, the efficiency of waste processing with different damage levels varies. The improved model classifies wastes at the recovery stage, thus alleviating the workload imposed on the waste reprocessing stage and improving the efficiency of waste remanufacturing. In addition to the abovementioned conditions, environmental issue is also a crucial factor for recycling.

The lower the severity of environmental pollution is for the model during the recycling process, the better the performance would be. Therefore, the environmental index of the two models is compared against each other, and the comparison result is indicated in Figure 8.

As shown in Figure 8, the environmental index of the improved model is 0.095, which is clearly higher than 0.016 under the original model. This is because the environmental index is affected by the remanufacturing rate. It also can be known that the higher the remanufacturing rate, the higher the degree of waste utilization, the fewer the waste parts, and the lower the environmental pollution rate, as a result of which the improved environmental index is higher than in the original model.

In summary, the improved model shows its superiority to the original model in terms of recycling efficiency, remanufacturing rate, and environmental index. Therefore, this model is considered to be advantageous in the actual

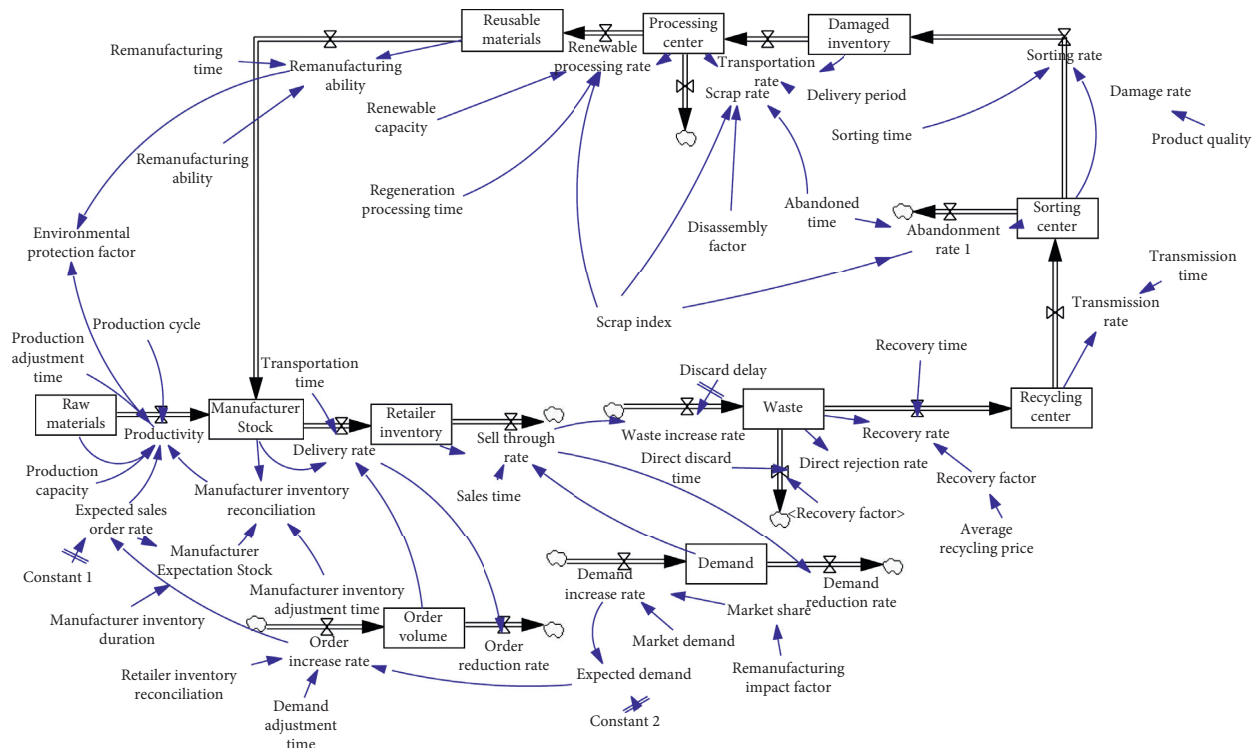


FIGURE 5: Dynamic model of Gree's original recycling framework system.

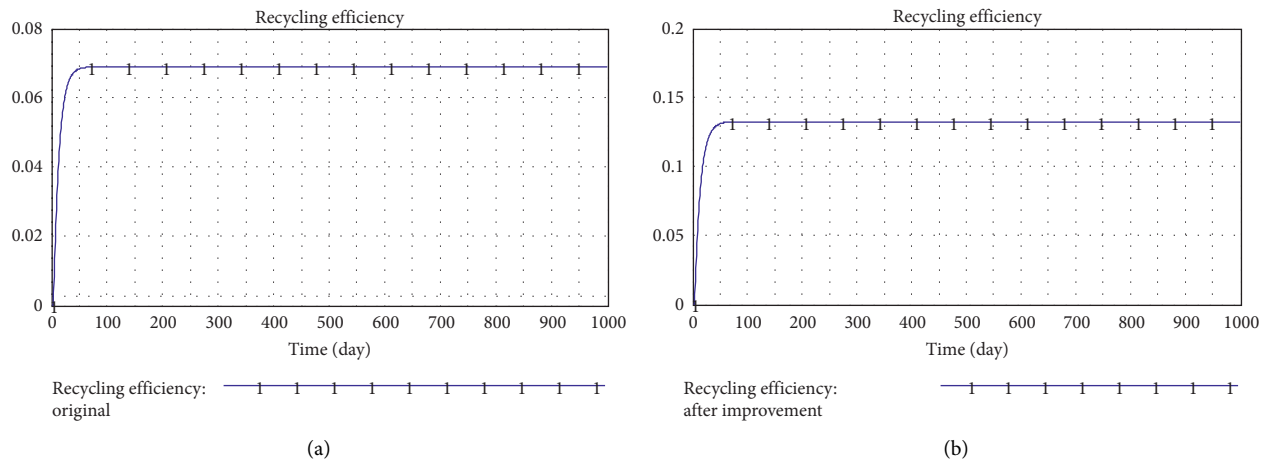


FIGURE 6: Comparison of recycling efficiency between (a) the original model and (b) the improved model.

environment of recycling. Further with this, both study and analysis are conducted for the improved model in the following section. The study mainly focuses on the two parts of classification, online and offline recycling.

Firstly, classification and recycling are studied. In this section, the impact of product quality [42] on system efficiency is mainly analyzed. The better the product quality is, the lower the part loss rate is for the product. Therefore, the relationship between product quality and damage rate can be established as shown in Figure 9.

However, combined with the actual situation, it is unlikely for the damage rate to increase indefinitely with the improvement of product quality. Therefore, the damage rate tends to stabilize with the improvement of product quality. The damage rate [43] for table function is obtained as follows:

The relationship is illustrated in Figure 9. Based on the relationship between product quality and damage rate, the results obtained from simulation are shown in Figure 10. The correlation between the members is expressed as follows:

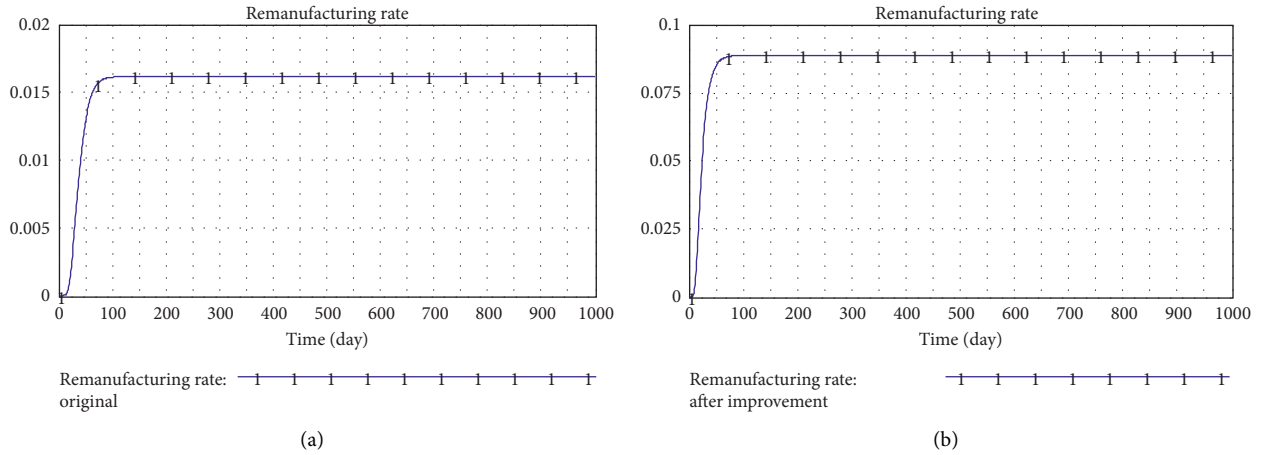


FIGURE 7: Comparison of remanufacturing rates between (a) the original model and (b) the improved model.

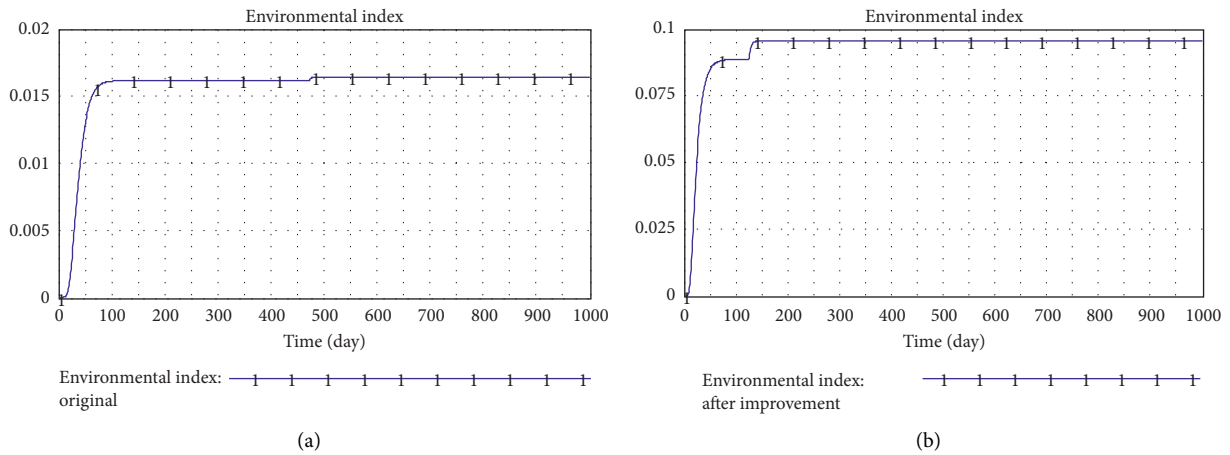


FIGURE 8: Comparison of environmental index between (a) the original model and (b) the improved model.

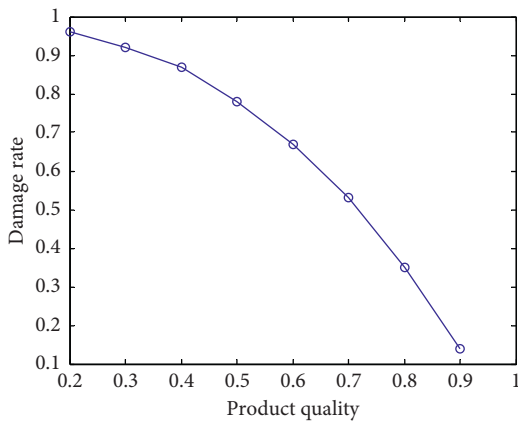


FIGURE 9: Relationship between product quality table and damage rate.

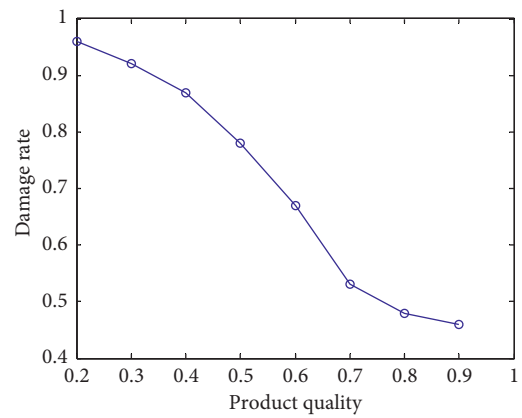


FIGURE 10: Product quality and damage rate function.

$$\begin{aligned}
D(t) = f(Q)\{ & [(0, 0) - (10, 1)], (0.2, 0.96), (0.3, 0.92), \\
& (0.4, 0.87), (0.5, 0.78), (0.6, 0.67), (0.7, 0.53), \\
& (0.8, 0.48), (0.9, 0.46)\}.
\end{aligned} \tag{16}$$

As shown in Figure 11(a), when $Q = (0.2, 0.5, 0.9)$, as the product quality improves, the sorting ratio of e-waste assigned by the sorting center to three different remanufacturing channels shows a significant change. Apparently, $V_1 = f(Q) \times 0.8$, $V_2 = (1 - f(Q)) \times 0.8$, $V_3 = 1 - \sum_{i=1}^2 V_i$, $f(Q) = \{0.96, 0.92, 0.87, 0.78, 0.67, 0.53, 0.48, 0.46\}$, the sorting ratios 1 and 2 gradually decrease as the product quality improves, but the sorting ratio 3 remains unchanged, which is because of the improvement of product quality. According to Figure 11(b) and the relationship between product quality and damage rate, the product damage rate is reduced, so that the number of parts that can be disassembled and reused in the product increases. In the meantime, the proportion of sorting ratio 2 increases. The rise in the number of detachable parts means that the amount of e-waste that cannot be directly utilized is reduced, as a result of which the e-waste ratio for the synthesis of new materials and the proportion of sorting ratio 2 are reduced. In addition, the improvement of product quality can only extend the life cycle of the product to a certain extent, and the integrity of the product cannot be guaranteed. Therefore, the e-waste ratio for direct market introduction does not change significantly, while the sorting ratio 3 remains unchanged. According to Figure 11(b), under the identical conditions, the changes in remanufacturing rate show the same trend as the sorting rate. Since the sorting ratio 3 is constant, the amount of e-waste directly put into the market also remains unchanged, so that the direct input rate shows no change.

According to $w_1 = [I(t) \times V_1/T_f / (1 + T_{t2}) - \beta + 1] \times [(1 - \alpha) \times C_s/T_s \times 0.8] / (C_z + t_{z1})$, $w_2 = [r \times I(t) \times V_2/T_f / (1 + (r/T_r)) \times c_z/t_{z2}] / (1 + (c_z/t_{z2}))$, $w_3 = [I(t) \times (V_3/T_f)] / (1 + T_t)$. The rate of remanufacturing ability changes with the change to the sorting ratio, since $\sum_{i=1}^3 V_i = 1$, and the sorting ratio 3 remains constant, as a result of which the sorting ratio 1 and the sorting ratio 2 are identical. However, according to Figure 11(b), the change rate of the remanufacturability rate is different, and the increase of the remanufacturability rate 2 is significantly higher than the decrease of the remanufacturing ability rate 1. Therefore, it can be concluded that the processing efficiency of reusing by disassembling e-waste is higher than the processing efficiency of synthesizing new materials.

This paper mainly relies on the environmental index to measure the system effect. As shown in Figure 12(a), system environmental index increases with product quality. Accordingly, the environmental index is affected by reusability and productivity. As Figure 12(b) reveals an insignificant change in productivity, it is impossible to observe its impact on the environmental index intuitively.

Therefore, further analysis by data is shown in Table 1.

It can be seen from Table 1 that when the product quality is taken $\{Q = 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9\}$, reusability increases as product quality improves, while productivity declines. The difference between Tables 1 and 2 is the value of the change in reusability and productivity when product quality is improved. It can also be seen that, when the quality of the product is improved, reusability is gradually increased and the productivity is gradually reduced, and the variation of productivity is lower than that of reusability. Therefore, both the proportion of reusable utilization in productivity and the environmental index are on the increase. It can be seen from the above that, because product quality affects the distribution ratio of e-waste flowing into different processing channels and the processing efficiency of e-waste varies between different channels, reusability shows an increase. The decrease in productivity is attributed to the increase in remanufacturing ability rate, which increases the number and the inventory of remanufactured products to a certain extent. Therefore, the manufacturer's expected inventory is met, the manufacturer's inventory adjustment range is reduced, the demand for new products is reduced, and productivity is in decline.

For the O2O recycling part, the impact of the recycling factor on the recycling efficiency and system performance is first studied. Since the recycling factor is positively associated with the average recycling price, the recycling factor increases as the average recycling price rises. However, due to the influence of the user's psychology and the total amount of product waste, the recycling factor cannot increase infinitely with the increase of price.

Therefore, the product recycling factor tends to be stable, and the recycling factor table function will be obtained. The details are shown in Figure 13.

Based on the relationship between the abovementioned recycling factor and the average recycling price, the results obtained from simulation are presented in Figure 14.

As revealed by Figure 14, when the recycling factor increases with the average recycling price, the O2O recycling rate increases, so that the collection rate also rises at a steady pace. In the meantime, the environmental index is also on the increase. When the recycling factor ranges between 0.8 and 0.9, the increase is insignificant, which is because when the recycling factor rises, both the amount of e-waste recovered through O2O and the total amount of recovered e-waste show an increase. The number of e-wastes allocated to each processing channel by the sorting center and the remanufacturability rate is on the rise, as a result of which the environmental index increases. In addition, since the product recycling factor is set to be flat after the simulation, the recycling factor tends to be stable, and the environmental index within this range is reduced.

According to Figure 15(a), the slope of the online recycling is higher than that of the offline recycling. Therefore, it is judged that the online recycling effect is better than the offline recycling effect. However, since the O2O recycling is also affected by other factors, it is necessary to

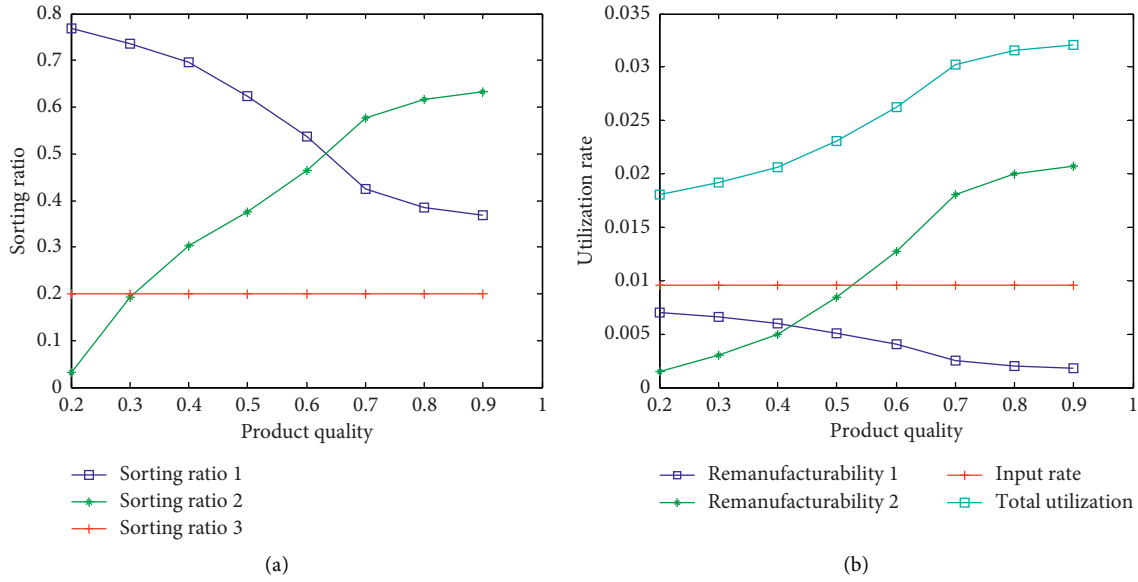


FIGURE 11: The variation of product quality as an influencing factor. (a) Product quality and sorting ratio. (b) Product quality and utilization rate.

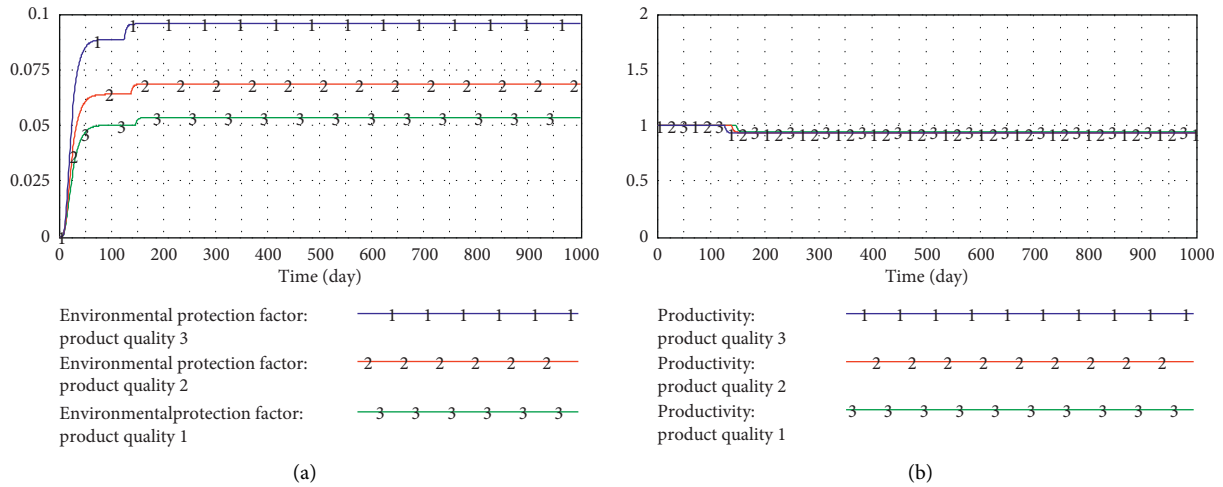


FIGURE 12: Simulation results of product quality as an influencing factor. Product quality 1 = 0.2; product quality 2 = 0.5; product quality 3 = 0. (a) Environmental production factor. (b) Productivity.

TABLE 1: Product quality’s impact change on total reusability, productivity, and environmental index.

Product quality	Total reusability	Productivity	Productivity	Difference 2	Environmental index
0.2	0.0181	0.9773	0	0	0.0186
0.3	0.0192	0.9770	0.0011	-0.0003	0.0197
0.4	0.0206	0.9766	0.0014	-0.0004	0.0212
0.5	0.0231	0.9760	0.0025	-0.0006	0.0238
0.6	0.0263	0.9752	0.0032	-0.0008	0.0270
0.7	0.0302	0.9742	0.0039	-0.0010	0.0310
0.8	0.0316	0.9738	0.0014	-0.0004	0.0325
0.9	0.0321	0.9737	0.0005	-0.0001	0.0331

further validate this conclusion. The verification results are shown in Figure 11.

According to $R_n(t) = d_n(t) / (d_n(t) + d_f(t))$, where $d_n(t)$ is the online processing rate at time t , and $d_f(t)$ is the

enthusiasm of the recycler at time t , it can be seen from Figure 11(a) and 11(b) that recovery rate increases with online processing efficiency, the proportion of the offline recycling decreases, and the total amount of e-waste

TABLE 2: Online processing efficiency analysis table.

Service	Time			
	1	1.5	2	2.5
0.1	0.1	0.067	0.05	0.04
0.2	0.2	0.13	0.1	0.08
0.3	0.3	0.2	0.15	0.12
0.4	0.4	0.27	0.2	0.16
0.5	0.5	0.33	0.25	0.2
0.6	0.6	0.4	0.3	0.24
0.7	0.7	0.47	0.35	0.28
0.8	0.8	0.53	0.4	0.32
0.9	0.9	0.6	0.45	0.36

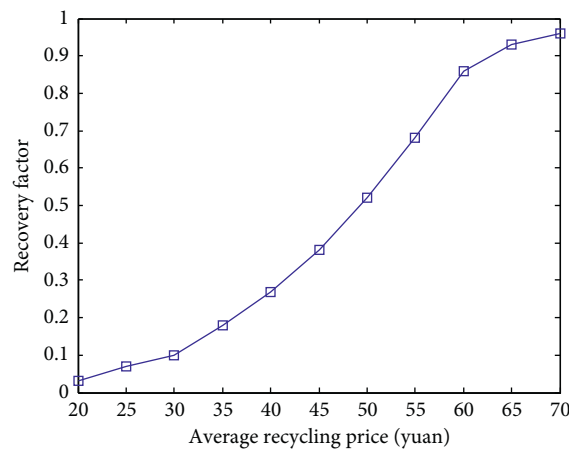


FIGURE 13: Recycling factor and average recycling price table function.

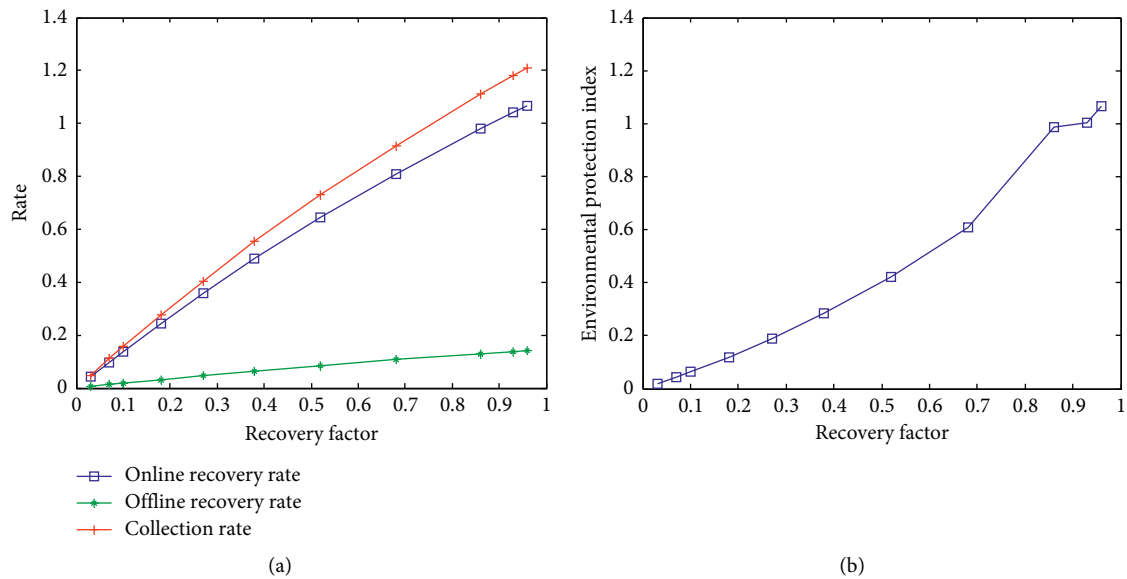


FIGURE 14: Simulation results of the recycling factor as an influencing factor. (a) Recovery factor and rate. (b) Recovery factor and environmental protection index.

recycling is on the rise. As shown in Figures 16(a) and 16(b), when the enthusiasm about recycling increases, the trend of O2O fluctuations is the opposite. At this time, the total amount of e-waste recycling shows a downward trend. It can

be seen that the higher the proportion of online recycling ratio, the more the amount of e-waste recovered in the system; the higher the proportion of offline recycling, the fewer the system recycles e-waste. This indicates that the

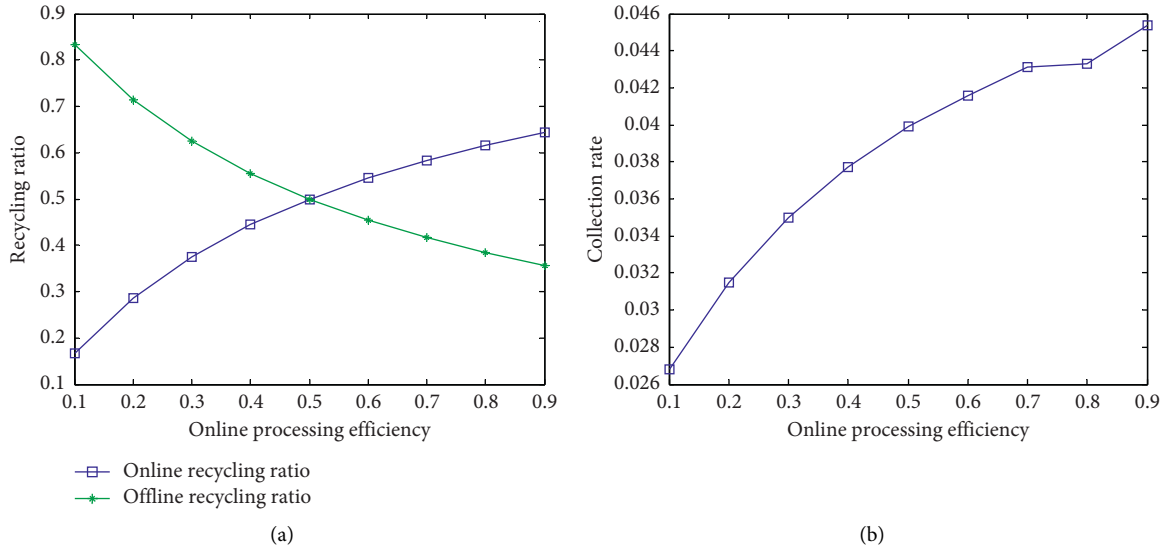


FIGURE 15: Online recycling efficiency analysis chart. (a) Online processing efficiency and recycling ratio. (b) Online processing efficiency and collection rate

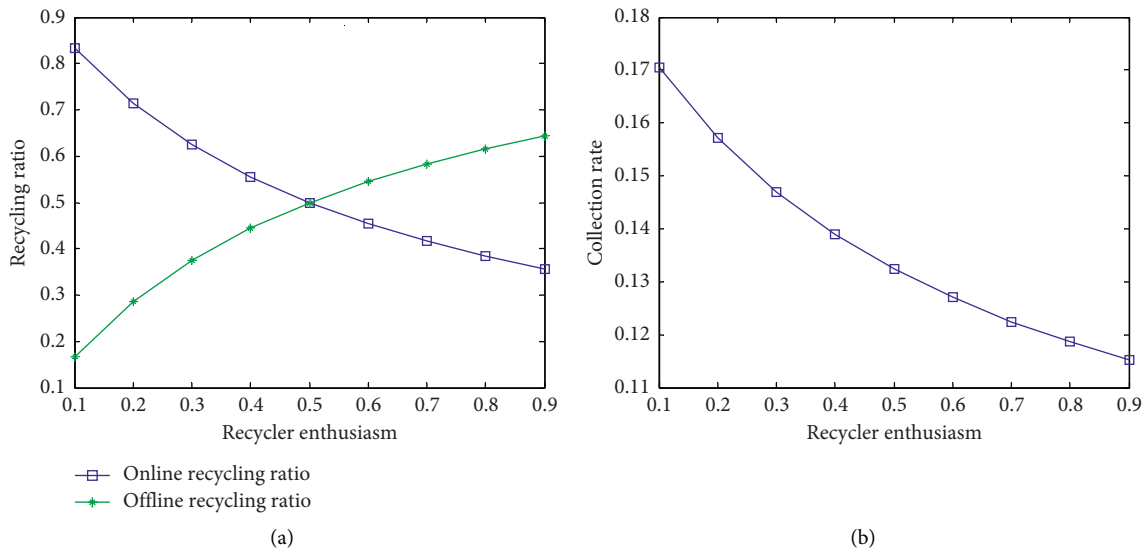


FIGURE 16: Offline recycling efficiency analysis chart. (a) Recycler enthusiasm and recycling ratio. (b) Recycler enthusiasm and collection rate.

online recycling efficiency is higher than the offline recycling efficiency.

According to $d_n = (q/t_o)$ (q is the quality of service and t_o is the order completion time), online processing efficiency is affected by online service quality and order completion time, while offline recycler enthusiasm is affected by recycling point coverage and recycler recycling capacity. Therefore, through Tables 2 and 3, the variation of the online processing efficiency and the enthusiasm about the offline recycler are analyzed.

As shown in Table 2, when the quality of service stays the same, the longer the order completion time, the lower the online processing efficiency. When the order completion

TABLE 3: Offline recycler enthusiasm analysis table.

Recycling point coverage	Recycling capacity		
	0.3	0.5	0.7
0.1	0.03	0.05	0.07
0.2	0.06	0.10	0.14
0.3	0.09	0.15	0.21
0.4	0.12	0.20	0.28
0.5	0.15	0.25	0.35
0.6	0.18	0.30	0.42
0.7	0.21	0.35	0.49
0.8	0.24	0.40	0.56
0.9	0.27	0.45	0.63

time is unchanged, the better the service quality, the higher the online processing efficiency. Thus, it can be concluded that the online processing efficiency is directly proportional to the quality of service and inversely proportional to the order completion time. Therefore, in order to improve the efficiency of online processing, companies need to improve the quality of service used at home and to reduce the length of online recycling service.

According to $d_f = v_s \times c_r$, it can be seen from Table 3 that when the recycling point coverage rate is constant, the recycling ability and the recycling enthusiasm that the offline recycler has is stronger. When the recycling capacity is constant, the recycling efficiency of the recycling point is higher and the recycling enthusiasm of the offline recycler is stronger. Therefore, in order to improve the recycling enthusiasm of offline recyclers, a large number of offline recycling stations should be constructed. Expanding recycling coverage is also supposed to increase recycling enthusiasm by increasing recycling prices and enforcing the measures to improve recycling capacity.

According to the abovementioned analysis, online recycling efficiency is higher than offline recycling efficiency. Therefore, in order to improve the efficiency of e-waste recycling, the focus needs to be placed on encouraging online recycling, improving the quality of online recycling services, and reducing the online order recycling time. However, through the combination with the actual situation, online recycling methods cannot be accepted by all members. Therefore, the offline recycling method cannot be completely abandoned, and the O2O combined recycling method should be adopted to improve the overall recycling efficiency.

5. Conclusion

In this paper, the dynamic analysis of the “O2O classification recycling” system is conducted to develop the system dynamics model. By performing a simulation of the system data, the following conclusions are drawn: in this system, the improvement of product quality is conducive to enhancing the recycling efficiency of e-waste to a certain extent, based on which the pollution caused by e-waste to the environment can be reduced. Therefore, if the environment index reaches its maximum, companies are supposed to improve the corresponding production technology and product quality. As for recycling, the e-waste recycling price is positively related to the e-waste recycling factor. Therefore, in order for improved efficiency of e-waste recycling, the e-waste recycling price ought to be raised accordingly within the range acceptable for the enterprise, which could increase the enthusiasm that consumers have about recycling and improve the efficiency of e-waste recycling. From the perspective of O2O recycling, under the same assumptions, the efficiency of online recycling is significantly higher than that of offline recycling. Therefore, it is recommended that consumers are proactively encouraged to adopt online recycling methods. However, in consideration of the practicalities, offline recycling is worth maintaining, as the co-existence of online recycling and offline recycling is

conducive to maximizing recycling coverage. In addition, online recycling efficiency is restricted by online processing rate, while online processing rate is determined by service quality and order completion time. Therefore, to enhance online recycling efficiency, enterprises should improve service quality and the pace of order processing.

Based on the system dynamics method, the dynamic simulation method is applied to analyze the case, which makes the research conclusion more reliable. In addition, on the basis of O2O recycling, the e-waste classification method is combined to achieve a significant improvement to the efficiency of recycling in the enterprise, which lays a solid foundation for the government to proceed with garbage recycling. However, if the company raises the recycling price and improves the recycling efficiency of e-waste, additional cost will be incurred. Therefore, it is necessary for the government to introduce corresponding incentive policies to increase the enthusiasm of enterprises about recycling. The research on government regulation will be conducted in detail in future articles.

Data Availability

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

Conflicts of Interest

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

Acknowledgments

This study was funded by the National Natural Science Foundation of China Youth Fund Project (71701056), the Heilongjiang Provincial Postdoctoral Funding Project (LBH-Z15100), the National Key Research Program of China (2016YFC0300104), and the Advance Research Project of Equipment of China (41421040301).

References

- [1] I. A. K. M. Khabiru, “A proposition for urban waste management and employment generation by community based organization (CBO):Bangladesh perspective,” in *Proceedings of 2012 International Conference on Environment Science and Engineering*, vol. 6, pp. 133–138, Bangkok, Thailand, April 2012.
- [2] A. K. Awasthi, X. Zeng, and J. Li, “Environmental pollution of electronic waste recycling in India: a critical review,” *Environmental Pollution*, vol. 211, pp. 259–270, 2016.
- [3] P. Sirada, “The management of waste from electrical and electronic equipment (WEEE) in Bangkok, Thailand,” in *Proceedings of the 6th International Conference on Biological, Chemical & Environmental Sciences (BCES-2016)*, Pattaya, Thailand, August 2016.
- [4] P. Tanskanen, “Management and recycling of electronic waste,” *Acta Materialia*, vol. 61, no. 3, pp. 1001–1011, 2013.
- [5] O. Ziegler, “Waste electrical and electronic equipment,” *EU Regulatory Decision Making and the Role of the United States*, Springer, Wiesbaden, Germany, 2013.

- [6] H. M. Wang, Y. J. Yu, and Q. Q. Liu, "Analysis of foreign E-waste recycling system and related regulates and their enlightenment to China," *Environmental Science and Management*, vol. 35, no. 9, pp. 1–5, 2010.
- [7] S. J. Qian and J. J. Ge, "Status and recommendations of the e-waste recycling in China," *Northern Environmental*, vol. 29, no. 3, pp. 58–60, 2013.
- [8] P. Janelle, "Why you need an E-waste recycling Program," *Buildings*, vol. 113, no. 2, 2019.
- [9] M. Sajid, J. H. Syed, M. Iqbal, Z. Abbas, I. Imran, and M. A. Baig, "Assessing the generation, recycling and disposal practices of electronic/electrical-waste (E-Waste) from major cities in Pakistan," *Waste Management*, vol. 84, pp. 391–401, 2019.
- [10] F. Giorgia, V. M. Edjabou, A. Boldrin, and T. Astrup, "Combustible waste collected at Danish recycling centres: characterisation, recycling potentials and contribution to environmental savings," *Waste Management*, vol. 89, pp. 354–365, 2019.
- [11] C. R. D. Oliveira, A. M. Bernardes, and A. E. Gerbase, "Collection and recycling of electronic scrap: a worldwide overview and comparison with the Brazilian situation," *Waste Management*, vol. 32, no. 8, pp. 1592–1610, 2012.
- [12] S. Rodrigues, G. Martinho, and A. Pires, "Waste collection systems. Part A: a taxonomy," *Journal of Cleaner Production*, vol. 113, pp. 374–387, 2016.
- [13] M. T. Mazon, A. M. M. de Azevedo, N. M. Pereira, and M. A. Silveira, "Does environmental regulation foster the diffusion of collaborative innovations? A study on electronics waste regulation on Brazils," *Procedia—Social and Behavioral Sciences*, vol. 52, pp. 259–268, 2012.
- [14] X. Li, F. Bi, Z. Han, Y. Qin, H. Wang, and W. Wu, "Garbage source classification performance, impact factor, and management strategy in rural areas of China: a case study in Hangzhou," *Waste Management*, vol. 89, pp. 313–321, 2019.
- [15] X. B. Xu, B. Yang, and X. L. Zhu, "Research on dual-channel recovery strategy of E-waste under Internet+ background," *Journal of Central China Normal University (Natural Science Edition)*, vol. 50, no. 5, pp. 683–688, 2016.
- [16] F. Yu, C. Y. Wang, and J. Wwi, "The system dynamics simulation involving the evolution of recycling and disposal channel on E-waste," *Ecological Economy*, vol. 32, no. 6, pp. 147–151, 2016.
- [17] H. Bai, J. Wang, and A. Z. Zeng, "Exploring Chinese consumers' attitude and behavior toward smartphone recycling," *Journal of Cleaner Production*, vol. 188, 2018.
- [18] Y. M. Jenni, L. K. Riitta, and P. Eva, "Electronic waste recycling in Finland: consumers' perceptions towards recycling and re-use of mobile phones," *Waste Management*, vol. 45, pp. 374–384, 2015.
- [19] L. G. Pilar and B. Adenso-Díaz, "Influence of distance on the motivation and frequency of household recycling," *Waste Management*, vol. 25, no. 1, pp. 15–23, 2004.
- [20] P. Kautish, J. Paul, and R. Sharma, "The moderating influence of environmental consciousness and recycling intentions on green purchase behavior," *Journal of Cleaner Production*, vol. 228, pp. 1425–1436, 2019.
- [21] R. M. d. S. Dutra, L. H. Yamane, and R. R. Siman, "Influence of the expansion of the selective collection in the sorting infrastructure of waste pickers' organizations: a case study of 16 Brazilian cities," *Waste Management*, vol. 77, pp. 50–58, 2018.
- [22] S. K. Jena and S. P. Sarmah, "Price and service co-opetition under uncertain demand and condition of used items in a remanufacturing system," *International Journal of Production Economics*, vol. 173, pp. 1–21, 2016.
- [23] J. Xie, W. Zhang, L. Liang, Y. Xia, J. Yin, and G. Yang, "The revenue and cost sharing contract of pricing and servicing policies in a dual-channel closed-loop supply chain," *Journal of Cleaner Production*, vol. 191, pp. 361–383, 2018.
- [24] J. D. Abbey, J. D. Blackburn, and V. D. R. Guide, "Optimal pricing for new and remanufactured products," *Journal of Operations Management*, vol. 36, no. 1, pp. 130–146, 2015.
- [25] S. Panda, N. M. Modak, L. E. Cárdenas-Barrón, and E. Leopoldo, "Coordinating a socially responsible closed-loop supply chain with product recycling," *International Journal of Production Economics*, vol. 188, pp. 11–21, 2017.
- [26] M. Haupt, E. Waser, J. C. Würmli, and S. Hellweg, "Is there an environmentally optimal separate collection rate?" *Waste Management*, vol. 77, pp. 220–224, 2018.
- [27] Y. Tang, Q. Zhang, Y. Li, H. Li, X. Pan, and B. McLellan, "The social-economic-environmental impacts of recycling retired EV batteries under reward-penalty mechanism," *Applied Energy*, vol. 251, 2019.
- [28] G. Sandin and G. M. Peters, "Environmental impact of textile reuse and recycling—a review," *Journal of Cleaner Production*, vol. 184, pp. 353–365, 2018.
- [29] G. Guilhem, P. Nicolas, and L. Bertrand, "Aluminium cables recycling process: environmental impacts identification and reduction," *Resources, Conservation & Recycling*, vol. 135, pp. 150–162, 2018.
- [30] G. C. d. O. Neto, A. d. J. C. Correia, and A. M. Schroeder, "Economic and environmental assessment of recycling and reuse of electronic waste: multiple case studies in Brazil and Switzerland," *Resources, Conservation & Recycling*, vol. 127, pp. 42–55, 2017.
- [31] M. Marconi, F. Gregori, M. Germani, A. Papetti, and C. Favi, "An approach to favor industrial symbiosis: the case of waste electrical and electronic equipment," *Procedia Manufacturing*, vol. 21, pp. 502–509, 2018.
- [32] M. Marconi, C. Favi, M. Germani, M. Mandolini, and M. Mengarelli, "A collaborative end of life platform to favour the reuse of electronic components," *Procedia CIRP*, vol. 61, pp. 166–171, 2017.
- [33] S. Park, "Factors influencing the recycling rate under the volume-based waste fee system in South Korea," *Waste Management*, vol. 74, pp. 43–51, 2018.
- [34] E. Trulli, N. Ferronato, V. Torretta, M. Piscitelli, S. Masi, and I. Mancini, "Sustainable mechanical biological treatment of solid waste in urbanized areas with low recycling rates," *Waste Management*, vol. 71, pp. 556–564, 2018.
- [35] D. Pablo, M. B. Andréa, and H. Nazmul, "Ensuring best E-waste recycling practices in developed countries: an Australian example," *Journal of Cleaner Production*, vol. 209, pp. 846–854, 2019.
- [36] S. F. Sidique, S. V. Joshi, and F. Lupi, "Factors influencing the rate of recycling: an analysis of Minnesota counties," *Resources, Conservation & Recycling*, vol. 54, no. 4, pp. 242–249, 2010.
- [37] M. B. Wang, Z. P. Du, and H. Duan, "Study on participant behavior game of electronic products reverse supply chain based on ECP," *Journal of Systems Science and Information*, vol. 5, no. 5, pp. 411–434, 2017.
- [38] R. K. Peng and Y. Y. Wang, "research on system dynamics simulation of electronic waste recycling strateg," *Chinese Collective Economy*, vol. 23, 2019.
- [39] E. Long, S. Kokke, D. Lundie, N. Shaw, W. Ijomah, and C.-c. Kao, "Technical solutions to improve global sustainable

- management of waste electrical and electronic equipment (WEEE) in the EU and China,” *Journal of Remanufacturing*, vol. 6, no. 1, 2016.
- [40] Z. P. Du and X. Q. Wang, “Study on reverse supply chain recycling mode for mobile phones based on O2O,” *Logistics Technology*, vol. 34, no. 12, pp. 198–201, 2015.
- [41] Gree, “Ministry of commerce of the People’s Republic of China department of circulation industry development,” 2017, <http://tfs.mofcom.gov.cn/article/bb/201803/20180302718391.shtml>.
- [42] N. M. Modak, N. Modak, S. Panda, and S. S. Sana, “Analyzing structure of two-echelon closed-loop supply chain for pricing, quality and recycling management,” *Journal of Cleaner Production*, vol. 171, pp. 512–528, 2018.
- [43] C. Z. Zheng, Z. X. Liu, and W. Shi, “Service and inventory control policies for seasonal deteriorating product,” *Industrial Engineering and Management*, vol. 16, no. 4, pp. 118–123, 2011.