Chapter 10
Green Manufacturing

Qunli Yuchi, Nengmin Wang, Qi Jiang, and Zhengwen He

Abstract Green manufacturing is an important part of enterprises' implementation of the green growth mode, and remanufacturing is one of the specific forms of green manufacturing. The development of the next generation Internet recycling model has increased the recycling channel of raw materials for remanufacturing and provided an effective guarantee for the effective implementation of remanufacturing. This chapter focuses on the relationship between green manufacturing and the enterprise green growth mode, and analyses the impact of obtaining remanufactured products from traditional channels and dual channels in enterprises' green growth model. Dual channel refers to considering both traditional channels and online channels. Then, this chapter construct a single-channel that only considering traditional channels and dual-channel remanufacturing recycling network model. These two models determined the location decisions of the distribution centre and recycling centre, distribution route, recycling route, online order distribution route and inventory decision of the remanufacturing supply chain under the two channels. To solve these two models, a genetic algorithm with local search is proposed. Through a sensitivity analysis of key parameters, it is concluded that the dual-channel recycling mode not only increases the recycling cost in the value chain but also increases the utilization rate of waste products, reduces the inventory cost and transportation cost of the distribution centre, and promotes the effective implementation of the green growth mode of enterprises.

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10.1 Green Manufacturing and Enterprises' Green Growth Model

10.1.1 Concept of Green Manufacturing

Green manufacturing is developed along the value chain of products. Through new technologies and control measures, this approach creates manufactured products in the way of "using materials and processing processes with minimal negative environmental impact, saving energy and natural resources, ensuring the safety of employees, society and consumers, and economically reasonable" [1] by comprehensively considering environmental impact and resource efficiency so that enterprises can improve their business performance while improving their green growth [2]. Focusing on the environmental problems in the manufacturing process, this paper proposes the concept of green manufacturing, which includes four aspects.

First, the problem areas involved in green manufacturing include manufacturing (including the entire process of the product life cycle), environmental protection and optimal utilization of resources [3].

Second, green manufacturing is a fully considered modern manufacturing mode and the embodiment of the circular economy mode in the modern manufacturing industry [4].

Third, the manufacturing process in green manufacturing mainly refers to the green production activities involved in the enterprise value chain [5].

Fourth, green manufacturing is an effective way to achieve green growth and economic performance of enterprises [6].

10.1.2 Basic Features of Green Manufacturing

There are essential differences between green manufacturing and traditional manufacturing, as shown in Table 10.1. The characteristics of green manufacturing can be summarized in the following four aspects: first, the goal is to achieve the economic performance and green growth of enterprises at the same time [6]; second, the means by which to achieve the goal is to innovate relevant production and service activities along the product value chain [5]; third, the main body of innovation consists of organizations and individuals dominated by enterprises and involved in relevant production and service activities on the product value chain [7]; fourth, through the synergy and complementarity of relevant subjects in the value chain, the entire manufacturing system can maintain its rapid response and good adaptability to the complex and changeable market environment [8].

Table 10.1 Differences between traditional manufacturing and green manufacturing

	Traditional manufacturing	Green manufacturing
The ultimate goal	Traditional manufacturing management mainly aims to realize the profit of enterprises, meet the requirements of consumers, and expand market share. These objectives ultimately aim to realize the economic interests of a core enterprise	The goal of management is not only to achieve economic benefits but also to pursue environmental protection, energy conservation and emission reduction, which not only have economic performance but also include the goal of green growth of enterprises
Range of activity	Traditional manufacturing usually designs, produces, and sells products according to market information and rarely considers the scrapping and recycling of products	Each activity will cause harm to the environment, from the acquisition of raw materials to the use of waste products and services. Therefore, the scope of green manufacturing activities is to innovate related production and service activities along the product value chain
Subject of action	Mainly include consumers and node enterprises in the value chain, not involving scrap and recycling	Including consumers, the government, and the node enterprises of the supply chain, the manufacturing enterprises that are in leading positions of the value chain should cooperate with other enterprises, ranging from the goal of saving resources and protecting the environment to formulating a model plan for green supply chain management, so that both the enterprises and the value chain can gain a sustainable competitive advantage

10.1.3 The Relationship Between Green Manufacturing and Enterprises' Green Growth

With the promotion of the green manufacturing mode, enterprises urgently need to build a green and sustainable value chain system to cope with the large amount of pressure placed of them due to energy conservation and environmental protection [9, 10]. As the front end of the enterprise value chain, green manufacturing is of great significance for building a green value chain system.

Although many enterprises have made many efforts in green manufacturing and have achieved good results, some enterprises are still relatively weak in regard to green manufacturing, which will limit the implementation effect of the green development of these enterprises and hinder their competitive position in the market. This is not conducive to the green growth of these enterprises [11]. Enterprises should develop an overall plan to improve all manufacturing activities involved in the value chain. Otherwise, the business performance, green growth and future competitiveness of the enterprise will be adversely affected. For example, recently, the clothes of a garment factory in Zhejiang Province were returned by the United States because the nickel content in the zipper exceeded the standard threshold, which resulted in a direct economic loss of US $1 million [2]. Previously, an international nonprofit organization conducted a survey on the environmental protection of China's garment industry. The survey results showed that there were environmental problems present in the green manufacturing process of these enterprises, which had a significant adverse impact on many world-leading garment brands predominantly made in China and further affected the synergy between green manufacturing and the growth of enterprises. These brands need to change their value chain system and reduce the use of pollutants in the production process. Therefore, many enterprises have realized the seriousness of environmental problems in the manufacturing process.

The implementation of green manufacturing will bring a certain amount of pressure to enterprises in the short term, such as rising costs and limited production capacity [12]. However, green manufacturing also provides opportunities for the future development of enterprises. If enterprises can actively promote the construction of green value chains, then they can improve market competitiveness, improve their green brand image, and achieve enterprise performance and green growth. At present, many scholars have studied the quantitative relationship between green manufacturing and enterprise performance; through green manufacturing, enterprises can achieve environmental protection production, improve their self-image, and improve their business performance while improving their green growth [6, 13, 14]. Many scholars believe that enterprises should not regard green manufacturing as a burden on economic activities. Instead, it should be seen as a prerequisite for sustainable economic development. The green growth of enterprises and the economic growth of enterprises should develop harmoniously and are mutually supportive and mutually reinforcing [15–17]. In other words, to maintain sustainable profitability and green growth, green manufacturing should be the bottom line of relevant enterprises. In turn, green manufacturing puts pressure on enterprises to pay more attention to resource efficiency and environmental impact [18].

As the direct executor of green manufacturing, enterprises should focus on the management of their green value chain to ensure the further development of enterprises [19]. The literature shows that enterprises need to take the following measures to actively promote green manufacturing to the green growth model [2]. (1) Enhance the environmental awareness of managers in the value chain and combine the responsibilities of managers with the environmental benefits of enterprises. (2) Base all business activities in the value chain on environmental benefits and eliminate nonenvironmental behaviours. (3) Strengthen the evaluation and audit of the environmental benefits of all activities in the value chain. (4) Use information technology to track the management process of the green value chain in real-time.

Based on the abovementioned advantages of green manufacturing, many enterprises, especially in high-polluting industries, have transformed their manufacturing processes into green manufacturing. Among them, a typical representative is the Tangshan Iron and Steel Group in the steel industry. In 2020, Tangsteel New District put forward the development concept of a green manufacturing general layout in

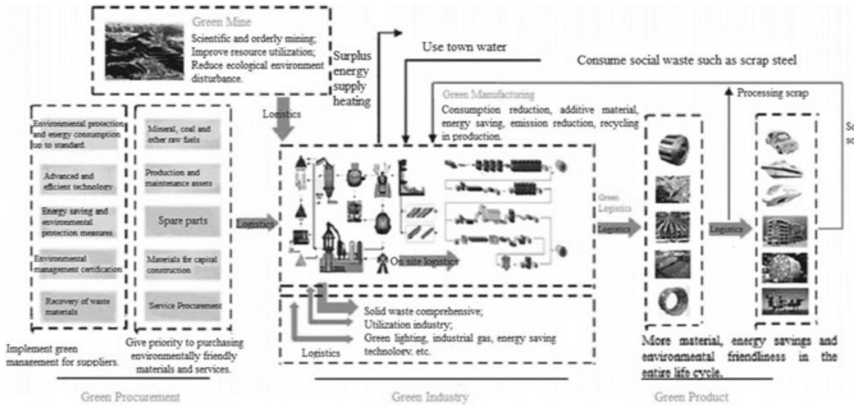

Fig. 10.1 Tang steel group's green manufacturing general layout development concept[1]

regard to planning, design, construction, and production and operation, as shown in Fig. 10.1. It has subsequently assembled a number of advanced environmental protection technologies at home and abroad and integrated them into all processes, as well as the overall process. More than 230 advanced environmental protection technologies and processes and more than 130 green manufacturing technologies in the steel industry are used for process and equipment configuration. In terms of energy, environmental protection and power, these processes focus on remote coverage and the centralized control of the entire process and the entire region to achieve carbon emission reduction in the entire process. Adhering to scientific and technological innovation, coordinating the research and development of key low-carbon technologies and low-carbon products, and implementing green manufacturing greatly reduce the environmental hazards in the production process of enterprises and achieve enterprise performance and green growth.

10.1.4 Typical Form of Green Manufacturing—Remanufacturing

The development of green manufacturing has become a consensus among enterprises [20]. Although the green manufacturing activities of each enterprise have their own characteristics; generally speaking, they are realized by reducing the waste of resources involved in the production and manufacturing activities in the enterprise value chain and improving the utilization rate of energy. Remanufacturing is based on the perspective of the enterprise value chain. One of the most effective ways to achieve green manufacturing is by recycling, processing and disposing of waste products to achieve resource conservation and energy utilization [21]. Remanufacturing is not a simple refurbishment process but rather a series of professional repairs, such

[1] http://www.cmisi.com.cn/default/index/newsDetails?newsId=888.

as dismantling, cleaning, repairing, reassembling, and testing the recovered products and components so that the quality of the recovered products can be restored to the same quality as new products [22]. In developed countries, the concept of remanufacturing was first proposed for economic considerations in the 1990s. With the continuous development of remanufacturing, remanufacturing has been broadly used in two major industries, namely, the auto parts and electronic/electrical industry sectors. For example, the remanufacturing of electronics such as copiers and disposable cameras is fairly common in Japan, and the U.S. auto parts remanufacturing industry has also grown steadily since the 1990s. In China, remanufacturing is still an emerging industry. The development of China's remanufacturing industry is carried out under the guidance of the Chinese government, and a pilot and demonstration system has been adopted to guide the large-scale development of remanufacturing enterprises. Remanufacturing is the development and extension of green manufacturing. Therefore, it is crucial to green development and the efficient use of resources [23].

For remanufacturing, the most important thing is to have a sufficient amount of recycled products to form a scale effect, thereby reducing the investment cost in the early stage of remanufacturing and improving the profitability of the enterprise while realizing the green growth of the enterprise. Next generation Internet recycling is the product of the deep integration of Internet technology and the recycling industry, which provides a new way for remanufacturing to increase the number of recycled products. Online channels can not only increase the total amount of recycling in the recycling market but also significantly improve the economic profits of enterprises. Professional recycling centres that dismantle and decompose waste products can also obtain more resources, reduce harmful emissions to the ecological environment, and improve enterprises' green growth. In recent years, with next generation Internet, an increasing number of recycling enterprises have built online recycling channels based on Internet technologies such as big data, cloud computing and artificial intelligence, relying on terminal platforms such as PC websites and mobile apps; they have then performed the integration of online and traditional offline recycling channels, such as the O2O recycling model represented by "Aihuishou,"[2] and the intelligent recycling machine recycling mode are represented by the Beijing "Yingchuang" company.[3] This recycling mode with both online and offline channels is called the dual-channel recycling mode.

10.2 Dual-Channel Remanufacturing

The emergence of the dual-channel model has broadened the traditional channels for remanufacturing to obtain waste products. The raw materials of remanufactured products can be obtained not only from traditional offline recycling channels but also from online platforms, which directly results in the demand for remanufactured raw

[2] https://www.aihuishou.com/.

[3] http://en.incomrecycle.com/.

materials and has an impact on the remanufacturing logistics network. An efficient remanufacturing logistics network is important for the successful implementation of remanufacturing. Remanufacturing logistics include the reverse logistics of transporting waste products from the place of consumption back to the place of production and the forward logistics of transporting remanufactured products from the place of production to the place of consumption, thereby forming a closed-loop logistics system. Most enterprises that have established traditional production and distribution logistics networks tend to expand on the basis of traditional production and distribution logistics networks to increase remanufacturing logistics functions. This saves costs without having too much impact on the existing network. The research in this chapter is also based on this remanufacturing logistics network.

Due to the sales and recycling carried out in traditional channels, manufacturers mainly focus on the demand and recycling of products from retailers (large customers), and the needs and recycling of customers (small customers) are met by retailers. However, the introduction of the dual-channel model allows online channels to segment and expand market demand and the number of products recycled by the original traditional retailers. This allows the original small customer needs and products to be recycled and directly completed by the manufacturer. As a result, enterprises adopting a dual-channel model need to redesign their value chain network and determine the location of individual facilities.

At present, there are few studies on logistics network optimization for remanufacturing. Optimizing the logistics network is an effective way to improve the operation efficiency of the enterprise supply chain and reduce the cost of the enterprise [24]. Different from traditional logistics design, remanufacturing logistics design should not only consider the distribution logistics of forward new products but also consider the reverse recycling logistics of waste products, thus forming a closed-loop supply chain system. Remanufacturing logistics network optimization problems include the production of new and remanufactured products, the establishment of distribution centres, the inventory of new and used products, the distribution of new products and the recycling route of used products, and the detection and disposal of used products. In summary, studying the optimization problem of remanufacturing logistics networks is actually studying the location-path-inventory problem of a closed-loop supply chain.

This chapter studies the location-inventory-routing problem in a multicycle closed-loop supply chain based on the new mode of remanufacturing and next generation Internet. To investigate the impact of adopting online channels into the remanufacturing integrated logistics network, two models are considered in this chapter. The first model is a single-channel model in which the manufacturer does not adopt a dual-channel model, and the system only includes traditional retail channels. The other model is a dual-channel model in which manufacturers adopt a dual-channel model, and the system includes both traditional retail channels and online channels. Both systems have the following commonalities. They both consist of a manufacturing remanufacturing centre (MRC), multiple potentially capacity-constrained distribution-collection centres (CDCCs), and a group of customers. The MRC produces both new products and remanufactured recycled products. This section assumes that remanufactured products and new products do not share the same sales channel. To save costs, CDCCs act not only as distribution centres but also as collection centres. In other words, a CDCC not only delivers new and remanufactured products to customers but also collects used products from customers. Recycling and remanufacturing rates for recycled items are known and assumed to be constant. To increase the company's flexibility in the supply chain, the logistics of recycled products collected from customers to CDCCs are undertaken by third-party logistics. The purpose of this chapter is to integrate and optimize facility location-allocation, inventory control, and vehicle routing in a multicycle closed-loop supply chain to minimize the overall system cost.

10.2.1 Manufacturers Do Not Adopt a Dual-Channel Model

To define the problem of the single-channel mode more clearly, this section expounds the decisions to be solved by forward logistics and reverse logistics. For systems in single-channel mode, in forward logistics, customer demand for new and remanufactured products is produced at the MRC and delivered to customers via CDCCs. Both requirements are deterministic but variable per cycle. To facilitate product tracking, each customer is assigned only one CDCC. Furthermore, customer needs are served by a homogeneous set of capacity-constrained vehicles, each of which departs from and returns to the same CDCC to which it belongs. In reverse logistics, recycled products are collected from customers and checked at CDCCs to determine if they can be remanufactured. If the returned product is remanufacturable, it will be shipped to the MRC, remanufactured at the MRC, and then resold through the CDCC to customers who need it at a lower price. The remanufacturing integrated logistics network of the studied single-channel mode is shown in Fig. 10.2.

To easily convert this problem into a model, this section uses the following notation. This section defines q as the remanufacturing cost of MRC. J is defined as the candidate CDCC set. The fixed setup cost of each CDCC $j, j \in J$ is f_j, and the capacity

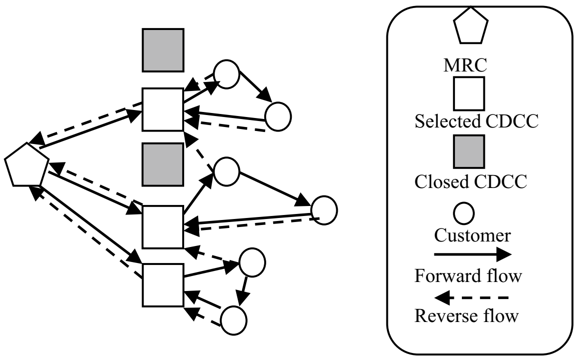

Fig. 10.2 Remanufacturing integrated logistics network under single channel mode

of each CDCC j is C_j. The inspection fee at CDCC $j, j \in J$ is e_j, and the processing fee at CDCC $j, j \in J$ is g_j. The transportation cost from MRC to CDCC $j, j \in J$ is a_j. I is used to represent a collection of customers. In this chapter, m represents different commodity types (n = new product retail, r = retail remanufactured product, on = online new product, or = online remanufactured product). T is the set of cycles. Each customer i, $i \in I$ has a certain nonconstant demand d_{itm} for m product in each period, $t \in T$, and the inventory carrying cost of customer i, $i \in I$ for m product is h_{im}. Customer i, $i \in I$ m has a recovery rate of α_{im} and a remanufacturable rate of product m of β_m. K is a set of vehicles with loading capacity U. For the convenience of notation, this section denotes the set of customers and potential CDCCs as S. In forward logistics, the transportation cost from node i to node j, $i \in S, j \in S$ is c_{ij}. In reverse logistics, the transportation cost between customer i, $i \in I$ and CDCC $j, j \in J$ is b_{ij}.

To obtain the optimal solution, the following variables need to be determined. The variable u_{ipkt} represents the quantity of product m delivered to customer i, $i \in I$ by vehicle k, $k \in K$ in period t, $t \in T$ in single-channel mode. The auxiliary variable l_{itpm} represents the quantity of product m delivered to customer i, $i \in I$ in period p, $p \in T$ to satisfy its demand in period t, $t \in T$ under single-channel mode. Decision variable $z_j = 1$ if CDCC $j, j \in J$ is established in single-channel mode; otherwise, $z_j = 0$. In the single-channel mode, if customer i, $i \in I$ is served by the established CDCC $j, j \in J$, the decision variable $y_{ij} = 1$; otherwise, it is 0. If the recycling activity of customer i, $i \in I$, is assigned to the open CDCC $j, j \in J$, the decision variable w_{ji} = 1. Otherwise, $w_{ji} = 0$. If vehicle k visits node j in cycle t, $t \in T, j \in s$ immediately visits node i, $i \in S$, and then $x_{ijkt} = 1$. Otherwise, $x_{ijkt} = 0$.

(1) Cost analysis under the single-channel mode. Under the single-channel mode, the total cost of the closed-loop supply chain system consists of the following costs.

   (a) Location cost. The cost of establishing CDCCs is $LC = \sum_{j \in J} f_j \cdot z_j$.
   (b) Inventory cost. The inventory holding cost of CDCCs is

$$IC = \sum_{t \in T} \sum_{i \in I} \left[\frac{1}{2}(h_{in} \cdot d_{\text{int}} + h_{ir} \cdot d_{irt}) + \sum_{p \in T, p < t} \left(h_{in} \cdot l_{inpt} + h_{ir} \cdot l_{irpt} \right)(t - p) \right.$$
$$\left. + \sum_{p \in T, p > t} \left(h_{in} \cdot l_{inpt} + h_{ir} \cdot l_{irpt} \right)(t - p + T) \right]$$

   (c) Transportation costs. The total transportation cost includes the transportation cost from MRC to CDCCs, transportation cost from CDCCs to customers, transportation costs from customers to CDCCs, and transportation cost from CDCCs to MRC.

- The transportation cost from MRC to CDCCs is $\sum_{t \in T} \sum_{j \in J} \sum_{i \in I} a_j \cdot (d_{\text{int}} + d_{irt}) \cdot y_{ij}$.
- The transportation cost from CDCCs to customers is $\sum_{i \in S} \sum_{j \in S} \sum_{k \in K} \sum_{t \in T} c_{ij} \cdot x_{ijkt}$.
- Transportation costs from customers to CDCCs. Due to the uncertainty of recycled products, CDCCs will use third-party logistics to collect waste products at a cost of $\sum_{t \in T} \sum_{j \in J} \sum_{i \in I} b_{ij} \cdot (\alpha_{in} \cdot d_{\text{int}} + \alpha_{ir} \cdot d_{irt}) \cdot w_{ji}$.
- Transportation cost from CDCCs to MRC. Waste products that can be used for remanufacturing are transported from customers to MRC for remanufacturing through CDCCs. Therefore, the cost is $\sum_{t \in T} \sum_{j \in J} \sum_{i \in I} a_j \cdot (\alpha_{in} \cdot \beta_n \cdot d_{\text{int}} + \alpha_{ir} \cdot \beta_r \cdot d_{irt}) \cdot w_{ji}$.

  Therefore, the total transportation cost is

$$
\begin{aligned}
TC = & \sum_{i \in S} \sum_{j \in S} \sum_{k \in K} \sum_{t \in T} c_{ij} \cdot x_{ijkt} \\
& + \sum_{t \in T} \sum_{j \in J} \sum_{i \in I} \big(b_{ij} \cdot (\alpha_{in} \cdot d_{\text{int}} + \alpha_{ir} \cdot d_{irt}) \cdot w_{ji} \\
& + a_j \cdot (d_{\text{int}} + d_{irt}) \cdot y_{ij} \big) \\
& + \sum_{t \in T} \sum_{j \in J} \sum_{i \in I} a_j \cdot (\alpha_{in} \cdot \beta_n \cdot d_{\text{int}} + \alpha_{ir} \cdot \beta_r \cdot d_{irt}) \cdot w_{ji}.
\end{aligned}
$$

- Inspection fee. The returned products are inspected in CDCCs, and the cost is

$$
INC = \sum_{t \in T} \sum_{j \in J} \sum_{i \in I} e_j \cdot (\alpha_{in} \cdot d_{\text{int}} + \alpha_{ir} \cdot d_{irt}) \cdot w_{ji}.
$$

- Disposal costs. Waste products that cannot be used for remanufacturing are discarded in CDCCs. The cost is

$$
\begin{aligned}
DC = & \sum_{t \in T} \sum_{j \in J} \sum_{i \in I} g_j \cdot (\alpha_{in} \cdot (1 - \beta_n) \cdot d_{\text{int}} \\
& + \alpha_{ir} \cdot (1 - \beta_r) \cdot d_{irt}) \cdot w_{ji}
\end{aligned}
$$

- Remanufacturing cost. The products that can be used for remanufacturing are remanufactured in MRC at a cost of

$$
RC = \sum_{t \in T} \sum_{j \in J} \sum_{i \in I} q \cdot (\alpha_{in} \cdot \beta_n \cdot d_{\text{int}} + \alpha_{ir} \cdot \beta_r \cdot d_{irt}) \cdot w_{ji}
$$

(2) Optimization model under single-channel mode. The model of the single-channel closed-loop location path inventory problem can be expressed as follows.

$$\min C_{single-channel} = LC + IC + TC + INC + DC + RC \tag{10.1}$$

subject to

$$\sum_{j \in S} x_{ijkt} - \sum_{j \in S} x_{jikt} = 0 \quad \forall i \in S, \forall k \in K, \forall t \in T \tag{10.2}$$

$$\sum_{j \in S} \sum_{k \in K} x_{ijkt} \le 1 \quad \forall t \in T, \forall i \in I \tag{10.3}$$

$$\sum_{j \in S} \sum_{k \in K} x_{jikt} \le 1 \quad \forall t \in T, \forall i \in I \tag{10.4}$$

$$\sum_{i \in I} \sum_{j \in J} x_{ijkt} \le 1 \quad \forall t \in T, \forall k \in K \tag{10.5}$$

$$x_{ijkt} = 0 \quad \forall i, j \in J, \forall t \in T, \forall k \in K, i \ne j \tag{10.6}$$

$$\sum_{i \in I} (u_{inkt} + u_{irkt}) \le U \; \forall t \in T, \forall k \in K \tag{10.7}$$

$$\sum_{i \in V} \sum_{j \in V} x_{ijkt} \le |V| - 1 \quad \forall k \in K, \forall t \in T, \forall V \subseteq I \tag{10.8}$$

$$\sum_{j \in J} y_{ij} = 1 \quad \forall i \in I \tag{10.9}$$

$$y_{ij} \le z_j \quad \forall i \in I, \forall j \in J \tag{10.10}$$

$$\sum_{j \in J} w_{ji} = 1 \quad \forall i \in I \tag{10.11}$$

$$w_{ji} \le z_j \quad \forall i \in I, \forall j \in J \tag{10.12}$$

$$\sum_{i \in I} w_{ji} \le M \sum_{i \in I} y_{ij} \quad \forall j \in J, M \text{ is a big number} \tag{10.13}$$

$$\sum_{i \in I} \left(y_{ij} \sum_{t \in T} (d_{\text{int}} + d_{irt}) \right) \le C_j \quad \forall j \in J \tag{10.14}$$

$$\sum_{v\in I} x_{vjkt} - \sum_{v\in S\backslash\{i\}} x_{ivkt} \le 1 + y_{ij} \quad \forall i \in I, \forall j \in J, \forall k \in K, \forall t \in T \tag{10.15}$$

$$\sum_{i\in I}\sum_{k\in K}\sum_{t\in T} x_{ijkt} \ge z_j \quad \forall j \in J \tag{10.16}$$

$$\sum_{i\in I} x_{jikt} \le z_j \quad \forall j \in J, \forall k \in K, \forall t \in T \tag{10.17}$$

$$\sum_{p\in T}\left(l_{inpt} + l_{irpt}\right) = d_{\text{int}} + d_{irt} \quad \forall i \in I, \forall t \in T \tag{10.18}$$

$$\sum_{p\in T}\left(l_{inpt} + l_{irpt}\right) = \sum_{k\in K}\left(u_{inkt} + u_{irkt}\right) \forall i \in I, \forall t \in T \tag{10.19}$$

$$\left(u_{inkt} + u_{irkt}\right) \le M \sum_{j\in S} x_{ijkt} \quad \forall i \in I, \forall k \in K, \forall t \in T \tag{10.20}$$

$$\sum_{j\in S} x_{ijkt} \le M\left(u_{inkt} + u_{irkt}\right) \quad \forall i \in I, \forall k \in K, \forall t \in T \tag{10.21}$$

$$\left(u_{inkt} + u_{irkt}\right) \le \min\left\{U, \sum_{p\in T}\left(d_{\text{int}} + d_{irt}\right)\right\} \quad \forall i \in I, \forall k \in K, \forall t \in T \tag{10.22}$$

$$\left(l_{inpt} + l_{irpt}\right) \le d_{\text{int}} + d_{irt} \quad \forall i \in I, \forall t, p \in T \tag{10.23}$$

$$x_{ijkt} \in \{0, 1\} \quad \forall i \in I, \forall j \in J, \forall k \in K, \forall t \in T \tag{10.24}$$

$$y_{ij} \in \{0, 1\} \quad \forall i \in I, \forall j \in J \tag{10.25}$$

$$w_{ji} \in \{0, 1\} \quad \forall i \in I, \forall j \in J \tag{10.26}$$

$$z_{ji} \in \{0, 1\} \quad \forall j \in J \tag{10.27}$$

$$l_{inpt} \in \mathrm{R}^+,\ l_{irpt} \in \mathrm{R}^+ \quad \forall i \in I, \forall t, p \in T \tag{10.28}$$

The total cost of the remanufacturing integrated logistics network in single-channel mode is Eq. (10.1). Constraint (10.2) ensures that the vehicle must leave from a node after entering it. Constraints (10.3) and (10.4) ensure that each vehicle can only serve one node for a period of time. Each vehicle only accesses one route at a time, guaranteed by constraint (10.5). Constraint (10.6) has only one CDCC on a path. Constraint (10.7) is the capacity constraint of the vehicle. Constraint (10.8) ensures that each path must contain a CDCC to avoid subpaths. Constraints (10.9) and (10.10) show that, in forward logistics, each customer must be served by an open CDCC. Constraints (10.11) and (10.12) indicate that only open CDCCs can recycle customer products in reverse logistics. Constraint (10.13) states that, in reverse logistics, if and only if a CDCC has been opened as a distribution centre in forward logistics can the CDCC can be opened as a recycling centre. Constraint (10.14) is the capacity constraint of CDCCs. Constraint (10.15) means that, if customer i is assigned to CDCC j, there must be a vehicle k starting its journey from CDCC j and visiting customer i. Constraints (10.16) and (10.17) ensure that vehicles will access a CDCC when and only when that CDCC is opened. The satisfaction of each customer's demand is guaranteed by constraints (10.18) and (10.19), and constraint (10.19) states that the sum of the quantity delivered from other periods to meet the customer in a certain period is equal to the quantity delivered by the vehicle. Constraints (10.20–10.22) ensure that, if vehicle k supplements a customer in cycle t, the corresponding vehicle should also visit the customer in this cycle. Constraint (10.23) ensures that the number of replenishment cycles t from cycle p is less than the customer's demand in cycle t. Constraints (10.24–10.28) represent the properties of decision variables and auxiliary variables.

10.2.2 The Manufacturer Adopts the Dual-Channel Mode

Online retail channels are added to the single-channel mode to form a dual-channel mode. The needs of customers' online retail channels are directly met by the MRC and provided to customers through third-party logistics. In addition, customers who buy products online recycle their waste products to CDCCs. Although the structure of the traditional retail industry remains unchanged in the dual-channel model, the online demand of customers may erode the number of some traditional retailers. The objective of this section is to reoptimize the decision-making of facility location, allocation, inventory control and vehicle routing in the dual-channel mode. The remanufacturing supply chain in dual-channel mode is shown in Fig. 10.3. This

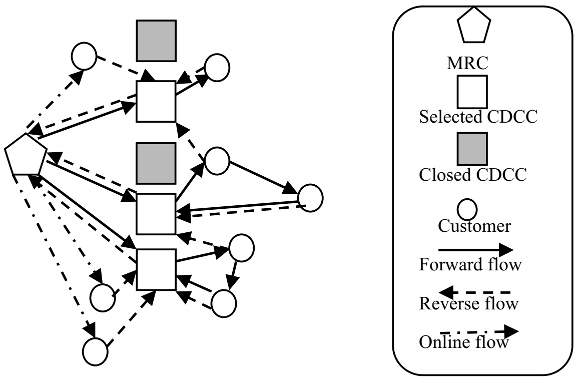

Fig. 10.3 Remanufacturing integrated logistics network under dual channel mode

supply chain mode is also a Location-routing-inventory problem under dual-channel in closed-supply chain (LIRP-CLDC).

Considering the addition of online retail channels, some new symbols and variables need to be introduced. In the online channel, the transportation cost from MRC to customer i, $i \in I$ is s_i. The variable representing the quantity of product m delivered to customer i, $i \in I$ by vehicle k, $k \in K$ in cycle t, $t \in T$ under dual channels is $u_{ipktdual}$. The auxiliary variable representing the quantity of product m passed to customer i, $i \in I$ in cycle p, $p \in T$ to meet its demand in cycle t, $t \in T$ is $l_{itpmdual}$. If CDCC j, $j \in J$ is established under dual channels, then $z_{jdual} = 1$; otherwise, it is 0. If customer i, $i \in I$ is served by the established CDCC j, $j \in J$, the decision variable $y_{ijdual} = 1$; otherwise, it is 0. If the recycling activity of customer i, $i \in I$, is assigned to the open CDCC j, $j \in J$, the decision variable $w_{jidual} = 1$. Otherwise, it is 0. If vehicle k accesses node j in cycle t, $t \in T$ and $j \in s$ immediately accesses node i, $i \in s$, then $x_{ijktdual} = 1$. Otherwise, $x_{ijktdual} = 0$.

(1) Cost analysis of the dual-channel model. As mentioned earlier in this section, this section posits that the demand of online channels may erode the demand of the original retail channels. Therefore, when using online channels, customers' needs for new products and remanufactured products are as follows.

$$d_{\text{int}dual} = (1-\chi)\cdot d_{\text{int}};\ d_{irtdual} = (1-\chi)\cdot d_{irt};$$
$$d_{iontdual} = \chi\cdot d_{\text{int}};\ d_{iortdual} = \chi\cdot d_{irt}.$$

In the dual-channel mode, the total cost of the supply chain system consists of the following costs.

(a) Location cost. The cost of establishing CDCCs in this chapter is

$$LC_{dual} = \sum_{j\in J} f_j \cdot z_{jdual}.$$

(b) Inventory cost. The inventory cost under dual-channel mode is

$$\begin{aligned} IC_{dual} = \sum_{t\in T}\sum_{i\in I}\Bigg[&\frac{1}{2}(h_{in}\cdot d_{\text{int}dual} + h_{ir}\cdot d_{irtdual}) \\ &+ \sum_{p\in T, p<t}\big(h_{in}\cdot l_{inptdual} + h_{ir}\cdot l_{irptdual}\big)(t-m) \\ &+ \sum_{p\in T, p>t}\big(h_{in}\cdot l_{inptdual} + h_{ir}\cdot l_{irptdual}\big)(t-p+H)\Bigg]. \end{aligned}$$

(c) Transportation costs. The total transportation cost includes the transportation cost from MRC to CDCCs, transportation costs from CDCCs to customers, transportation costs from customers to CDCCs, transportation costs from CDCCs to MRC, and transportation costs from MRC to customers.

- Transportation cost from MRC to CDCCs is

$$\sum_{t\in T}\sum_{j\in J}\sum_{i\in I} a_j \cdot (d_{\text{int}dual} + d_{irtdual}) \cdot y_{ijdual}.$$

- Transportation cost from CDCCs to customers is

$$\sum_{i\in S}\sum_{j\in S}\sum_{k\in K}\sum_{t\in T} c_{ij} \cdot x_{ijktdual}.$$

- Transportation costs from customers to CDCCs is

$$\sum_{t\in T}\sum_{j\in J}\sum_{i\in I} b_{ij} \cdot (\alpha_{in} \cdot d_{\text{int}dual} + \alpha_{ir} \cdot d_{irtdual} \\ + \alpha_{io} \cdot (d_{iontdual} + d_{iortdual})) \cdot w_{jidual}.$$

- Transportation cost from CDCCs to MRC is

$$\sum_{t\in T}\sum_{j\in J}\sum_{i\in I} a_j \cdot (\alpha_{in} \cdot \beta_n \cdot d_{\text{int}dual} + \alpha_{ir} \cdot \beta_r \cdot d_{irtdual} \\ + \alpha_{io} \cdot \beta_o \cdot (d_{iontdual} + d_{iortdual})) \cdot w_{jidual}.$$

- Transportation cost from customers to MRC is

$$\sum_{t\in T}\sum_{i\in I} (d_{iontdual} + d_{iortdual}) \cdot s_i.$$

Therefore, the total transportation cost is

$$TC_{dual} = \sum_{i\in S}\sum_{j\in S}\sum_{k\in K}\sum_{t\in T} c_{ij} \cdot x_{ijktdual} + \sum_{j\in J}\sum_{i\in I} b_{ij} \cdot \left[\alpha_{in} \cdot d_{\text{int}dual} + \alpha_{ir} \cdot d_{irtdual} \right. \\ \left. + \alpha_{io} \cdot (d_{iontdual} + d_{iortdual})\right] \cdot w_{jidual} + \sum_{t\in T}\sum_{j\in J}\sum_{i\in I} \left[a_j \cdot (\alpha_{in} \cdot \beta_n \cdot d_{\text{int}dual} \right. \\ + \alpha_{ir} \cdot \beta_r \cdot d_{irtdual} + \alpha_{io} \cdot \beta_o \cdot (d_{iontdual} + d_{iortdual})) \cdot w_{jidual} \\ \left. + a_j \cdot (d_{\text{int}dual} + d_{irtdual}) \cdot y_{ijdual}\right] + \sum_{t\in T}\sum_{i\in I} (d_{iontdual} + d_{iortdual}) \cdot s_i$$

(d) Inspection cost. The inspection cost is

$$INC_{dual} = \sum_{t\in T}\sum_{j\in J}\sum_{i\in I} e_j \cdot (\alpha_{in} \cdot d_{\text{int}dual} + \alpha_{ir} \cdot d_{irtdual} \\ + \alpha_{io} \cdot (d_{iontdual} + d_{iortdual})) \cdot w_{ji}$$

(e) Discard cost. The discard cost is

$$DC_{dual} = \sum_{t\in T}\sum_{j\in J}\sum_{i\in I} g_j \cdot (\alpha_{in} \cdot (1-\beta_n) \cdot d_{\text{int}dual} + \alpha_{ir} \cdot (1-\beta_r) \cdot d_{irtdual} + \alpha_{io} \cdot (1-\beta_o) \cdot (d_{iontdual} + d_{iortdual})) \cdot w_{jidual}$$

(f) Remanufacturing cost. The remanufacturing cost is

$$RC_{dual} = \sum_{t\in T}\sum_{j\in J}\sum_{i\in I} q \cdot (\alpha_{in} \cdot \beta_n \cdot d_{\text{int}dual} + \alpha_{ir} \cdot \beta_r \cdot d_{irtdual} + \alpha_{io} \cdot \beta_o \cdot (d_{iontdual} + d_{iortdual})) \cdot w_{jidual}$$

(2) Optimization model of the dual-channel mode. Therefore, for the dual-channel mode, the remanufacturing integrated logistics network optimization model is as follows.

$$\min\ C_{dual-channel} = LC_{dual-channel} + IC_{dual-channel} + TC_{dual-channel} + INC_{dual-channel} + DC_{dual-channel} + RC_{dual-channel} \tag{10.29}$$

subject to

$$\sum_{j\in S} x_{ijktdual} - \sum_{j\in S} x_{jiktdual} = 0 \quad \forall i \in S, \forall k \in K, \forall t \in T \tag{10.30}$$

$$\sum_{j\in S}\sum_{k\in K} x_{ijktdual} \le 1 \quad \forall t \in T, \forall i \in I \tag{10.31}$$

$$\sum_{j\in S}\sum_{k\in K} x_{jiktdual} \le 1 \quad \forall t \in T, \forall i \in I \tag{10.32}$$

$$\sum_{i\in I}\sum_{j\in J} x_{jiktdual} \le 1 \quad \forall t \in T, \forall k \in K \tag{10.33}$$

$$x_{ijktdual} = 0 \quad \forall i, j \in J, \forall t \in T, \forall k \in K, i \ne j \tag{10.34}$$

$$\sum_{i\in I} (u_{inktdual} + u_{irktdual}) \le U \quad \forall t \in T, \forall k \in K \tag{10.35}$$

$$\sum_{i\in V}\sum_{j\in V} x_{ijkt} \le |V| - 1 \quad \forall k \in K, \forall t \in T, \forall V \subseteq I \tag{10.36}$$

$$\sum_{j\in J} y_{ijdual} = 1 \quad \forall i \in I \tag{10.37}$$

$$\sum_{j\in J} w_{jidual} = 1 \quad \forall i \in I \tag{10.38}$$

$$y_{ijdual} \le z_{jdual} \quad \forall i \in I, \forall j \in J \tag{10.39}$$

$$w_{jidual} \le z_{jdual} \quad \forall i \in I, \forall j \in J \tag{10.40}$$

$$\sum_{i\in I} w_{jidual} \le M \sum_{i\in I} y_{ijdual} \quad \forall j \in J,\ M \text{ is a big number} \tag{10.41}$$

$$\sum_{i\in I}\left(y_{ijdual}\sum_{t\in T}(d_{\text{int}dual} + d_{irtdual})\right) \le C_j \quad \forall j \in J \tag{10.42}$$

$$\sum_{v\in I} x_{vjktdual} - \sum_{v\in S\setminus\{i\}} x_{ivktdual} \le 1 + y_{ijdual}\, \forall i \in I, \forall j \in J, \forall k \in K, \forall t \in T \tag{10.43}$$

$$\sum_{i\in I}\sum_{k\in K}\sum_{t\in T} x_{ijktdual} \ge z_{jdual} \quad \forall j \in J \tag{10.44}$$

$$\sum_{i\in I} x_{jiktdual} \le z_{jdual} \quad \forall j \in J, \forall k \in K, \forall t \in T \tag{10.45}$$

$$\sum_{p\in T}\left(l_{inptdual} + l_{irptdual}\right) = d_{\text{int}dual} + d_{irtdual} \quad \forall i \in I, \forall t \in T \tag{10.46}$$

$$\sum_{p\in T}\left(l_{inptdual} + l_{irptdual}\right) = \sum_{k\in K}(u_{inktdual} + u_{irktdual}) \quad \forall i \in I, \forall t \in T \tag{10.47}$$

$$(u_{inktdual} + u_{irktdual}) \le M \sum_{j\in S} x_{ijktdual} \quad \forall i \in I, \forall k \in K, \forall t \in T \tag{10.48}$$

$$\sum_{j\in S} x_{ijktdual} \le M(u_{inktdual} + u_{irktdual}) \quad \forall i \in I, \forall k \in K, \forall t \in T \tag{10.49}$$

$$(u_{inktdual} + u_{irktdual}) \le \min\left\{U, \sum_{t\in T}(d_{\text{int}dual} + d_{irtdual})\right\} \quad \forall i \in I, \forall k \in K, \forall t \in T \tag{10.50}$$

$$\left(l_{inptdual} + l_{irptdual}\right) = d_{inpdual} + d_{irpdual} \quad \forall i \in I, \forall t, p \in T \tag{10.51}$$

$$x_{ijktdual} \in \{0, 1\} \quad \forall i \in I, \forall j \in J, \forall k \in K, \forall t \in T \tag{10.52}$$

$$y_{ijdual} \in \{0, 1\} \quad \forall i \in I, \forall j \in J \tag{10.53}$$

$$w_{jidual} \in \{0, 1\} \quad \forall i \in I, \forall j \in J \tag{10.54}$$

$$z_{jidual} \in \{0, 1\} \quad \forall j \in J \tag{10.55}$$

$$l_{inptdual} \in \mathrm{R}^{+}, \; l_{irptdual} \in \mathrm{R}^{+} \quad \forall i \in I, \forall t, p \in T \tag{10.56}$$

The objective function of the dual-channel model is Eq. (10.29). Adding online channels to the single-channel model forms a dual-channel model, while the traditional retail structure remains unchanged. In addition, customers' online channel needs are met by the MRC and provided to customers through third-party logistics (3PL). Therefore, there are no additional constraints in the dual-channel model. Constraints (10.30–10.56) have the same meaning as constraints (10.2–10.28).

10.2.3 Solution of the Model

The location inventory path problem is an NP-hard problem. Reverse logistics and the online mode are also added to the research problems in this chapter, which further increases the difficulty of solving the model. It is difficult to solve NP-hard problems in a reasonable time; thus, heuristic methods are widely used to solve location inventory path problems. In this part, we propose a genetic algorithm combined with a local search process (GALS). The genetic algorithm has good global search ability but weak local search ability, so it adopts local search to avoid local optimization.

The GALS algorithm proposed in this section starts with a set of initial solutions called group (P). Every solution in the population is represented by a chromosome. The main process of GALS is to perform chromosome evolution through continuous iteration (*it*). This process is called generation. In each generation process, chromosome (*i*) is evaluated by *fitness (i)*. The fitness function proposed in this paper is the objective function. The next generation is generated using a crossover operator, mutation operator and local search program. The generation used to generate the next generation is called the parent generation. The next generation is called offspring. The algorithm uses the mutation rate (p_{mutation}) and local search rate (p_{ls}) to selectively accept mutation and local search. In addition, in each generation, the best solution is stored (if found). When the stop condition is met, the iteration ends. Table 10.2 outlines the pseudocode of the proposed GALS.

The GALS algorithm proposed in this chapter improves the performance of the genetic algorithm in the following three aspects: first, the algorithm applies the anti-learning algorithm (OBL) to produce a better initialization solution; second, a path crossover operator (RCX) is adopted; third, a memory operator is proposed to prevent the loss of good solutions.

Table 10.2 Overall flow of the GALS algorithm

```
Algorithm 1: Overall flow of the GALS algorithm
Steps 0: //Initialize
      Generating chromosomes with population size p by
Algorithm 2;
  for i = 1 to P do
    Computing chromosomes i fitness(i) by using Theorem 1;
  end for
  fitness(bestsolution) = min{fitness(i)};
  bestsolution = {i | fitness(i) = fitness(bestsolution)}
Steps 1: //Main process
  While(it ≤ α_max or it ≤ iter_max)
  // Crossover
  Select two collateral by binary competition parent 1 and
parent 2
  Apply the crossover operation to generate two children 1 and
children 2
  Add children 1 and children 2 to that population P
  Move out the two worst from P
  for i = 1 to P do
  // Mutation
  if random < p_mutation
  Perform mutation operation (i)
  end if
  //Local search
  if random < p_ls then LSswap(i) end if
  If random < p_ls then LSinsert(i) end if
  If random < p_ls then LS2-opt(i) end if
  Feasibility repair
  //Memory
  if fitness(i) < fitness(Best Solution) then
    Fitness(bestsolution): = fitness(i)
         Best Solution: = i
         α: = 0
  else α: = α + 1
  iter = iter + 1
  end for
  end while
Step 2: Output that optimal solution
```

10.2.4 Sensitivity Analysis

In this section, we analyse the parameters used in LIRP-CLDC that affect the optimal value of both channels. Thus, parameters b_{ij}, e_j, g_j, h_{in}, h_{ir}, q, s_i, α_{in}, α_{ir}, β_{in}, β_{ir} and χ are considered. In Table 10.3, these parameters are changed by the percentages within the range of $[-50\%, 50\%]$. OBJ1 is the objective value of LIRP-CLDC under a single channel, and OBJ2 is the objective value of LIRP-CLDC under dual channels. GAP1 is calculated by (the objective value of LIRP-CLDC under a single channel after the parameters change—the objective value of LIRP-CLDC under a single channel without changing the parameters)/the objective value of LIRP-CLDC under

Table 10.3 Sensitivity analysis of parameters of LIRP-CLDC under both strategies

		b_{ij}	e_j	g_j	h_{in}	h_{ir}	Q	s_i
50%	OBJ1	1,333,080.85	1,213,327.90	1,210,541.7	1,329,335.96	1,210,650.28	1,209,727.11	–
	GAP1	11.20	1.21	0.98	10.89	0.99	0.91	–
	OBJ2	631,996.66	601,473.80	602,594.12	631,255.61	607,425.63	601,629.97	631,695.15
	GAP2	6.07	0.95	1.14	5.95	1.95	0.98	6.02
40%	OBJ1	1,257,016.67	1,212,839.89	1,209,850.69	1,279,183.22	1,211,359.69	1,208,647.55	–
	GAP1	4.86	1.17	0.92	6.71	1.05	0.82	–
	OBJ2	622,858.37	601,305.52	601,202.05	621,045.18	603,349.27	600,866.46	622,908.98
	GAP2	4.54	0.92	0.90	4.23	1.26	0.85	4.55
30%	OBJ1	1,234,993.00	1,209,542.07	1,206,523.02	1,220,815.1	1,209,538.17	1,205,479.35	–
	GAP1	3.02	0.90	0.65	1.84	0.90	0.56	–
	OBJ2	612,954.65	600,216.77	598,620.27	611,046.4	603,265.93	599,986.06	614,672.65
	GAP2	2.88	0.74	0.47	2.56	1.25	0.70	3.16
20%	OBJ1	1,227,283.93	1,204,922.16	1,204,354.11	1,209,929.32	1,203,425.98	1,201,943.32	–
	GAP1	2.38	0.51	0.46	0.93	0.39	0.26	–
	OBJ2	609,248.07	596,985.66	596,752.23	602,987.22	602,040.06	599,368.99	607,860.85
	GAP2	2.25	0.20	0.16	1.20	1.04	0.60	2.02
10%	OBJ1	1,218,279.89	1,204,504.72	1,198,810.88	1,202,580.98	1,203,038.30	1,202,100.78	–
	GAP1	1.63	0.48	0.00	0.32	0.35	0.28	–
	OBJ2	608,175.40	596,165.88	597,755.11	599,597.67	596,563.31	598,716.74	598,693.65
	GAP2	2.07	0.06	0.33	0.63	0.13	0.49	0.48
0%	OBJ1	1,198,786.94	1,198,786.94	1,198,786.94	1,198,786.94	1,198,786.94	1,198,786.94	–
	GAP1	0.00	0.00	0.00	0.00	0.00	0.00	–
	OBJ2	595,816.96	595,816.96	595,816.96	595,816.96	595,816.96	595,816.96	595,816.96
	GAP2	0.00	0.00	0.00	0.00	0.00	0.00	0.00

(continued)

Table 10.3 (continued)

		b_{ij}	e_j	g_j	h_{in}	h_{ir}	Q	s_i
−10%	OBJ1	1,193,491.96	1,198,527.26	1,195,123.87	1,192,858.93	1,194,951.10	1,196,394.56	–
	GAP1	−0.44	−0.02	−0.31	−0.49	−0.32	−0.20	–
	OBJ2	585,601.97	593,744.16	595,580.51	580,245.61	595,461.52	594,490.08	587,012.22
	GAP2	−1.71	−0.35	−0.04	−2.61	−0.06	−0.22	−1.48
−20%	OBJ1	1,179,683.78	1,192,231.08	1,190,245.59	1,175,902.87	1,183,881.86	1,196,153.86	–
	GAP1	−1.59	−0.55	−0.71	−1.91	−1.24	−0.22	–
	OBJ2	570,466.06	592,308.74	592,571.34	579,594.53	590,784.73	594,385.74	576,044.47
	GAP2	−4.25	−0.59	−0.54	−2.72	−0.84	−0.24	−3.32
−30%	OBJ1	1,162,217.25	1,195,241.18	1,188,047.2	1,162,956.62	1,188,138.82	1,191,321.19	–
	GAP1	−3.05	−0.30	−0.90	−2.99	−0.89	−0.62	–
	OBJ2	565,796.90	591,598.68	586,105.60	570,466.06	590,117.25	592,930.23	571,863.52
	GAP2	−5.04	−0.71	−1.63	−4.25	−0.96	−0.48	−4.02
−40%	OBJ1	1,120,648.70	1,190,805.57	1,186,783.77	1,131,601.25	1,180,749.36	1,189,882.76	–
	GAP1	−6.52	−0.67	−1.00	−5.60	−1.50	−0.74	–
	OBJ2	555,414.29	589,500.37	586,068.68	565,931.21	589,805.52	591,454.96	566,201.48
	GAP2	−6.78	−1.06	−1.64	−5.02	−1.01	−0.73	−4.97
−50%	OBJ1	1,117,511.8	1,177,339.94	1,180,978.48	1,109,098.18	1,179,560.94	1,188,883.44	–
	GAP1	−6.78	−1.79	−1.49	−7.48	−1.60	−0.83	–
	OBJ2	548,590.75	588,902.30	584,909.85	558,312.53	585,022.1	589,815.94	558,729.04
	GAP2	−7.93	−1.16	−1.83	−6.29	−1.81	−1.01	−6.22

a single channel after the parameters change*100%. GAP2 is calculated similarly. In this table, the objective value of LIRP-CLDC under a single channel is increased by 11.2% when b_{ij} increases by 50% and increased by 10.89% when h_{in} increases by 50%. Moreover, when b_{ij} and h_{in} decrease by 50%, the objective value decreases by 6.78% and 7.48%, respectively. s_i is the per transportation cost from the MRC to the customer, which only influences the cost of LIRP-CLDC under dual channels. s_i also represents the 3PL cost. Then, when b_{ij} increases by 50%, the objective value of LIRP-CLDC under dual channels is increased by 6.07%, when h_{in} increases by 50%, the objective value is increased by 5.95% and when s_i increases by 50%, the objective value is increased by 6.02%. When b_{ij}, h_{in} and s_i decrease by 50%, the objective value decreases by 7.93%, 6.29% and 6.22%, respectively. The remaining parameters have little effect on the objective values. In addition, the objective values under a single channel cost more than the objective values under dual channels. This indicates that, if the company adopts the dual-channel strategy, the company can reduce the cost. Moreover, all the parameters considered in this table influence the objective value of both strategies. Company managers should take them into consideration when making decisions.

The parameters α_{in} and α_{ir} influence the quantity of returned products, and the parameters β_{in} and β_{ir} affect the quantity of repairable products. These parameters are changed within the range [0, 1]. The sensitivity analysis of these parameters is shown in Tables 10.4 and 10.5. Tables 10.4 and 10.5 depict the changes in costs under a single channel. The costs of the dual-channel strategy have the same trend as those of a single channel. From Table 10.4, we can see that the cost of establishing CDCCs is not changed when parameters α_{in} and α_{ir} change. The inventory cost is decreased when α_{in} and α_{ir} increase, while the transportation cost, inspection cost, disposal cost and repair cost are increased when parameters α_{in} and α_{ir} increase. Then, the objective values are increased when α_{in} and α_{ir} increase. In Table 10.5, the location cost is also unchanged, the inventory cost is also decreased when β_{in}

Table 10.4 Sensitivity analysis of parameters α_{in} and α_{ir}

α_{in}	α_{ir}	LC	IC	TC	INC	DC	RC	OBJ1
0	0	6562	701,293.00	388,240.00	0	0	0	1,096,095.00
0.1	0.2	6562	700,492.46	419,206.00	9663.7	14,478.42	4848.98	1,155,251.56
0.2	0.3	6562	677,682.01	444,181.86	17,009.0	23,437.96	8360.84	1,167,516.29
0.3	0.4	6562	675,009.66	453,566.20	31,798.8	23,456.60	8393.68	1,198,786.94
0.4	0.5	6562	674,510.22	462,037.02	77,854.6	25,234.96	8785.92	1,258,156.51
0.5	0.6	6562	674,316.00	481,032.76	78,373.4	57,709.22	10,332.09	1,309,019.13
0.6	0.7	6562	667,964.63	546,540.16	92,799.0	67,824.12	14,274.06	1,402,315.34
0.7	0.8	6562	661,192.00	591,416.33	107,893.2	78,984.88	24,622.48	1,470,670.89
0.8	0.9	6562	660,613.38	614,061.89	122,152.4	89,755.04	32,532.96	1,525,677.67
0.9	1	6562	600,504.97	686,138.11	137,222.2	100,851.34	36,446.86	1,567,725.48
1	1	6562	600,237.00	785,990.76	147,150.0	107,677.20	39,314.80	1,686,931.76

Table 10.5 Sensitivity analysis of parameters β_{in} and β_{ir}

β_{in}	β_{ir}	LC	IC	TC	INC	DC	RC	OBJ1
0	0	6562	705,755.58	389,785.67	24,394.0	24,394.00	0	1,150,891.25
0.1	0	6562	683,811.38	424,366.56	24,394.0	23,057.87	2997.72	1,165,189.57
0.2	0.1	6562	679,665.87	447,567.76	24,399.8	23,143.06	3944.00	1,185,282.49
0.3	0.2	6562	675,009.66	453,566.20	31,798.8	23,456.60	8393.68	1,198,786.94
0.4	0.3	6562	655,926.91	494,562.96	48,942.4	11,731.56	8896.68	1,226,622.51
0.5	0.4	6562	648,320.63	498,206.83	49,117.4	10,750.48	22,708.26	1,235,665.60
0.6	0.5	6562	643,178.50	526,391.45	49,213.4	6791.68	27,547.88	1,259,684.91
0.7	0.6	6562	641,043.52	540,895.67	49,247.4	3617.30	32,461.74	1,273,827.63
0.8	0.7	6562	637,336.39	555,412.68	49,276.0	3401.39	37,385.84	1,289,374.30
0.9	0.8	6562	624,000.15	572,805.67	49,304.4	3126.40	42,452.28	1,298,250.90
1	0.9	6562	611,963.74	609,381.97	49,355.0	1886.40	47,436.60	1,326,585.71

and β_{ir} increase, and the transportation cost, inspection cost and repair cost are also increased when β_{in} and β_{ir} increase. However, the disposal cost is decreased when β_{in} and β_{ir} increase. The objective values are increased when β_{in} and β_{ir} increase.

The parameter χ represents the proportion of customers who buy products from online channels. This parameter only affects the cost under dual channels, and the parameter changes from 0 to 0.8. The results are shown in Table 10.6. In Table 10.6, $\chi = 0$ indicates that the company adopts the single-channel model. $\chi > 0$ means that the company adopts the dual-channel model. It can be seen from Table 10.6 that, with the increase in χ, the cost of site selection remains unchanged, the cost of inventory, transportation and disposal decreases, and the cost of inspection and remanufacturing increases with the increase in χ. As χ increases, the total cost of dual channels decreases. This suggests that enterprises adopting dual channels can reduce operating costs.

Table 10.6 Sensitivity analysis of parameter χ

χ	LCdual	ICdual	TCdual	INCdual	DCdual	RCdual	OBJ2
0	6562	675,009.66	453,566.20	31,798.8	23,456.60	8393.68	1,198,786.94
0.1	6562	558,720.99	411,380.41	95,734.9	23,187.08	11,694.36	1,107,279.74
0.2	6562	530,018.58	401,221.59	105,902.1	23,143.06	12,110.76	1,078,958.09
0.3	6562	516,901.41	347,941.52	143,209.6	23,082.86	12,202.28	1,049,899.67
0.4	6562	496,219.80	336,431.42	160,236.2	23,003.76	12,300.20	1,034,753.38
0.5	6562	392,426.86	335,668.45	181,472.0	21,447.18	12,341.98	949,918.47
0.6	6562	357,481.74	331,745.68	190,413.0	21,392.82	12,351.62	919,946.86
0.7	6562	175,796.97	306,802.43	246,434.2	21,343.61	12,376.92	769,316.13
0.8	6562	89,652.55	108,915.71	357,020.8	21,274.00	12,391.90	595,816.96

In summary, the above sensitivity analysis can be summarized into the following two aspects.

(1) Because the dual-channel mode will directly distribute the customers originally distributed by the retailer to the manufacturer, and this portion of the customers directly distributed by the manufacturer will reduce the links of the retailer and reduce the inventory cost and transportation cost, the dual-channel mode can bring higher profits to the enterprise than the single-channel mode.

(2) If the proportion of recycled products is greater than the proportion of recycled products that cannot be used for remanufacturing, remanufacturing enterprises can obtain more profits. This is because recycled products that can be used for remanufacturing provide additional profit means for remanufacturing, although the production cost is now high. In contrast, if the recycled products are not suitable for remanufacturing, it will cause losses to the remanufacturer because the waste products can only be discarded. Therefore, decision-makers can invest in quality improvement actions to increase the proportion of remanufactured products in the production process to achieve a higher proportion of remanufactured products.

10.3 Summary

This chapter first defines the basic concept of green manufacturing and clarifies the connotation, characteristics, and relationship with the green growth of enterprises. Then, the most direct and effective way to realize green manufacturing, namely, remanufacturing, is introduced. Finally, this chapter models analyses the remanufacturing problem under the traditional retail channel and the dual-channel configuration, and uses a new genetic algorithm combined with local search to solve the problem. The solution shows that, for enterprises, customers with less demand and recycling volume will be diverted to online channels, and these customers can be directly delivered to by manufacturers, which reduces transportation costs and inventory due to the reduction of retailers' links. Enterprises can reduce their total operating costs by adopting a dual-channel model. In addition, through the implementation of the dual-channel model, enterprises can improve their recycling rate of waste products, thereby increasing their ratio of remanufactured products and enabling themselves to obtain more profits compared to the profits obtained under the single-channel model.

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