Research on services decision-making in closed-loop supply chain dominated by a logistics provider

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Abstract
Remanufacturing is an advanced form of recycling in circular economy. In order to promote the development of remanufacturing, the government gradually uses subsidy policies to regulate and intervene related enterprises. In this paper, we assume that a closed-loop supply chain consists of an original equipment manufacturer (OEM) producing new products from raw materials, a remanufacturer producing re-manufactured products from used items directly collected from customers, and a logistics provider which sells and distributes two products as a monopolist in the given market. By constructing game model in which logistics provider is a leader and OEM and remanufacturer are the equal status followers, we solve chain members’ optimal services decision-making under government subsidy. Finally, considering the government subsidy, we analyze the impact of remanufacturer service level and the logistics provider service scope on members’ equilibrium decision-making. Analysis shows that government subsidy policies are always profitable for enterprises. The OEM and the logistics provider have the same choice. They would choose the subsidy policy for the service scope of the logistics supplier in order to improve the service level of new products and the service scope of the logistics supplier. The remanufacturer would believe that subsidizing the service level of remanufactured products is more effective in improving his own profits.

Keywords Service · Re-manufacturing · Logistics provider · Closed-loop supply chain

Introduction
In recent years, the economic benefits of recycling expired products and the environmental protection have been widely recognized in the field of theory and practice. The closed-loop supply chain can recycle these products in the hands of consumers and utilize their residual value. Thierry (1995) developed a system model for closed-loop supply chain. And Guide and Van Wassenhove (2009) considered the closed loop supply chain has a wide range of business prospects. Today’s supply chain systems are becoming more and more complex than just selling new products through a traditional single channel. The development of the Internet provides a new communication method for suppliers and consumers in the supply chain. More and more consumers are willing to purchase products directly through the Internet, and there are more and more manufacturers to establish online direct sales channels such as ThinkPad, HP, and Dell. China’s online retail sales reached 13.1 trillion Yuan in 2021, up to 14.1% year on year, or 3.2% points faster than the previous year, according to the National Bureau of Statistics. At the same time, the government has also started to implement various policies to support and promote the development of remanufacturing industry.
time, independent electronic retailers play a considerable role in the operation of the supply chain.

This article is mainly referred to the four parts literature. The first part is about the different modes of closed-loop supply chains (CLSC) and their impacts. Managers broadly agree that the entry of third-party remanufacturers (TPRs) is detrimental to original equipment manufacturers (OEMs), and social planners broadly agree that a non-discriminatory uniform pricing policy is more desirable than a buyer-specific pricing policy. Zou et al. (2012) studied the difference between authorization and outsourcing for the TPR. The result revealed that the TPR prefers authorization than outsourcing when consumer acceptance of remanufactured products is low. Authorization is better for environment with low consumer acceptance, while outsourcing is better for all parties and environment with high consumer acceptance. Another analysis showed that regardless of the pricing policy, third-party remanufacturing could lead to a triple win to the supplier, the OEM, and the TPR and the uniform pricing policy may result in an absolute reduction in social welfare (Wu and Zhou 2019). Maryam et al. (2019) proposed an analytical coordination model to not only cover all three dimensions, environment, social responsibility, and welfare of sustainability in a CLSC but also to align different decisions made in competitive forward and reverse logistics. Further, Khoshidvand et al. (2021) developed a hybrid modeling for a green and sustainable closed-loop supply chain; the supply chain coordination and supply chain network design are simultaneously considered in this model. Companies started to close the loop in their supply chains to comply with the regulations and increase the sustainability of their systems. It Influenced scholars to focus on the social impact of closed-loop supply chains. Panda et al. (2017) explored channel coordination in a socially responsible manufacturer-retailer CLSC by considering two areas—profit maximization and social responsibility through product recycling. The manufacturer is socially responsible and exhibits it by recycling of used product that it collects through the retailer using the reverse channel. It is found that the channel’s non-profit maximizing motive through social responsibility practice generates higher profit margin than the profit maximizing objective. Nikunja et al. (2019) developed a socially responsible CLSC model that considered donation, as a social responsibility, and recycling of the used products for environmental sustainability. They found the best socially responsible environmental friendly decentralized channel structure by a comparative analysis. Mehmet et al. (2020) investigated the economic and environmental effects of closing the loop in supply chains. In their study, demand, return rate, carbon cap, carbon, and carbon tax policies are considered. They found that closing the loop in supply chain does not always bring cost reduction, and the benefit may increase under low carbon caps.

The second part of the literature is about the profitability and strategy study of remanufactured products in CLSC. Atasu et al. (2008) provided an alternative and complementary approach to investigate the profitability of remanufacturing systems. Their research showed that remanufacturing is profitable once it is above the existing threshold such as the remanufacturing cost savings and the green segment size. The governmental subsidies and fees have a significant impact on remanufacturing. Mitra and Webster (2008) examined the effects of government subsidies as a means to promote remanufacturing activity. In particular, they considered a subsidy proportional to remanufacturing volume and allocated between manufacturers and remanufacturers. They found that the introduction of subsidies increases
remanufacturing activity, and subsidy sharing creates incentives for the manufacturer to design a product that is more suitable for remanufacturing and to be more open to efforts to increase the return rate of end-of-life products. Another study showed that higher subsidies advocate a manufacturer’s intention to lean towards remanufacturing activities under given manufacturing and consumption fee scenarios. And the subsidies from government to the manufacturer will maximize channel profit and total surplus. (Jena et al. 2018). In addition, there are many factors that can have an impact on the remanufacturing business. Li et al. (2017) proposed a two-stage model to study the optimal price and production quantity of new and remanufactured products. The result shows that both the life cycle phase and consumers’ perception have an impact on the original equipment manufacturer’s decision whether to allow the third-party remanufacturer in the remanufacturing business. Kovach et al. (2018) analyzed how salesforce incentives influence a firm’s remanufacturing strategy and profitability. They proposed a model with differentiated linear commissions for new and remanufactured products. By offering different commissions for new and remanufactured products, companies can expand the conditions favorable to remanufacturing and significantly increase profits. He et al. (2019) found that the retailer will always join the collection competition, which does not dent the cost vantage of remanufacturing, but the competition fails to enhance the recovery efficiency. From the above studies on remanufactured products, especially in the studies on government subsidies, the subjects being subsidized or incentivized are often manufacturers, and the services of logistics providers are not included in the study.

The fourth type of literature is about impact of service in the process of manufacturing and selling products. Cohen and Whang (1997) used the product life cycle model to study a set of strategic choices facing manufacturers as they design the joint product/service bundle for a product which may require maintenance and repair support after its sale. In their study, the after-sales service is included in the framework of the game, and the resulting outcome is applied to support the valuation of alternative product designs in explicit consideration of the tradeoff between profit from product sale and from the provision of after-sales service. Tsay and Agrawal (2000) studied a distribution system composed of one manufacturer and two retailers, and the two retailers compete on product prices and services. Their study explained when the retailers will pursue low-price strategies, and when they will instead emphasize service. Xia and Gilbert (2007) investigated how opportunities to invest in demand enhancing services for a product line affect the interactions between a manufacturer and her dealer. That is, the services that enhance demand, such as after-sales support and warranty repairs, are provided by the manufacturer or entrusted to the dealer. Based on the manufacturer-Stackelberg game model, Wu (2012) studied the manufacturer and remanufacturer through a traditional retailer to choose their respective decisions under the conditions of price and service competition. From this literature, it can be seen that the research is mainly focused on whether the services are performed and by whom in the studies on the impact of services on products and vendors. There is a lack of further research on the mechanisms of service impact, especially from a supply chain perspective. This article has a strong correlation with Wu (2012)’s research. However, we emphasize the importance of service elasticity and service competition of consumers’ demand for products. The introduction of logistics suppliers to replace traditional retailers to sell new products and remanufactured products is a major innovation of this paper. Under the premise that the logistics supplier is the leader, we mainly discuss the impact of service elasticity and service competition on the equilibrium decision-making of supply chain members and the choice of subsidy mechanism for supply chain members when the government provides two kinds of subsidies.

Model

We assume that there is an original equipment manufacturer (OEM) using raw materials to produce new products in the closed-loop supply chain, a remanufacturer that makes use of recycled waste products, and a logistics provider that sells and distributes the above two products. The hypothesis of re-manufacturing in the closed-loop supply chain is mainly about the following: first, the quality of new products is the same as the quality of remanufacturing products, so the manufacturer sells both products according to the same price; second, although we assume that there is no difference in the quality of the two products, in fact, consumers’ willingness to pay for new products and remanufactured products is different. Therefore, the demand for these two products is different. In our model, the logistics provider is also responsible for recycling the expired waste products and delivering them to the remanufacturer. And we assume that the amount of the expired waste products recovered is equal to the amount of the remanufactured products. So, the unit payment that the logistics provider gets from the original equipment manufacturer as $2h$, since logistics companies distribute remanufactured products and recycle waste products (Savaskan et al. 2004; Govindan et al. 2012). And we assume that new products and re-manufacturing are the same in performance. Logistics companies independently determine the sales price of these two products, and each manufacturer produces only one product. The two manufacturers have the opportunity to increase their needs by bundling some services on the product, while
logistics providers have the opportunity to increase their needs by expanding the range of services. All supply chain members must make decisions before the sales quarter. In order to make the re-manufacturing process smoothly, the remanufacturer must first determine the degree of remanufacturing \( \tau (0 \leq \tau \leq 1) \); \( \tau \) is the proportion of recycled parts used by the unit of production in the manufacture. The two manufacturers choose their respective service levels \( s_j \), the subscript \( j \) can be \( r \) and \( n \), which represent remanufactured products and new products. Assume that the direct selling price of new products and remanufacture products selling products is \( p \), the cost of production is \( c \), and \( \gamma_r \) and \( \gamma_n \) respectively represent the degree of service competition and the service flexibility of market demand. The logistics provider chooses the logistics service scope \( l \) to determine the market scope. Prices and service information are published in the market before the selling season begins. We assume that the two manufacturers have sufficient production capacity to meet the quantity ordered by the logistics provider and are able to deliver a certain quantity of the goods ordered to the logistics provider before the selling season. The logistics provider is a monopolist in the market under consideration, and other products in this market and different market areas are also under consideration, but these have no effect on the demand for the two products produced. At the same time, we believe that supply chain members are independent-risk neutral and profit maximizing decision-makers. They choose their decisions in turn according to the logistics provider-Stackelberg game model in a fair competitive environment, and each member has complete information about the other members.

**Demand and profit function**

Demand function is

\[
d_j = (\alpha_j - \beta_j p + \beta_j s_j - \gamma_j s_j)l, k \neq j, \alpha_j, \beta_j, \alpha_s, \beta_s, l \geq 0
\]

(1)

OEM’s profit function is

\[
\pi^M_r = (p - c - h)d_n - \frac{ms^2}{2}, (p - c - h > 0)
\]

(2)

\( \frac{ms^2}{2} \) is the cost of service, and \( m \geq 0 \).

Reproduction product manufacturer’s profit function is

\[
\pi^M_n = (p - c - 2h + \delta \tau)d_n - \frac{ms^2}{2} - \frac{b\tau^2}{2}, (p - c - 2h + \delta \tau > 0)
\]

(3)

\( \delta = c - cr, c(1 - \tau) + cr\tau = c - \delta \tau \), \( cr \) refers to the full remanufacturing cost. \( \frac{b\tau^2}{2} \) is the total cost of recycling, and \( b \geq 0 \).

Logistics provider’s profit function is

\[
x^l = x^l_r + x^l_n = (2d_r + d_n)h - \frac{mll^2}{2}
\]

(4)

\( \frac{mll^2}{2} \) is the logistics provider cost, and \( h \) is the unit product revenue of the logistics provider, paid by the manufacturer \( h, ml \geq 0 \).

**Model solution and analysis**

The implementation of the “old for new” and “old for reuse” policies has solved the problem of shortage of raw materials in remanufacturing production to a certain extent. When there are enough old pieces, in order to encourage manufacturers to participate in remanufacturing and improve remanufacturing technology and service levels, the government also subsidizes remanufacturers to varying degrees, such as subsidies for one-time investment in building factories, research and development, and production. And, the state specifically provides freight subsidies for home appliance recycling companies and grants fixed subsidies according to the types, specifications, and transportation distances of recycled old home appliances. The transportation distance refers to the fair distance between the actual location of the recycling enterprise and the actual location of the dismantling and processing enterprise. The specific criteria are approved and published by the local relevant authorities. Therefore, in this section, we only consider the government’s subsidies to the service level of remanufacturers and the service scope of logistics providers. Suppose \( T_\nu \) is the government’s subsidy rate for the service level of remanufactured products and \( I_\nu \) is the government’s subsidy rate for the logistics provider’s service range. Next, we study the closed-loop supply chain decision in two subsidies.

The profit function of logistics providers, remanufacturers, and original equipment manufacturers is a secondary concave function of the logistics range \( l \) and service level \( s_r, s_n \). That is, each supply chain member has the optimal choice for maximizing profits, and in competition, each member can make its own optimal strategy according to the decision of other members. In order to obtain the optimal balanced decision of the logistics range \( l \), we use the inverse method to obtain \( s^*_r, s^*_n \) by determining the profit maximization reaction function of the original equipment manufacturer (OEM) and the remanufacturer and then substituting \( s^*_n, s^*_r \) into the logistics company to determine its profit maximization reaction function to obtain \( l^* \); finally, substituting \( l^* \) into \( s^*_n, s^*_r \) can get a balanced decision.

**Decision analysis of the government’s subsidies for re-manufacturing services**

When the government subsidizes the service level of the remanufacturer, the demand function, the profit function of the original equipment manufacturer (OEM), and the profit
function of the logistics provider remain unchanged. The profit function of re-manufacture is
\[ \pi^M_r = (p - c - 2h + \delta r) d_r - \frac{m^2_s}{2} - \frac{b r^2}{2} + T sr s_r \] (5)

Remanufacturers and original equipment manufacturers determine their profit maximization reaction function, \( k \neq j \in \{r, n\} \), and obtain the first derivative \( \frac{\partial(\pi^M_r)}{\partial s_r} = 0 \), \( \frac{\partial(\pi^M_r)}{\partial s_n} = 0 \), and then we can obtain the following formula.
\[ s^n_p = -\frac{(p - h + c) r s}{m} \] (6)
\[ s^r_p = \frac{(p - c - 2h + \delta r) r s + T sr}{m} \] (7)

Logistics business determines the maximized reaction function \( l^* \in \argmax(l^r, s^n_p, s^r_p, \frac{\partial \pi^M}{\partial l} = 0, \) and the following formula can be obtained.
\[ l^* = \frac{-l(2 \beta_r - \gamma_s) T_M + (a_n + 2a_r - 3 \beta_r p)m h}{2b \eta h(p - c - h)(\beta_r - 2 \gamma_s) + (p - c - 2h + \delta r)(2 \beta_r - \gamma_s) - m m} \] (8)

where \( \beta_r h(p - c - h)(\beta_r - 2 \gamma_s) + (p - c - 2h + \delta r)(2 \beta_r - \gamma_s) - m m < 0 \).

Substitute formula (8) into formula (6) and formula (7), we can have the following function.
\[ s^n = \frac{-l(p + c + h \kappa 2 \beta_r - \gamma_s)(p + c + h \kappa 2 \beta_r - \gamma_s) - m m}{2b \eta h(p - c - h)(\beta_r - 2 \gamma_s) + (p - c - 2h + \delta r)(2 \beta_r - \gamma_s) - m m} \] (9)

\[ s^* = \frac{T sr \beta_r h(p - c - h)(\beta_r - 2 \gamma_s) + (p - c - 2h + \delta r)(2 \beta_r - \gamma_s) - m m}{(p - c - 2h + \delta r)(2 \beta_r - \gamma_s) - m m} \] (10)

Substitute formula (8), (9), and (10) into demand function \( d_n = (a_n - p + \beta_r p + \beta_r p - \gamma_s h, l \in \{r, n\} \neq j, a_n, \beta_n, \beta_r, l \geq 0 \), then we can get the equilibrium demand function \( d^*_n \) and \( d^*_r \). Same as above, bring the formula (8), (9), (10), and \( d^*_n \) separately into the remanufacturer’s profit function \( \pi^M_r = (p - c - 2h + \delta r) d_r - \frac{m^2_s}{2} - \frac{b r^2}{2} + T sr s_r \), the original equipment manufacturer’s profit function \( \pi^M_n = (p - c - h) d_n - \frac{m^2 n}{2} \), then we can get the equilibrium profit \( \pi^M_r, \pi^M_n, \pi^r, \pi^n \).

**Lemma 1.** When \( 2 \beta_r > \gamma_s, s^n_r \) and \( T sr \) are positively correlated. When \( 2 \beta_r \leq \gamma_s, s^n_r \) is independent of \( T sr \). And when \( 2 \beta_r < \gamma_s, s^n_r \) and \( T sr \) are negatively correlated.

**Corollary 1.** Whether the service level of new products is positively correlated with the service subsidy of remanufactured products \( (T sr) \) depends on service flexibility and service competition. If the service flexibility is greater than the level of service competition, the service level of the new product is related to the service subsidy of remanufacturing \( T sr \). In other words, government subsidies for the service of remanufactured goods will directly improve the service level of new products. Otherwise, it is negatively correlated; if the service elasticity is the same as the service competition, the service level of the new product is not related to the service level subsidy of the remanufactured product; that is, since the service subsidy increases the service level of remanufactured products, the amount of subsidies has no effect on the service level of the new products. Suppose \( m m \) is large enough to make \( b \eta h[p - c - h(\beta_r - 2 \gamma_s) + 2p - c - 2h + \delta r(2 \beta_r - \gamma_s)] - m m < 0 \), thus the service level of remanufactured products is positively correlated with its subsidy \( T sr \). In other words, government subsidies to the service level of remanufactured goods will directly improve the service level of remanufactured goods.
Or the original equipment manufacturer may not improve or even lower the service level of the new product.

Lemma 2. When $2\beta_s > \gamma_s$, $l^*$ and $T_{sr}$ are positively correlated. When $2\beta_s = \gamma_s$, $l^*$ is independent of $T_{sr}$. And when $2\beta_s < \gamma_s$, $l^*$ and $T_{sr}$ are negatively correlated.

Corollary 2. Whether the service scope of the logistics provider is positively correlated with the service level subsidy of remanufactured goods depends on the service elasticity and service competition degree. If the service elasticity is greater than the service competition degree, the service scope of the logistics provider is positively correlated with the service level subsidy of remanufactured goods. That is, government subsidies for remanufactured goods will directly expand the service scope of logistics providers; otherwise it will be negatively correlated. If the service elasticity is the same as the service competition, then the service scope of the logistics provider is not related to the service level subsidy of remanufactured products, that is, the government’s subsidy of the service of remanufactured products has no effect on the service scope of the logistics provider.

When the service elasticity is greater than the degree of service competition, the increase of service subsidy $T_{sr}$ of remanufactured products will improve the service level of new products and remanufactured products, thus increasing the demand of the two products. Then the service scope of the logistics provider may be expanded to meet the needs of customers, so at this time, the service scope of the logistics provider is positively correlated with the service level subsidy of remanufactured products. When the service elasticity is less than the service competition, the increase of service subsidy SRT for remanufactured goods will improve the service level of remanufactured goods and thus increase the demand for remanufactured goods. However, the service level of the new product will decrease, thereby reducing its demand. The total demand for the two products may decrease, and the service scope of the logistics provider will also be reduced.

Decision analysis of the government’s subsidies for logistics providers

When the government subsidizes the service level of logistics providers, the demand function, original equipment manufacturer’s profit function, and remanufacturer’s profit function remain unchanged. Logistics providers’ profit function is as the following function.

$$ f_j = \arg\max_{s_j} \pi^M_j(s_j, s^k, T, l), k \neq j, j = \{r, n\}, \text{ and solving the first derivative } \frac{\partial \pi^M_j(l)}{\partial s_j} = 0, \frac{\partial \pi^M_l(l)}{\partial s_n} = 0, \text{ we have}$$

$$ s^p_j = \frac{-(p + h + c)\beta_j l}{m} \quad (12) $$

$$ s^p_r = \frac{(p - c - 2h + \delta \tau)\beta_r l}{m} \quad (13) $$

Logistics providers determine the maximized reaction function maximized $l^* \in \arg\max_l \{l, s^p_r, \beta_r l\}, \frac{\partial \pi}{\partial l} = 0$, and we have

$$ l^* = \frac{-[(a_n + 2a_r - 3\beta_r p)h - T_l]m}{2\beta_n h[(p - c - h)(\beta_i - \gamma_i) + (p - c - 2h + \delta \tau)(2\beta_s - \gamma_s)] - \gamma_m} \quad (14) $$

where, $\beta_i h(2p - c - h)(\beta_i - \gamma_i) + 2(p - c - 2h + \delta \tau)(2\beta_s - \gamma_s) = \gamma_m < 0$.

Substituting formula (14) into formula (12) and formula (13), we can calculate the following formula,

$$ s^*_n = \frac{T_r \beta_r (p - c - h) - (p - c - h)(a_n + 2a_r - 3\beta_r p)h\beta_r}{2\beta_n h[(p - c - h)(\beta_i - \gamma_i) + (p - c - 2h + \delta \tau)(2\beta_s - \gamma_s)] - \gamma_m} \quad (15) $$

$$ s^*_r = \frac{T_r \beta_r (p - c - 2h + \delta \tau) - 2(p - c - 2h + \delta \tau)(a_n + 2a_r - 3\beta_r p)\beta_r h}{2\beta_n h[(p - c - h)(\beta_i - \gamma_i) + (p - c - 2h + \delta \tau)(2\beta_s - \gamma_s)] - \gamma_m} \quad (16) $$

Then substitute these formulas (14), (15), (16) into the demand function $d_j = (a_j - \beta_j p + \beta_j \gamma_j)l$, $k \in \{r, n\} \neq j, a_n, s, \beta, \gamma, l \geq 0$, then we can get the equilibrium demand functions $d^*_n$ and $d^*_r$. Same as above, bring the formulas (14), (15), (16), and $d^*_n$ and $d^*_r$ separately into the logistics providers’ profit function $\pi^1 = \pi^r + \pi^r + T_r$, the equipment manufacturer’s profit function, and the remanufacturers’ profit function, then we can get the equilibrium profit $\pi^M_r, \pi^M_r, \pi^{M1}$.

Lemma 3. $s^*_n$ is positively correlated with $T_l$, and $s^*_r$ is positively correlated with $T_l$.

Corollary 3. The service level of new products is positively correlated with the service subsidies of logistics provider; that is, the government subsidizes the logistics business service which will directly improve the service level of new products. The service level of remanufactured products is positively correlated with the service scope subsidy of the logistics provider, that is, the government’s subsidy to the service level of logistics providers will directly improve the service level of the remanufactured products.

When subsidizing the service scope of the logistics providers, it will indirectly reduce the costs of the two
manufacturers. Because the income of the logistics provider is paid by the two manufacturers, the overall cost of the product will also be reduced. Therefore, when the product price remains unchanged, the two manufacturers can invest more in product services to improve the product’s service level.

**Lemma 4.** $\Gamma$ is positively correlated with $T_r$.

**Corollary 4.** The scope of services of logistics providers is positively correlated with their subsidies; that is, government subsidies for logistics providers will directly expand the scope of services. When subsidizing the logistics providers’ service range, it will enable logistics companies to reduce their own costs and more actively expand the scope of services in order to obtain more benefits.

Through the analysis in this section, we find that the two subsidy modes have different impacts on the profits of supply chain members. Obviously, the service subsidy of remanufactured products directly stimulates the remanufacturer to obtain higher profits. Both the service level of new products and the service scope of the logistics supplier are positively correlated with the service scope subsidy of the logistics supplier, so the profits of the OEM and the logistics supplier increase accordingly. Only when the service elasticity is greater than the service competition, the service level of new products and the service scope determined by the logistics supplier would increase with the service subsidy of remanufactured products, and both the OEM and the logistics supplier are in a favorable position in the market.

**Comparative analysis of two kinds of subsidy forms**

When the government subsidizes the service level of remanufactured goods and the service scope of the logistics provider, the impact on the service level of the original equipment manufacturer (OEM) and the remanufacturer and the service scope of the logistics provider is shown in the table below:

As we can see from Table 1, whether it is subsidies for remanufactured product service levels or logistics providers’ service scope, the impact of the subsidy rate on the service level of new products, the service level of remanufactured products, and the service scope of logistics providers will be restricted by parameters such as service elasticity $\beta_s$, service competition $\gamma_s$, unit service cost coefficient $m$, and remanufacturing cost saving coefficient $\delta$.

**Numerical simulation and analysis**

In order to study the impact of subsidies on the closed-loop supply chain more intuitively, we use numerical simulation to compare the efficiency of the two forms of subsidies. The parameter assignment in this process refers to the relevant research setting of Wu (2012), where we set $a_n = 25$, $\alpha_r = 10$, $h = 0.1$, $c = 1.5$, $\delta = 0.5$, $r = 0.5$, $m = 20$, $b = 5$, $p = 3$, $\beta_p = 5$, $\beta_s = 4$, and $\gamma_s = 3$.

**Comparison of the subsidy efficiency of the two types of subsidies to the scope of logistics service providers**

It can be seen from Fig. 1 that both subsidies will increase as the logistics provider’s optimal service range increases. The amount of government subsidy for the service level of remanufactured products increased from 2 to 6, while the amount of subsidy for the service range of the logistics provider barely increased. And the gap will expand as the scope of logistics providers increases. It means that in order to improve the service scope of the logistics provider, it is more efficient to directly subsidize the service scope of the logistics provider than to subsidize the service level of the remanufactured products. Intuitively speaking, subsidizing the service scope of logistics providers will more directly expand the services scope of logistics providers, and the effect will be more obvious. Subsidizing the service level of remanufactured products will help to attract a wider range of consumers.

### Table 1 Closed-loop supply chain decision under two kinds of subsidies

| Subsidy form                             | Balanced decision |
|-----------------------------------------|-------------------|
| Government subsidies for re-manufacturing service level | $\Gamma' = \frac{\beta_p (p - 2 + a_r - 2h - \gamma_s h m) + \beta_s (p - 2 + a_r - 2h - \gamma_s h m)}{2h (p - 2 + a_r - 2h - \gamma_s h m)}$ |
| Government subsidies for logistics providers’ service scope | $\Gamma' = \frac{\beta_p (p - 2 + a_r - 2h - \gamma_s h m) + \beta_s (p - 2 + a_r - 2h - \gamma_s h m)}{2h (p - 2 + a_r - 2h - \gamma_s h m)}$ |
to purchase remanufactured products, thereby indirectly expanding the service range of logistics providers. The effect is not significant than directly subsidizing the service scope of logistics providers.

**Comparison of the subsidy efficiency of the two kinds of subsidy forms on the new products’ service level**

As shown in Fig. 2, the amount of the two subsidies will increase with the improvement of the optimal new products’ service level. When the service level of the new product is [0, 0.03], the government’s subsidy for the service level of the remanufactured product increases rapidly from 0 to 5000. However, the subsidy amount for the logistics supplier’s service range increases slowly from 0 to 600 as the service level of new products increases. And its gap will expand with the increase of new products’ service level. This means that in order to improve the service level of new products, it will be more efficient to directly subsidize the service scope of the logistics provider than to subsidize the service level of remanufactured products.

**Comparison of the subsidy efficiency of the two types of subsidies on the service level of remanufactured products**

As shown in Fig. 3, the amount of the two subsidies will increase with the improvement of the remanufactured products’ optimal service level. As the service level of...
remanufactured goods increases, the amount of government subsidy for the range of services provided by the logistics provider increases from 0 to 455. The subsidy for the service level of remanufactured goods only increased from 0 to 25. And its gap will expand with the increase of remanufactured products' service level. It means that in order to improve the service level of remanufactured products, it will be more efficient to directly subsidize the remanufacturers than to subsidize logistic providers. Intuitively, subsidizing the service level of remanufactured products will more directly improve the service level of remanufactured products, and the effect will be more obvious. Subsidizing the service scope of logistic providers will help the logistics provider to reduce the cost so as to reduce the total cost of the product. Remanufacturers can invest more in services to improve service levels with the same price, but the result is not more significant than subsidies for remanufactured products.

**Comparison of subsidy efficiency of two subsidy forms on remanufactured product’s output**

As shown in Fig. 4, the amount of the two subsidies will increase with the improvement of the remanufactured products’ optimal service level. When the service level of the remanufactured product is [0,1], the subsidy amount of the
service scope provided by the government to the logistics supplier is almost maintained at the level of 5250. Service level subsidy for remanufactured product increased from 0 to 500. This means that in order to increase the demand for remanufactured products, directly subsidizing manufacturers will be more efficient than subsidizing logistics providers.

**Comparison of subsidy efficiency of two subsidy forms on remanufacturing ratio**

Since this paper considers a closed-loop supply chain including remanufacture, various forms of subsidies will have an impact on each member of the closed-loop supply chain, so it is necessary to study the impact of two forms of subsidy policies on the remanufactured products ratio. We use $K$ to represent the proportion of remanufactured products in the total output when subsidies are carried out and $K = \frac{d^r}{d^r + d^n}$.

From Fig. 5, we can know that both subsidies will increase as the optimal remanufacturing ratio increases. When the remanufacturing ratio is [0,0.15], the government’s subsidy for the service level of remanufactured products increases rapidly from 5250 to 10,000. However, as the remanufacturing ratio increased, the amount of subsidy for the service range of the logistics provider increased slowly, from 0 to 330. And the gap will widen as the remanufacturing ratio increases. This means that in order to increase the remanufacturing ratio, directly subsidizing the service level of remanufactured products will be more efficient than subsidizing the service scope of logistics providers.

**Conclusion**

In this paper, we investigate the service decisions of a logistics supplier, where an original equipment manufacturer (OEM) produces new products from raw materials and a remanufacturer produces remanufactured products from second-hand items collected from customers. Then we study the influence of government subsidies to the remanufacturer’s service level and the logistics supplier’s service scope on supply chain member selection strategy and verify the economic significance of government subsidies. The results show that the service level of new products and service scope of the logistics provider are positively correlated with service subsidy of remanufactured products when service elasticity is greater than service competition. Both the service level of new products and the service scope of the logistics provider are positively correlated with the service scope subsidies of the logistics provider. Whether the government subsidizes the service level of the remanufacturer or the service scope of the logistics supplier, it can improve the service level of remanufacturing and the service scope of the logistics supplier. This has great incentive significance for enterprises to produce remanufactured products and logistics enterprises to expand service scope. In order to improve the service level of new products and the service scope of the logistics provider, from the perspective of the OEM and logistics provider, the subsidy policy of choosing the service scope of the logistics supplier has obvious advantages. However, when the remanufacturer’s goal is to improve the service level of remanufactured products, the optimal remanufacturing ratio, and the demand for remanufactured products, it is more efficient to subsidize the service level of remanufactured products.

**Fig. 5** The relationship between optimal remanufacturing ratio and two kinds of subsidies
Appendix

1. Symbols and Their Meaning

| Symbol | Meaning |
|--------|---------|
| $j$    | $j \in \{r, n\}$, $r$, and $n$ represent remanufactured products and new products, respectively |
| $b$    | Remanufacturer’s recovery cost |
| $c$    | Each manufacturer’s product cost |
| $d_j$  | Market demand for product $j$, $j \in \{r, n\}$ |
| $m$    | Manufacturer’s service investment cost |
| $m_l$  | Logistics costs of logistics providers |
| $s_j$  | The service level of product $j$ |
| $p$    | For the selling price of the product, it is assumed that the new product will sell for the same price as the remanufactured product |
| $l$    | The service scope of logistic providers |
| $s$    | Cost savings in remanufacturing |
| $\tau$ | Degree of remanufacturing |
| $\pi$  | Profit function |
| $a_j$  | The market basis of product $j$ refers to the market size when the product price is fixed and there is no service |
| $\beta_j$ | Represents the service flexibility of market demand |
| $\gamma_j$ | The degree of competition for services |

Subscript

| Subscript | Meaning |
|-----------|---------|
| $r, n$    | $r$ and $n$ represent remanufactured products and new products, respectively |
| $s$       | Service |
| $l$       | Logistic providers |

Superscript

| Superscript | Meaning |
|-------------|---------|
| $M$         | Manufactures |
| $b$         | The optimal reaction function |
| *           | Nash Equilibrium |

2. Proof of Corollary 1

\[
\frac{\partial l^*}{\partial m_l} = \frac{(-\alpha_n - \alpha_r + 2\beta_p)p_m^2}{[2\beta, h(\beta_\tau - \gamma_\tau)(2p - 2c - 2h + \delta \tau) - m_m]^2} < 0, \\
\frac{\partial s_n^*}{\partial m_l} = \frac{(-p + c + h)\beta_r(a_n + a_r - 2\beta_p)p_m}{[2\beta, h(\beta_\tau - \gamma_\tau)(2p - 2c - 2h + \delta \tau) - m_m]^2} < 0, \\
\frac{\partial s_r^*}{\partial m_l} = \frac{(-p + c + h - \delta \tau)\beta_r(a_n + a_r - 2\beta_p)p_m}{[2\beta, h(\beta_\tau - \gamma_\tau)(2p - 2c - 2h + \delta \tau) - m_m]^2} < 0.
\]

Due to $\frac{\partial \tau}{\partial m_l} < 0$, $\frac{\partial s_n^*}{\partial m_l} < 0$, $\frac{\partial s_r^*}{\partial m_l} < 0$, $l^*$, $s_n^*$, $s_r^*$ decreases with the increase of $m_l$.

3. Proof of Corollary 2

\[
\frac{\partial r^*}{\partial m} = \frac{-2\alpha_n + \alpha_r - 2\beta_p\rho}{[2\beta, h(\beta_\tau - \gamma_\tau)(2p - 2c - 2h + \delta \tau) - m_m]^2}. \\
\frac{\partial s_n^*}{\partial m} = \frac{(-p + c + h)\beta_r(a_n + a_r - 2\beta_p)p_m}{[2\beta, h(\beta_\tau - \gamma_\tau)(2p - 2c - 2h + \delta \tau) - m_m]^2} < 0, \\
\frac{\partial s_r^*}{\partial m} = \frac{(-p + c + h - \delta \tau)\beta_r(a_n + a_r - 2\beta_p)p_m}{[2\beta, h(\beta_\tau - \gamma_\tau)(2p - 2c - 2h + \delta \tau) - m_m]^2} < 0.
\]

Because $\frac{\partial s^*_n}{\partial m} < 0$, $\frac{\partial s^*_r}{\partial m} < 0$, $s^*_n$, $s^*_r$ decrease with the increase of $m$. When $\beta_\tau > \gamma_\tau$, $\frac{\partial \tau}{\partial m} < 0$, $s^*_n$ decrease with the increase of $m$; When $\beta_\tau < \gamma_\tau$, $l^*$ increases as $m$ increases; When $\beta_\tau = \gamma_\tau$, $l^* = (a_n + a_r - 2\beta_p)p_m$ is not affected by the change of $m$.

4. Proof of Corollary 3

\[
\frac{\partial l^*}{\partial \tau} = \frac{2\alpha_n + \alpha_r - 2\beta_p\rho}{[2\beta, h(\beta_\tau - \gamma_\tau)(2p - 2c - 2h + \delta \tau) - m_m]^2}, \\
\frac{\partial s_n^*}{\partial \tau} = \frac{2(p - c - h)\beta_r^2(a_n + a_r - 2\beta_p)p_m^2}{[2\beta, h(\beta_\tau - \gamma_\tau)(2p - 2c - 2h + \delta \tau) - m_m]^2} < 0, \\
\frac{\partial s_r^*}{\partial \tau} = \frac{-\beta_r(a_n + a_r - 2\beta_p)p_m^2}{[2\beta, h(\beta_\tau - \gamma_\tau)(2p - 2c - 2h + \delta \tau) - m_m]^2} > 0.
\]

When $\beta_\tau > \gamma_\tau$, $\frac{\partial l^*}{\partial \tau} > 0$, $\frac{\partial s^*_n}{\partial \tau} > 0$, $l^*$ increases as $\tau$ increases, and $s^*_n$ increases with the increase of $\tau$; when $\beta_\tau < \gamma_\tau$, $\frac{\partial l^*}{\partial \tau} < 0$, $\frac{\partial s^*_n}{\partial \tau} < 0$, $l^*$ decreases with the increase of $\tau$, and $s^*_n$ decreases with the increase of $\tau$; when $\beta_\tau = \gamma_\tau$, $l^* = (a_n + a_r - 2\beta_p)p_m$, $s^*_n = (p - c - h)\beta_r(a_n + a_r - 2\beta_p)p_m/l$, $s^*_r$, and $\tau$ are not related. Since $\frac{\partial \tau}{\partial \tau} > 0$, $s^*_r$ increases with the increase of $\tau$. The effect of $\delta$ on $l^*$, $s^*_n$, $s^*_r$ is the same as that of $\tau$.

5. Proof of corollary 4

\[
\frac{\partial r^*}{\partial c} = \frac{4(-\alpha_n - \alpha_r + 2\beta_p)p_m^2}{[2\beta, h(\beta_\tau - \gamma_\tau)(2p - 2c - 2h + \delta \tau) - m_m]^2}, \\
\frac{\partial s_n^*}{\partial c} = \frac{\beta_r(a_n + a_r - 2\beta_p)p_m^2}{[2\beta, h(\beta_\tau - \gamma_\tau)(2p - 2c - 2h + \delta \tau) - m_m]^2} < 0, \\
\frac{\partial s_r^*}{\partial c} = \frac{-\beta_r(a_n + a_r - 2\beta_p)p_m^2}{[2\beta, h(\beta_\tau - \gamma_\tau)(2p - 2c - 2h + \delta \tau) - m_m]^2} < 0.
\]

When $\beta_\tau > \gamma_\tau$, $\frac{\partial r^*}{\partial c} < 0$, $\frac{\partial s^*_n}{\partial c} < 0$, $l^*$ decreases with the increase of $c$, and $s^*_r$ decreases with the increase of $c$; When $\beta_\tau < \gamma_\tau$, $\frac{\partial r^*}{\partial c} < 0$, $l^*$ expands with the increase of $c$, and $\frac{\partial s^*_n}{\partial c}$ depends on the size of $[2\beta, h(\beta_\tau - \gamma_\tau) + m_m]$. Since $\frac{\partial \tau}{\partial c} < 0$, $s^*_n$ decreases with the increase of $c$. When $\beta_\tau = \gamma_\tau$, $l^*$ and $c$ are not related, $\frac{\partial s^*_n}{\partial c} < 0$, $s^*_r$, $s^*_r$. 

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decreases with the increase of $c$, and the decreasing trend is the same.

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Declarations

Ethics approval The manuscript discusses supply chain issues and includes only theoretical analysis and numerical simulation of supply chains. Therefore, it does not address any ethical issues.

Consent to participate The manuscript only includes numerical simulation, so it does not involve participants and consent to participate.

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