**Responsibility disengagement or sharing? Cooperative fulfilling mechanism of** **solid waste management in the remanufacturing supply chain**

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**Abstract**

Due to limited resources and meager profits, collectors have insufficient motivation to fulfill their responsibilities, resulting in severe secondary pollution in the recycling process. Therefore, it is necessary to focus on the interests of collectors to motivate them to fulfill their solid waste management (SWM) responsibilities better. This paper focuses on remanufacturers' altruistic behavior in the context of collectors' compliance. Based on the Stackelberg game method, this paper constructs decision-making models for remanufacturers concerned or not concerned about the interests of collectors and compares the optimal decision-making outcomes of each model. The study finds that: (1) Based on remanufacturers’ altruistic concerns, a coordination mechanism for sharing responsibility-fulfilling costs for collectors can motivate them to fulfil their responsibilities and improve the performance of the remanufacturing supply chain. (2) The proportion of the remanufacturer's share of the responsibility cost for the collector should not be too low, which is not conducive to encouraging the collector to fulfill the responsibility. However, the sharing proportion should not be too high, as this will increase the burden on the remanufacturer. This paper demonstrates the applicability of remanufacturers to moderately share responsibility costs for collectors to incentivize collectors to fulfil their responsibilities. The findings bridge the gap in research on SWM in remanufacturing supply chains. The management insights from this paper are expected to help remanufacturing supply chain companies establish a reuse behavior model that addresses the challenges that SWM faces to improve remanufacturing supply chain performance.

**Keywords**: solid waste management, remanufacturing supply chain, Stackelberg game, responsibility-fulfilling cost-sharing

**1. Introduction**

With the advancement of science and technology, the life cycle of products is gradually shortening resulting in more solid waste flows into the global market, which has a highly negative impact on the environment (Wang et al. 2019). According to the "Global E-waste Monitoring 2020" report released by the United Nations, the total amount of e-waste generated globally in 2019 reached 53.6 million metric tons, an increase of about 21% compared to 2014. SWM is vital to promoting sustainable economic and social development (Bux et al. 2020). Achieving a balance between the economy and the environment requires the development of the remanufacturing industry (Mondal et al. 2022). Therefore, it is an inevitable social requirement for remanufacturing supply chain enterprises to fulfill their SWM responsibilities (Cai and Choi 2019).

It is critical for emerging countries to understand the opportunities and challenges relating to solid waste reuse and recycling in order to improve resource utilization and ensure environmental protection (Chien et al. 2021). In emerging countries, in the face of fierce market competition, m any companies often gain a competitive advantage at the expense of the environment (Sun et al. 2021; Tian et al. 2021; Liao 2018). This is particularly true for collectors at the front end of the remanufacturing supply chain. In China, the upstream collectors in the remanufacturing supply chain are mostly small- and medium-sized enterprises (SMEs), which recycle more than 65% of the waste products in the market. However, these enterprises generally have poor financing ability and weak anti-risk ability (Gu et al. 2016). Meanwhile, in addition to the recycling costs and transportation costs, the collectors also need to bear the environmental resource costs generated by avoiding the environmental pollution of the recycled products (Hou et al. 2020; Sun et al. 2019; Lin et al. 2017). In order to reduce costs, some low-efficiency collectors do not carry out standardized treatment of recycled solid waste and so evade environmental responsibility.

As a community of interests, collectors and remanufacturers present the characteristics of "one damns all". Collectors' failure to fulfill their environmental responsibilities will inevitably have an important impact on the performance of the remanufacturing supply chain. Therefore, encouraging collectors to fulfill their SWM responsibilities has become a considerable challenge in developing the remanufacturing supply chain.

Facing severe waste management and environmental challenges, in May 2015 the China State Council promulgated the "Made in China 2025" paper, emphasizing "clean and green production" (China State Council 2015). To increase the scale of remanufacturing in China, in February 2016, the Ministry of Industry and Information Technology of China (MIIT) announced the "List of Pilot Remanufacturing Enterprises" (MIITC 2016) to promote remanufacturing supply chain enterprises to strengthen their waste management activities. However, SWM still has many problems in China's remanufacturing supply chain, highlighted by the severe secondary pollution caused by improper solid waste disposal (Zhang and Xu 2019). For example, in automobile remanufacturing, the data show that nearly 70% of the scrapped vehicles in China have not been dismantled in a standardized manner from 2011 to 2018 (CII 2019).

The environmental pollution of the remanufacturing supply chain has attracted the attention of scholars. However, existing research focuses on the configuration problem of responsibility – that is, how to allocate responsibilities in the supply chain to make the entire supply chain more profitable (Yuan et al. 2021; Hosseini-Motlagh et al. 2020; Tian et al. 2020; Ni et al. 2015, 2010; Jacobs and Subramanian, 2012). Moreover, attention to the insufficient motivation for collectors to fulfill their responsibilities is lacking. A few papers employ the bargaining model to study the coordination mechanism of remanufacturing supply chain enterprises' responsibility performance (Rezaei and Maihami 2020; Jafarian et al. 2019; Yamaguchi and Kusukawa 2018; Agrawal et al. 2016). However, it is costly for remanufacturers to comprehensively supervise collectors' performance in their responsibilities because of the difficulty of secondary detection of waste products. Bargaining contracts are insufficient to restrict collectors' evasion of responsibilities effectively. In addition, some studies report that government subsidies encourage enterprises to fulfill their duties (Mondal et al. 2022; Song et al. 2020; Wang et al. 2015). However, the large volume of collectors relying entirely on government subsidies is unsustainable for the government. Therefore, it is essential for enterprises, governments and society to establish a market- and contract-based coordination mechanism among supply chain members to motivate collectors to improve their responsibility performance.

Based on the above analysis, this paper will explore the following questions: (1) Does the remanufacturer's practice of sharing the cost of compliance with collectors based on altruistic concerns motivate collectors to fulfil their duties? (2) How much responsibility should the remanufacturer share with the collector to improve the overall responsibility-fulfilling level and performance of the supply chain? Hence, this paper constructs a Stackelberg game decision-making model dominated by remanufacturers and analyzes the decision results when remanufacturers are concerned or not concerned about the interests of collectors. Moreover, it proposes a supply chain coordination mechanism based on responsibility-fulfilling cost-sharing to narrow the research gap.

Specifically, this paper makes original contributions in the following aspects. *First*, it contributes to the literature on the sustainability of the remanufacturing supply chain by encouraging collectors with insufficient motivation to actively fulfill SWM responsibilities to reduce secondary pollution in recycling. This is a new sustainability frontier beyond the traditional supply chain coordination paradigm. *Second*, unlike the existing literature that focuses on stimulating supply chain companies to fulfill their responsibilities through government incentives, this paper emphasizes the role of market mechanisms and proposes that the efficiency of government subsidies is not necessarily more effective than that of the market mechanism. It constructs a supply chain coordination mechanism where core remanufacturers share part of the responsibility cost for collectors. Moreover, simulation analysis proves the effectiveness of this mechanism. *Finally*, this paper provides practical insights for China and other countries/regions to overcome SWM obstacles in their remanufacturing supply chains.

The rest of this paper is arranged as follows: Section 2 reviews the relevant literature. Section 3 describes the problem and puts forward hypotheses. Section 4 proposes the decision models for remanufacturers who do not care about collectors and those who care about collectors and compares the equilibrium results of different models. Section 5 verifies the proposition through a numerical example analysis. Section 6 states the policy implications of this paper. Section 7 concludes the study.

**2. Literature review**

Overall, this section is relevant to the study in three areas: the impact of fulfilling SWM responsibilities on supply chains, SWM in emerging economies, and coordination mechanisms for supply chain companies to cooperate in fulfilling SWM responsibilities.

*2.1.* *The impact of fulfilling SWM responsibilities on the supply chain*

To promote the sustainable development of the supply chain it is necessary to encourage the development of lean manufacturing tools to reduce costs, increase efficiency (Naeemah and Wong 2022), and emphasize recycling and remanufacturing of waste products to ensure harmony between manufacturing and the environment. In addition, although supply chain enterprises fulfilling SWM responsibilities will increase the costs of enterprise operations to a certain extent (Ni et al. 2010), this process is also a new opportunity for supply chain members (Mondal et al. 2022). Hicks et al. (2004) proposed that improved waste management practices can simultaneously reduce disposal costs and generate additional value by creating a new supply chain of reusable or recycled materials. Ghalehkhondabi and Maihami (2020) found that the waste supply chain is more profitable under an integrated management structure. Ni et al. (2010) and Song et al. (2020) pointed out that most consumers are more inclined to buy socially responsible and environmentally friendly products, and green remanufacturers should pay more attention to environmental responsibility to improve the capacity of waste product recycling (Yuan et al. 2021).

Wang et al. (2011) found that it would be more beneficial to consider investing more in environmental protection when the market demand is great. Meanwhile, Wu et al. (2020) studied the joint deci

sion-making problem of environmentally responsible investment, pricing, and recycling rate. They found that corporate environmentally responsible investment is proportional to recycling rate and retail price. Sadeghi Ahangar et al. (2021) developed a sustainable municipal solid waste treatment system that optimizes human resources and pollution disposal while considering the cost. Araee et al. (2020) proposed a route-planning model suitable for hazardous waste transfer to consider economic, social, and route risks, which are vital in building an efficient and safe network for the treatment of dangerous urban waste.

*2.2. SWM in the supply chain of emerging economies*

Emerging economies are developing rapidly (Bao and Lu 2020), while the contradiction between economic development and the environment is becoming more serious, and the impact high volumes of solid waste has not been effectively alleviated (Bui et al. 2022). Dwivedy and Mittal (2012) found that informal recycling has already caused some negative impacts in India, so alternative systems should be explored using reuse as a policy tool with appropriate interventions on existing disposal practices in developing countries. Moktadir et al. (2021) found that "inefficient sewage treatment," "changes in consumer preferences," "inappropriate dumping of solid waste," "price and cost volatility," and "fiscal changes" are key risk factors in the successful implementation of sustainable supply chain management practices in emerging economies. Baidya et al. (2020) found that storage, semi-informal collection, and e-waste quality were significant issues for processing plants. Their results were validated with two case studies in India and China.

Many scholars have put forward corresponding suggestions for SWM in emerging economies in this context. Kumar (2017) proposed that attitudes moderated by "responsibility" and perceived control have a more significant impact on recycling behavior than subjective norms and interests. Chavez and Sharma (2018) assessed the profitability and environmental friendliness of closed-loop supply chains in the Mexican automotive market, providing evidence that closed-loop supply chains are profitable and environmentally friendly in emerging economies such as Mexico. Bui et al. (2022) also emphasized that developing countries must promote waste reuse and recycling, and building a sustainable SWM model can help solve this problem.

*2.3. The coordination mechanism for supply chain companies to cooperate in fulfilling SWM responsibilities*

Prior research focused on allocating the environmental responsibility of supply chain companies. Ni et al. (2010) established wholesale price contracts between upstream suppliers and downstream companies, proving that the best allocation of environmental responsibilities can effectively improve supply chain profits. Jacobs and Subramanian (2012) studied a two-tier supply chain composed of suppliers and manufacturers. They explored the impact of the sharing of recycling responsibilities on the total profit of the supply chain. Pazoki and Zaccour (2019) found that shifting all recycling responsibilities to retailers would result in higher recycling rates but would reduce the number of remanufactured products, which could facilitate the recycling of used products but not be conducive to remanufacturing.

In recent years, scholars have discovered that the allocation of responsibilities of supply chain companies cannot effectively resolve insufficient motivation to implement responsibilities. Panda and Modak (2016) attested that supply chain members are more inclined to fulfill responsibilities of the other party. Under the cooperation, the fair sharing of responsibilities can effectively coordinate the supply chain. To this end, many scholars have conducted extensive research on the coordination mechanism that promotes the collaborative performance of supply chain companies in fulfilling their responsibilities. They mainly focused on the two aspects of the supervision mechanism and the incentive contract. Early studies primarily paid attention to regulatory mechanisms (Klassen and Vereeck 2012). Recent studies, however, have shown that supervision mechanisms alone cannot fully mobilize the enthusiasm of enterprises to fulfill their responsibilities. In contrast, incentive contracts can improve their willingness to fulfil their duties, and formulating reasonable incentive contracts can significantly enhance corporate responsibility and economic benefits in the supply chain (Hosseini-Motlagh et al. 2020; Ghosh and Shah 2015).

Most research on remanufacturing supply chain companies considers government supervision and incentive mechanisms (Pazoki and Zaccour 2019). Wang et al. (2015) reported on the government's reward-punishment mechanism and found that increasing the leader's responsibility can increase the recycling rate to a certain extent. Wu et al. (2019) pointed out that government subsidies effectively promote enterprises to improve technical input in the green supply chain. Mondal and Giri (2021) constructed a game model based on the production competition environment to explore the decision-making problem of the green closed-loop supply chain. They concluded that government subsidies significantly affect the sales of green products.

Most of the above studies assume that the decision-maker is entirely rational. In reality, however, participants incorporate their own emotions and other "irrational" factors into their decisions. A typical representative of this supply chain decision-making model is altruistic concerns decision-making (Loch and Wu 2008). Lin (2019) found that altruistic preference plays a vital role in the equilibrium results of the supply chain; in particular, under certain conditions, the altruistic preference can increase a firm's profits.

In short, the environmentally responsible management of solid waste has become an essential research topic in the remanufacturing supply chain. However, existing research fails to pay sufficient attention to collectors who are not motivated to fulfill their responsibilities. Starting from the altruistic concerns of remanufacturing enterprises for collectors, this paper studies the mechanism of promoting collectors to fulfill their responsibilities and provides a new theoretical perspective for advancing the research on the environmental responsibility of remanufacturing supply chains. This paper is different from the existing research that focuses on government subsidies to motivate companies to perform their responsibilities. It emphasizes that the market mechanism based on supply chain coordination to encourage companies to fulfill their responsibilities can provide a decision-making reference point for remanufacturing supply chain companies. In terms of specific methods, this paper designs an approach of responsibility-fulfilling cost-sharing to improve the performance level of collectors and supply chains, and proves the applicability to the field.

The papers most relevant to this paper are Ni et al. (2010), Wang et al. (2015), Wu et al. (2020), and Hosseini-Motlagh et al. (2020). Table 1 shows the differences between this paper and the cited literature.

**Table 1** Differences between this paper and existing literature

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Paper | Whether to consider the collector's responsibility | Whether to consider concerns about collectors | Whether to consider the market mechanism | Whether to consider the sharing of responsibility-fulfilling costs |
| Ni et al.（2010） | × | × | √ | × |
| Wang et al.（2015） | √ | × | × | × |
| Wu et al.（2020）  | × | × | √ | × |
| Hosseini-Motlagh et al.（2020） | × | × | √ | × |
| This paper | √ | √ | √ | √ |

**3. Problem formulation and hypothesis**

This paper studies the two-echelon remanufacturing supply chain composed of the *upstream* collector and the *downstream* remanufacturer. The SWM activities of supply chain companies are regarded as necessary to fulfill environmental responsibility. The collector is responsible for the recycling and processing of waste. The remanufacturer is responsible for remanufacturing and selling to end consumers and uses both new parts and recycled waste in the manufacturing process.  and are the unit costs of the remanufacturer using new parts and waste products, respectively.  is the unit manufacturing cost of the remanufacturer. The market demand is .  represents the unit recycling cost of the collector.  and  are the unit purchase prices of the recycled waste and the new parts, respectively. The remanufacturer sells products on the market at a price . The recycling rate is .  and  are the SWM responsibility level (SWMRL) of the collector and the remanufacturer, respectively.  is the proportion of the responsibility-fulfilling cost borne by the collector, and  is the proportion of the responsibility-fulfilling cost shared by the remanufacturer for the collector.

is the benefit function of the supply chain members  in the model , and  represents the responsibility level function of the supply chain members  in the model . The superscript  can take the values of respectively, showing four scenarios where (i) the collector fulfills its responsibility independently, (ii) the remanufacturer fulfills its responsibility independently, (iii) the collector and the remanufacturer fulfill their responsibilities respectively, and (iv) the remanufacturer is concerned about the cost of the responsibility of the collector. The subscript *j* can take the values , representing the collector and the remanufacturer. Other assumptions are as follows:

**Assumption 1**: Assuming that consumers in the final market respond positively to the SWM behavior of node companies in the remanufacturing supply chain. Referring to related literature (Song et al. 2020; Hosseini-Motlagh et al. 2020; Ni et al. 2010), this paper assumes the remanufacturing supply chain's demand function as . In this equation,  represents the potential market capacity,  is the market sales price of the remanufacturer, and  illustrates the SWMRL on product demand, which can also be regarded as the consumer's sensitivity coefficient to the SWMRL. are the SWMRL of the collector and the remanufacturer, respectively. The sum of the two is the overall SWMRL of the remanufacturing supply chain.

**Assumption 2**: Referring to relevant research (Song et al. 2020; Hosseini-Motlagh et al. 2020; Ni et al. 2010), the fulfillment of SWM responsibilities by supply chain enterprises will increase the costs of enterprise operations to a certain extent. This paper assumes that the SWMRL cost functions of the collector and the remanufacturer are  and , respectively, where represent the SWMRL cost coefficient of the collector and the remanufacturer, respectively. The larger the , the higher the cost of the collector and the remanufacturer will be at the same level of the SWMRL.

**Assumption 3**: It is assumed that all recycled waste products can be used for remanufacturing, and the remanufacturer uses new components but also all recycled waste for manufacturing; that is, remanufactured products consist of new parts and recycled waste, and the unit cost of the remanufacturer using new parts is higher than the unit cost of using recycled products () (Mondal et al. 2022; Wang et al. 2019, 2015).  is the cost saved for remanufacturing using recycled products. Referring to the research of Wang et al. (2019, 2015) and Savaskan et al. (2004), the unit manufacturing cost is assumed to be .

**Assumption 4**: Collectors and remanufacturers are entirely rational and aim to maximize profits (Wu et al. 2020; Raza 2018). At the same time, to ensure a reasonable price, it is necessary to meet  (Wu et al. 2020).

**Assumption 5**: To simplify the model, this paper refer (Yuan et al. 2021) and suppose that the sales cost of the remanufacturer and the fixed recycling cost of the collector are both zero to simplify the calculation.

The symbols and definitions of related variables in the model are shown in Table 2.

**Table 2** Related parameters and decision variables

|  |  |  |
| --- | --- | --- |
| Variable | Symbol | Definition |
| Decision variables |  | Product market price |
|  | Waste recycling price |
|  | SWMRL for collectors |
|  | SWMRL for remanufacturers |
| Related parameters |  | The unit cost for remanufacturers to manufacture with new parts |
|  | The unit cost of remanufacturer manufacturing from waste |
|  | Savings from remanufacturing using recycled products， |
|  | Collector's unit recovery cost |
|  | The unit purchase price of new parts purchased by remanufacturers |
|  | Waste recycling rate |
|  | Product potential market capacity |
|  | Consumer sensitivity to SWMRL |
|  | The SWMRL cost coefficient for collectors |
|  | The SWMRL cost coefficient for remanufacturers |
|  | The proportion of SWMRL costs borne by collectors |
|  | Collector's benefit |
|  | Remanufacturer's benefit |

Then, the remanufacturer's concerns with the collector and its lack of concern are compared based on the Steinberg game approach. At the same time, this paper considers that, due to the maximization of interests by enterprises, both remanufacturers and collectors may choose to fulfill their responsibilities or not fulfill their responsibilities. Therefore, three decision-making models are proposed based on the Steinberg game method under the condition that the remanufacturer does not care about the collector. There are three situations in which (i) the collector fulfills its responsibility independently, (ii) the remanufacturer fulfills its responsibility alone, and (iii) the collector and the remanufacturer fulfill each respective responsibility.

The Steinberg game method is an analysis paradigm that positions the roles of game players as "leaders" and "followers". It is generally used to analyze players' decisions in different positions but affecting each other. As a leader in the supply chain, it prioritizes the decision-making process. In contrast, followers can only passively follow and make decisions after the leader makes a decision. Referring to the literature (Hosseini-Motlagh et al. 2020; Wang et al. 2019; Ni et al. 2015; Savaskan et al. 2004), this paper assumes that the remanufacturer is the leader of the supply chain. The order of the game is as follows: the remanufacturer determines ,  according to the principle of maximization of interests, and the collector further determines , and  according to the decision of the remanufacturer.

**4. Decision model and comparative analysis**

*4.1. The remanufacturer does not concern about the collector decision model*

*4.1.1 The collector fulfills responsibility independently (Scenario C)*

When the collector meets its commitment alone, , , at this time:

The maximizing target benefits of the collector is:  (1)

The maximizing target benefits of the remanufacturer is:  (2)

According to the backward induction method, the first-order condition of about  is

.

Assuming that the collector and the remanufacturer have the same marginal revenue (Guo et al. 2011; Jorgensen and Zaccour 2003, 1999), then .

Substituting the above formula into the benefit function of the remanufacturer, it gets:

 . (3)

Find its first derivative concerning  and make it equal to 0 to obtain:

 (4)

On this basis, further, it gets:

 (5)

 (6)

 (7)

 . (8)

*4.1.2. The remanufacturer fulfills responsibility independently (Scenario R)*

When the remanufacturer fulfills its responsibility alone, , , at this time:

The maximizing of the target benefits of the collector is:  (9)

The maximizing of the target benefits of the remanufacturer is：  (10)

Assuming that the collector and the remanufacturer have the same marginal cost, then .

Substitute it into the remanufacturer's benefit function and find its first derivative concerning . Make it equal to 0, to see:

 (11)

 (12)

. (13)

Substitute the benefit function to get:

 (14)

 (15)

*4.1.3. The collector and the remanufacturer fulfill each respective responsibility (Scenario CR)*

When both the collector and the remanufacturer fulfill their SWM responsibilities but do not consider the remanufacturers to help the collector share responsibility costs, ,  , at this time:

The maximizing of the target benefits of the collector is:  (16)

The maximizing of the target benefits of the remanufacturer is:

. (17)

According to the backward induction method, first, find the first derivative of  concerning , and set it equal to 0.  can be obtained.

As above, through the assumption of equal marginal revenue,  can be obtained. Substitute  into , find its first derivative for , set it to 0, and then combine  to obtain an equilibrium solution:

(18) (19)

 (20)

 (21)

 (22)

. (23)

*4.2. The remanufacturer concerns about the collector (scenario RAC)*

Incorporating the responsibility cost ratio *t* of the collector into the decision model, at this time the remanufacturer shares the responsibility costs for the collector, so the maximizing of the target benefits of the collector is:

 (24)

The maximizing of the target benefits of the remanufacturer is:

. (25)

As above, through the assumption of equal marginal revenue, can be obtained, and according to the first derivative of  for  , which is 0,  is obtained. Substituting the benefit function of the remanufacturer, and finding its first derivative concerning , set it to 0, and obtain:

(26) (27)

 (28)

 (29)

 (30)

. (31)

By analyzing the equilibrium result when the remanufacturer is concerned about the collector, Proposition 1 is obtained.

**Proposition 1**: Under the precondition of  (for , there is always  ).

(1) The recycling rate of the collector is inversely proportional to the unit's wholesale price of waste products.

(2) The recycling rate of the collector is directly proportional to the collector's and remanufacturer's levels of responsibility and economic benefits.

**Proof**:

Because of ,  is a permanent existence.

, where  is the potential market capacity. The quantity is large enough and  exists. Hence , the purchase price of the remanufacturer to recycle waste products from the collector decreases with the increase in the recycling rate.

, where  is the unit recovery cost of the collector, and  is the unit purchase price of the new parts purchased by the remanufacturer, , then, . The recycling rate increases and the level of responsibility of the collector also increases. That is, the cost to the collector to fulfill the responsibility increases.

; similarly, the level of commitment of the remanufacturer increases as that of the collector increases.

, because , then , ; , the economic benefits of the collector and the remanufacturer are proportional to the recycling rate.

Similar to the studies by Wu et al. (2020) and Yuan et al. (2021), Proposition 1 shows that when remanufacturers are concerned about collectors, they can push collectors to increase recycling rate, ultimately improving the level of responsibility and performance of supply chain companies.

*4.3 Model comparison and analysis*

By comparing the equilibrium solutions of the models in the three situations that do not consider the remanufacturer's concerns to the collector, Propositions 2 and 3 are obtained.

**Proposition 2**: Under the preconditions of , there will always be , .

**Proof:**

, because, under the constraint conditions, both A and B are less than 0, so ; that is , and ; that is .

Observing Proposition 2 shows that the benefit of the collector is less than that of the remanufacturer when only the collector fulfills their responsibility. In contrast, when the remanufacturer only performs their duties, the revenue of the remanufacturer is less than that of the collector. Because fulfilling commitment will inevitably increase the cost of the performing party, resulting in a rise in the incomes of other enterprises in the supply chain than the performing entity itself, the non-fulfilling party can accrue higher benefits by "free-riding". As a rational economic subject, the responsible party inevitably has unbalanced psychology and chooses to lower the responsibility level appropriately to reduce costs and transfer the responsibility to the other supply chain members. It is necessary to encourage all entities in the supply chain to fulfill their duties rather than let one entity take complete responsibility in order to avoid transferring one party's responsibilities.

**Proposition 3**: Under the preconditions of ,  ,  , , , , .

**Proof**:

, , Under the constraint conditions, D and E are negative, hence, ;

, , F and G are negative, hence, ;

,. With the help of Mathematica software, it is judged that , because H and I are higher than 0, so there is ;

The same is proved: , , .

Analyzing Proposition 3 shows that when both the collector and the remanufacturer fulfill their responsibilities, each subject's level of benefit and responsibility in the remanufacturing supply chain is higher than when only one party fulfills their responsibility. At this time, the responsibility level and profit of the remanufacturing supply chain system also improve. This conclusion is similar to that of Ni et al. (2015). Further analysis of this result shows that when only one party meets the duty, the fulfilling party pays the cost of commitment. Still, the income growth level is less than that of the non-fulfilling party, resulting in imbalanced psychology. The SWM investment also decreases, and the level of responsibility decreases. When both the collector and the remanufacturer fulfill their duty, the remanufacturing supply chain has a higher level of commitment. The collector and remanufacturer will invest more in preventing secondary pollution and ensuring product quality, thereby stimulating consumers' purchase intention and positively responding to the remanufacturing supply chain's responsibility activities. Furthermore, when SWMRL significantly affects product demand, the larger the market size demand will be. The collector and the remanufacturer will invest more time and energy in SWM to obtain higher profits.

Proposition 4 is obtained by comparing the equilibrium solution of the model, considering the remanufacturer's concerns regarding the collector and without them.

**Proposition 4**: Under the conditions of , (for , there always exists ), when , , ; when , , , , , and when , the responsibility level and economic benefits of the remanufacturer reach the maximum when the remanufacturer is concerned about the collector.

**Proof**:

, when , . Because the J, K is less than 0, there are . When , the opposite is true; that is, .

, , when , , because the M, N is less than 0, there are . When , the opposite is true; that is, .

, . Then solve inequalities under constraints; the results are or . At this time, , . Then solve inequalities under conditions; the results are or . At this time, , . It can be seen from the above that under the preconditions of , there always exists ;

,.

With the help of Mathematica software, it is judged that when , S and T are both higher than 0, so  can be obtained.

For the partial derivative of  to *t*, get , set it to 0, and get ; for the partial derivative of concerning *t*, get , set it to 0, and get . That is, when , reach their maximum.

From Proposition 4, the remanufacturer shares a particular responsibility cost for the collector, enabling both to achieve a higher level of responsibility and economic benefits. Specifically, when the proportion of the collector's responsibility is between 1/2 and 1, the levels of responsibility and economic benefits of the collector and the remanufacturer are higher than if they fulfill obligations, respectively. Hence, considering the remanufacturers' concern about the collector is better than without it when . Wu et al. (2020) implemented supply chain coordination using revenue-sharing contracts, and Ni et al. (2010) used wholesale price contracts to achieve supply chain coordination. Unlike their research, this paper found that remanufacturers can also achieve supply chain coordination by caring about collectors. Remanufacturers share responsibility costs for collectors, avoid the double marginalization problem in non-cooperation, and increase the profitability of supply chain node companies and the supply chain as a whole.

Expressly, the remanufacturer relieves the economic pressure on the non-core member of the supply chain (the collector) when it bears part of the responsibility-fulfilling cost for the collector. However, the collector's and the remanufacturer's economic benefits and responsibility levels may be lower when the latter share most of the former's responsibility-fulfilling cost than the benefits realized when the remanufacturer is not concerned about the collector. Hence, both parties coordinate to set an appropriate cost-sharing proportion to ensure that each entity can obtain higher profits when the remanufacturer is concerned about the collector. When the remanufacturer shares a small part of the responsibility-fulfilling cost, both parties' responsibility and economic benefits are improved. From the perspective of the remanufacturer, to maximize profits, it will choose to bear about one-third of the responsibility-fulfilling cost for the collector. At this time, the collector's benefits and responsibility levels may not be at the highest level. However, they are higher than those under the other situations, so the conditions for cooperation between the two are met.

**5. Numerical results and discussions**

*5.1.* *Numerical results*

In this section, Matlab software is used to simulate the equilibrium results to analyze the influence of the main parameters on decision-making and verify the propositions presented in Sections 4 and 5. According to Wang et al. (2019), the recycling price  and the recycling rate *τ* of waste products are 10 and 0.5, respectively. Furthermore, because the procurement cost of new parts is higher than the recycling cost of waste products, the purchase cost of the new component  is set as 50. In addition, since the remanufacturing cost of used products will not exceed the production cost of new products (Modak et al. 2018), the production cost  is set for manufacturing using new parts only. The production cost of using scrap products and combining some new materials for manufacturing , so then. Referring to Modak et al. (2018), the potential market capacity of the product is set as α=500, and the SWMRL cost coefficient is of the collector. Referring to Ma et al. (2017) on the impact of environmental responsibility level on product demand, the consumer sensitivity to SWMRL is set as *a*=2, and the SWMRL cost coefficient is of the remanufacturer.

*5.1.1.* *Analysis of the influence of main parameters on equilibrium results of remanufacturing supply chain*

Taking the remanufacturer's concern about the collector as an example, the effect of the recycling rate on the equilibrium decision results is first analyzed. Since *t* = 2/3, the remanufacturer's responsibility level and economic performance achieve the maximum value, so take *t* = 2/3 to verify the impact of the recycling rate on other equilibrium results in the case of responsibility-fulfilling cost-sharing. Table 3 lists the equilibrium results under different recycling rates in the case of responsibility-fulfilling cost-sharing to visualize the impact of recycling rate on other values.

**Table 3** Influence of recycling rate on other equilibrium outcomes under responsibility-fulfilling cost-sharing

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| *τ* | *w* | *yc* | *yr* | *πc* | *πr* |
| 0.1 | 3933.08 | 294.231 | 130.769 | 76952.7 | 83365.4 |
| 0.2 | 1994.62 | 297.692 | 132.308 | 78774 | 85338.5 |
| 0.3 | 1348.46 | 301.154 | 133.846 | 80616.6 | 87334.6 |
| 0.4 | 1025.38 | 304.615 | 135.385 | 82480.5 | 89353.8 |
| 0.5 | 831.538 | 308.077 | 136.923 | 84365.7 | 91396.2 |
| 0.6 | 702.308 | 311.538 | 138.462 | 86272.2 | 93461.5 |
| 0.7 | 610 | 315 | 140 | 88200 | 95550 |
| 0.8 | 540.769 | 318.462 | 141.538 | 90149.1 | 97661.5 |
| 0.9 | 486.923 | 321.923 | 143.077 | 92119.5 | 99796.2 |

Table 3 shows that the recycling rate is inversely proportional to the collector's unit wholesale price of waste products and is proportional to the responsibility levels and economic benefits of the collector and remanufacturer, which verifies Proposition 1.

Moreover, the remanufacturer is the core enterprise in the remanufacturing supply chain. The remanufacturer's SWMRL cost coefficient and consumer's sensitivity coefficient to the SWMRL behavior of the remanufacturer are related. Therefore, the impact on the economic benefits and responsibility levels of the collector, the remanufacturer, and the overall supply chain when the remanufacturer's SWMRL cost coefficient and the consumer's sensitivity coefficient to the SWMRL change within a certain range are analyzed.

|  |
| --- |
| 图1-5**Fig. 1**. The impact of the remanufacturer's SWMRL cost coefficient and consumer's SWMRL sensitivity coefficient on the collector's responsibility level.  |
|  图1-6**Fig. 2**. The impact of the remanufacturer's SWMRL cost coefficient and the consumer's SWMRL sensitivity coefficient on the remanufacturer's responsibility level. |
|  图1-7**Fig. 3.** The impact of the remanufacturer's SWMRL cost coefficient and the consumer's SWMRL sensitivity coefficient on the economic benefits of the collector. |
|  图1-8**Fig. 4**. The impact of the remanufacturer's SWMRL cost coefficient and the consumer's SWMRL sensitivity coefficient on the economic benefits of the remanufacturer. |

Findings from Figs. 1-4:

(1) Under the prerequisite conditions , as the remanufacturer's SWMRL cost coefficient increases, the cost of fulfilling the responsibility for the remanufacturer to maintain the same level of responsibility also grows. Hence, the remanufacturer reduces the level of commitment to lowering costs. With the increase of the consumer's sensitivity coefficient to SWMRL, the remanufacturer's responsibility level and economic benefits have been improved when the remanufacturer's SWMRL cost coefficient is small. The impact of changes in the consumer's sensitivity coefficient to SWMRL on the levels of responsibility and economic benefits of the collector and the remanufacturer has gradually weakened when the remanufacturer's SWMRL cost coefficient continues to increase.

(2) The change in the remanufacturer's SWMRL cost coefficient has a less obvious impact on the responsibility levels and economic benefits of the collector and the remanufacturer when the consumer's sensitivity coefficient to SWMRL is small. At this time, the remanufacturer believes that increasing the SWMRL cannot bring about more market demand and therefore tends to maintain the same level of responsibility. Along with the increased consumers' sensitivity to the SWMRL, the impact of the remanufacturer's SWMRL cost coefficient on the collector's and remanufacturer's responsibility and economic benefits gradually decreases.

(3) In addition to the impact on the profitability of the remanufacturer, the collector will also be affected when the remanufacturer's SWMRL cost coefficient and the consumer's sensitivity coefficient to the SWMRL change. The higher the SWMRL cost coefficient of the remanufacturer is, the lower the responsibility level and economic benefits of the collector. When the consumer's sensitivity coefficient to SWMRL increases, the level of responsibility of the collector gradually increases. However, its economic benefits show a trend of increasing first and then decreasing. This indicates that, with increased consumer sensitivity to SWMRL, the collector is more inclined to grow its responsibility level to increase revenue. However, an excessively high level of responsibility has also led to excessively high responsibility-fulfilling costs which, on the contrary, reduced the economic benefits of collectors.

The simulation analysis in Figures 1-4 shows that the SWMRL of remanufacturers and collectors is jointly affected by the SWMRL cost coefficient and the consumer's SWMRL sensitivity coefficient. Increased consumer sensitivity will encourage supply chain members to improve their responsibility performance. But the increase in responsibility fulfilling costs will also reduce the motivation of supply chain members to strengthen their responsibility performance. This further illustrates the need to share responsibility fulfilling costs.

*5.1.2.* *Comparative analysis of simulation results in multiple scenarios*

Next, this section simulates remanufacturers' and collectors' responsibility levels and economic benefits under different responsibility fulfillment situations. The purpose is to clearly show the changes in remanufacturing supply chain companies' economic benefits and responsibility levels without considering remanufacturers' concern for collectors and remanufacturers' concern for collectors to verify the proposition proposed in this paper.

The levels of commitment and changes in the economic benefits of the collector and remanufacturer in different situations are compared, taking the collector's SWM responsibility proportion *t* as an independent variable and obtaining the following results.

|  |  |
| --- | --- |
| 图5(18号）**Fig. 5**. The changing trend of the collector's responsibility level with the proportion of the collector's responsibility. | 图6(18号）**Fig. 6**. The changing trend of the remanufacturer's responsibility level with the proportion of the collector's responsibility. |
| 图7(18号）**Fig. 7.** The changing trend of the economic benefit of the collector with the proportion of the collector's responsibility. | 图8(18号）**Fig. 8.** The changing trend of the economic benefits of the remanufacturer with the proportion of the collector's responsibility. |

The revenue in the case where only the collector fulfills its responsibilities is lower than when only the remanufacturer fulfills its responsibilities in terms of the economic benefits of the collector (as shown in Fig. 7). The revenue where only the remanufacturer fulfills the responsibility is lower than the revenue where only the collector fulfills the responsibility regarding the economic benefits of the remanufacturer (as shown in Fig. 8). The above situation is consistent with Proposition 2. Meanwhile, combined with Figs. 7 and 8, it can be seen that the collector and the remanufacturer have higher levels of responsibility and economic benefits when they meet their responsibility, respectively, than when only one party fulfills their responsibility. Hence, Proposition 3 is verified.

It can be seen from Figs. 5-8 that, when 0.5 < *t* < 1, the levels of responsibility and economic benefits of collectors and remanufacturers in the RAC case are higher than in the case where the remanufacturer does not care about the collector (cases C, R, CR). By observing the change of responsibility levels and economic benefits of collector and remanufacturer with the proportion of collector's responsibility under the RAC situation, it is found that the remanufacturer can achieve the highest level of responsibility and economic benefit at *t*= 2/3. The above analysis verifies Proposition 4. The cooperative scenario based on shared SWM responsibility can enable remanufacturers and collectors to achieve higher SWMRL and economic benefits than the case in the non-cooperative scenario.

The above results are further explained here. When remanufacturers share most of the responsibility cost for collectors, remanufacturers will face tremendous economic pressure, so they will choose to reduce their SWMRL to lower costs. However, the low level of SWMRL has led to a decline in market demand. Ultimately, it will affect the economic benefits of the company. In this case, the two companies' levels of responsibility fulfilling and economic benefits are deficient. On the other hand, when the remanufacturer shares a small responsibility cost for the collector, the collector has to bear a significant responsibility cost. To reduce costs, collectors will appropriately mitigate their responsibility level. Remanufacturers as downstream enterprises will face an increase in processing costs. At this time, remanufacturers are highly vulnerable to the lack of responsibility of collectors, which will reduce the level of responsibility fulfilling and economic benefits of remanufacturers. However, when remanufacturers bear modest compliance costs for collectors, the economic pressure on remanufacturers decreases. Their willingness to invest in SWM increases SWMRL and stimulates market demand. Therefore, the economic benefits of both collectors and remanufacturers also increase, and collectors will also increase their SWMRL under the incentive of economic benefits.

The above analysis shows that the proportion of remanufacturing enterprises sharing responsibility and fulfillment costs for collectors should not be too high. If it is too high, this reduces remanufacturers' motivation to fulfill their SWM responsibilities. But at the same time, it cannot be too low, as this is not conducive to incentivizing collectors to fulfill their responsibilities. Therefore, the remanufacturing supply chain needs to set a reasonable proportion of responsibility fulfillment cost-sharing. Otherwise, it will not take full advantage of remanufacturers' concerns about collectors. Specifically, this paper finds that when remanufacturers bear one-third of the responsibility cost for collectors, they will achieve the highest responsibility and economic benefits.

The existing literature fails to pay attention to collectors with insufficient motives to fulfill their responsibilities, and the limited literature on collectors' fulfillment of responsibilities focuses on government subsidies. Unlike these papers, this paper finds that remanufacturers appropriate share the responsibility-fulfilling costs for collectors, which can motivate collectors to actively fulfill their responsibilities and improve the overall responsibility fulfilling level of the supply chain, thereby helping to solve the problem of secondary pollution in recycling.

*5.2. Discussion*

This paper has extended the existing literature. *First*, in the current articles considering the responsibility of remanufacturing supply chain enterprises (Wu et al. 2020; Ni et al. 2010), remanufacturers often become the focus of scholars due to their central position in the supply chain. However, collectors tend to be neglected due to the poor economic effect of third-party recycling (Wu et al. 2020; Savaskan et al. 2004). This paper has considered the responsibility fulfillment of collectors in depth and focused on how to encourage collectors with insufficient motivation to actively fulfil SWMR in emerging economies such as China, where there are many collectors. *Second*, in promoting the responsibility of supply chain members, many articles have considered the role of the government (Mondal et al. 2022; Song et al. 2020; Wang et al. 2019, 2015) and shown that the government can urge enterprises to fulfill their responsibilities through regulatory measures such as subsidies or penalties.

However, the large volume of collectors relying entirely on government subsidies is unsustainable for the government. As an alternative, this paper uses the internal incentive contract of the supply chain. Through the core enterprise of the supply chain, the remanufacturer shares the recovery cost for the collector to urge the collector to fulfil their responsibilities to realize the sustainability of the remanufacturing supply chain. *Finally*, Wu et al. (2020) studied the coordination mechanism of remanufacturing supply chain enterprises' responsibility fulfillment based on the bargaining model of supply chain members' negotiating power. However, due to the difficulty of secondary inspection of waste products, it is very costly for remanufacturers to comprehensively supervise the collectors' performance of their responsibilities, which provides opportunities for collectors to evade responsibility. Therefore, bargaining contracts make it difficult to motivate collectors to fulfil their responsibilities effectively. Unlike Wu and colleagues’ research, this paper innovatively considers that the remanufacturer will share a specific responsibility fulfilling cost for the collector to improve their enthusiasm for responsibility fulfillment. It finds that remanufacturers moderately share responsibility fulfilling costs for collectors, which motivates collectors to fulfil their responsibilities and thus is more conducive to realizing the sustainability of the remanufacturing supply chain. This paper can solve the problem of collectors evading responsibility due to the difficulty of detecting waste products and achieve the sustainability of the remanufacturing supply chain without relying on government subsidies.

**6. Implications**

 Solid waste also contains a considerable economic value. Recycling and remanufacturing and strengthening the responsible management of solid waste can make full use of the resources available to develop solid waste (Bergeron 2017) and effectively solve the environmental pollution problem (Tsai et al. 2020). However, collectors have insufficient incentives to fulfill their responsibilities in emerging market countries such as China due to meager profits, resulting in severe secondary pollution during the recycling process (Ohajinwa et al. 2018).

This paper finds that remanufacturers sharing responsibility fulfilling costs for collectors can overcome the insufficient motivation of collectors to fulfil responsibility and provide new ideas for promoting the sustainable development of remanufacturing supply chains. Specifically, this paper contributes theoretically to research on the sustainability of remanufacturing supply chains. Bounded rationality has attracted the attention of many scholars in recent years because it is more in line with the reality of corporate decision-making (Wang et al. 2021). This paper introduces bounded rationality-based altruistic concerns into the body of research on the remanufacturing supply chain and finds that remanufacturers' altruistic concerns can help improve the responsibility fulfillment of collectors in a disadvantaged position. This paper goes beyond the traditional whole rationality-based supply chain coordination paradigm and makes a theoretical contribution to the remanufacturing supply chain sustainability literature.

Based on the Stackelberg game, this paper develops an analytical framework for SWM responsibility in the remanufacturing supply chain. The results show that when the responsibility-sharing coefficient of the remanufacturer meets certain conditions, the responsibility levels and profits of the remanufacturer and the collector can be improved. This paper expands the applicability of game theory methods to study SWM responsibility in remanufacturing supply chains and provides a basis for future research based on game theory. Subsequent scholars can conduct empirical analysis based on this paper.

**7. Conclusion**

Large volumes of waste are generated in tandem with economic and environmental development, which has brought significant challenges to the world's sustainable development agenda. In response to this challenge, the Chinese government has vigorously promoted a circular economy, including remanufacturing supply chains, in the past decade. Because Chinese collectors are generally small in scale, limited in resources, and low in risk resistance, they tend to evade fulfilling the responsibility of SWM to reduce operation costs. At the same time, the high price and difficulty of recycled product detection also give collectors opportunities to adopt opportunistic behaviors. These factors generate severe secondary pollution in recycling and low market acceptance of remanufactured products, leading to a problematic situation in the remanufacturing supply chains. In the remanufacturing supply chain, the insufficient motivation for collectors to fulfill their SWM responsibilities and the lack of research make this issue worth studying.

This paper considers remanufacturers as the focal firm of the remanufacturing supply chain to take its altruistic concerns to collectors, targeting the insufficient motivation for collectors to fulfill their environmental responsibilities. It proposes a supply chain coordination mechanism in which the remanufacturers share part of the responsibility for the fulfillment costs of the collectors. The main findings of this paper are as follows: *First*, the coordination mechanism based on remanufacturers sharing part of the responsibility fulfilling costs for collectors can motivate collectors to fulfil their responsibilities and improve the performance of the remanufacturing supply chain. *Second*, the proportion of remanufacturers helping collectors to share responsibility fulfilling costs cannot be too low as this is not conducive to motivating collectors to fulfill their responsibilities. On the other hand, it cannot be too high, as this will reduce the remanufacturer's motivation to fulfil responsibilities. *Third*, remanufacturers need to set a reasonable ratio of responsibility fulfilling cost-sharing, which can prompt collectors to fulfil their responsibilities and improve the overall responsibility fulfilling level and performance of the remanufacturing supply chain.

Unlike studies that take profit maximization as the goal of corporate decision-making, this paper proposes that corporate decision-making will include "irrational" behaviors such as altruistic concern. The altruistic concern of the core company over other members can help increase the sustainability of the supply chain. Specifically, because the remanufacturer's responsibility fulfilling cost-sharing increases the collector's responsibility fulfilling motivation, promotes the overall social welfare level of the supply chain, and generates a general compensation mechanism under the residual conditions of cooperation. In that way, supply chain members can achieve win-win results.

Unlike the case whereby manufacturers rely on government subsidies, this paper finds that, based on an internal coordination mechanism, remanufacturers can motivate collectors to actively fulfil their responsibilities and improve the overall level of responsibility performance in the supply chain, thus helping to solve the problem of secondary pollution in recycling. This finding is significant because the Chinese government has introduced several policies to encourage the development of the recycling and remanufacturing industry. However, these policies appear insufficient to address the country’s secondary pollution problem in recycling. This paper provides new ideas for promoting SWM in the remanufacturing supply chain. Moreover, this paper found that remanufacturers need to ensure a reasonable proportion of responsibility fulfillment cost-sharing. That is, this responsibility fulfillment cost-sharing is limited. On the one hand, this can improve the collector's motivation to fulfill the responsibility, and on the other hand, it will not impose a high economic burden on the remanufacturer. This paper clarifies the conditions for incentivizing collectors to fulfil their responsibilities and makes more accurate decisions for remanufacturers' managers to motivate collectors with insufficient motivation to fulfill their responsibilities to improve the SWMRL in the remanufacturing supply chain. This finding has a significant reference value.

This paper assumes that the market demand information is entirely determined and that there is symmetrical information for remanufacturers and collectors. In the future, it will be possible to study the cooperative mechanism responsibility fulfillment of the remanufacturing supply chain enterprises under situations of incomplete information. In addition, this paper assumes that market demand is affected by sales prices and responsibility fulfilling levels. However, in practice, market demand may also be affected by emergencies, so the remanufacturing supply chain in this situation may require the attention of scholars.

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