ALLIANCE STRATEGY OF CONSTRUCTION AND DEMOLITION WASTE RECYCLING BASED ON THE MODIFIED SHAPLEY VALUE UNDER GOVERNMENT REGULATION

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Abstract. Construction and demolition waste (CDW) recycling enterprises have an imperfect operation system, which leads to low recovery rate and low production profits. A feasible method to improve this situation involves seeking a high-efficiency enterprise alliance strategy in the CDW recycling system composed of manufacturers, retailers and recyclers and designing a reasonable and effective coordination mechanism to enhance their enthusiasm for participation. First, we constructed a Stackelberg game model of CDW recycling under government regulation and analyzed the optimal alliance strategy of CDW recycling enterprises under punishment or subsidy by the government as a game leader. In order to ensure the stable cooperation of the alliance, we used the Shapley value method to coordinate the distribution of the optimal alliance profit and improved the fairness and effectiveness of the coordination mechanism through modification of the unequal rights factor. Finally, based on the survey data of Chongqing, we further verified the conclusion through numerical simulation and analyzed changes in various parameters at different product costs. The results show that the alliance strategy and coordination mechanism can improve the CDW recovery rate, improve the recycling market status, and increase the production profits of enterprises.

1. Introduction. Construction and demolition waste (hereafter referred to as building products CDW) not only occupy a large amount of land resources, but incineration and landfills can also cause environmental pollution [50]. Since the early 1990s, this issue has aroused great concern from the Chinese government and researchers. Various laws and policies such as the Regulations on Environmental
Protection Management of Construction Projects and the Regulations on Urban CDW Management have been released. From a domestic perspective, CDW recycling equipment and treatment technology have improved under the intervention of government policies and laws, but the “China Resources Comprehensive Utilization Annual Report (2014)” issued by the National Development and Reform Commission shows that Chinese architecture waste accounts for 30-40% of total solid waste, and the average recovery rate is only approximately 5%. The recycling rate is not good, especially for public construction projects, which are result of the rapid development in China in the past 20 years. These projects, which meet the needs of social urbanization and economic development, use public resources to build and maintain social management facilities to enhance public interest [37] and will gradually enter the retirement period. In the next few decades, this will inevitably become the main source of large amounts of CDW. Moreover, local governments have stipulated that public construction projects should preferentially recycle and utilize recycled product [12, 13, 1]. The reason for the above situation is that CDW resource enterprises have characteristics of high cost, low profit and uncertainty of returns [35]. Furthermore, other obstacles also affect the participation of enterprises in CDW resources, such as inadequate management systems, insufficient economic incentives [3, 44], immature recycling technology, an underdeveloped market for remanufactured products, and an imperfect operating system for the recycling market [50, 16, 38]. Among them, the profitability of recycling enterprises is particularly prominent; however, in response to this problem, scholars have proposed to promote recycling through government regulation or subsidies [4, 14, 34], enterprise capacity improvement, and alliance cooperation [20, 25, 26]. In fact, there have been successful cases of enterprise alliance cooperation. For example, the Ministry of Industry and Information Technology Demonstration Project (Beijing Lianlv Group Construction and Demolition Waste Resource Integration Project) managed the urban building demolition of a project in Changping District using the CDW Recycling 3.0 model. The removal efficiency was improved while reducing disposal costs and secondary pollution. It is a successful case of cooperation between upstream and downstream enterprises in CDW resources. The literature and actual cases show that enterprise alliances are a viable way to promote the recycling of CDW.

However, not all alliances will produce such good results. For example, in November 2017, two well-known logistics companies in China announced the formation of an alliance, but only for about two months, the cooperation was terminated due to uneven distribution of interests. Regarding the profit distribution of alliance enterprises, if there is no fair and effective contract, the alliance will face huge risks that will eventually lead to disintegration, corporate interests will be impaired, and recycling efficiency will be reduced; therefore, designing a contract that rationally distributes corporate profits and reduce the risk of corporate default is also an urgent problem to be solved.

This study builds a closed loop supply chain for CDW including manufacturers, retailers, contractors (consumers) and recyclers. Based on the Stackelberg game, the government participates in the game and punishes (or subsidizes) the company’s products, and companies in the supply chain can freely form alliances. We have solved the problem of an optimal alliance strategy and interest coordination under different alliances when the government aims to promote the recovery of CDW and maximize the comprehensive benefits for the society, economy and environment. This study can provide a theoretical basis for a government punishment (subsidy)
strategy, a recycling market operation strategy for CDW supply chain enterprises, and a guarantee and support for improving the welfare of the whole society and effectively carrying out CDW recycling.

The rest of this article is organized as follows. Section 2 presents a literature review. Section 3 describes the model and assumption. Section 4 shows the optimal alliance strategy and correlation theorem. Section 5 discusses the supply chain coordination based on the Shapley value. In Section 6, two CDW recycling enterprise in Chongqing are selected for numerical simulation. Finally, Section 7 concludes and lists topics for future research.

2. Literature review. This literature review mainly focuses on the application of supply chain theory in CDW management, the application of a contract for supply chain member cooperation, and the application of the Shapley value method to solve alliance problems.

In order to alleviate the negative impact on the environment caused by CDW and promote the stable development of the CDW recycling industry, the management of CDW has gradually become the focus of research in recent years. In terms of theoretical research, the intensity of supervision and fees, fines, waste disposal costs, and illegal dumping can affect the decision-making behavior of building contractors and government departments from the perspective of evolutionary game theory [5]. Z. Ding et al. [7] used system dynamics to study a simulation of the environmental performance of China’s CDW reduction management, noting that government supervision should be strengthened to reduce waste sources. In the case of a mismatch between supply and demand in the CDW recycling market, Liu et al. [27] studied the optimal strategy for recyclers to adjust their recycling capacity and their impact on profits through the establishment and analysis of a nonlinear programming model. Fu et al. [11] designed a reverse logistics network model based on the balance between the CDW recovery rate and cost considering government subsidies to determine the optimal processing center location and shipping route. In terms of empirical research, Jin et al. [19] explored the recent movement and current situation of China’s CDW recycling through empirical investigation and review cases. They noted that government oversight has a significant impact on China’s current waste management practices. Esa et al. [9] developed a causal cycle diagram (CLD) for managing CDW to study the management of CDW generated by the Malaysian government at different stages of construction and they determined that regulation was an appropriate strategy. Mak et al. [33] used behavioral theory to analyze the behaviors of various stakeholders (contractors, governments, etc.) in CDW management and concluded that government regulations and economic incentives will promote recycling behavior.

The existing literature studies CDW management from the aspects of pricing, behavioral decision-making, and influencing factors. However, few studies have used the feasible approach of alliance cooperation to promote recycling to solve the CDW resource strategy, and studies rarely provide reasonable and effective computational models and quantitative analysis methods. In addition, if reasonable profit distribution is not made for the alliance, it will affect the formation of alliances or the long-term cooperation after the alliance is formed. Therefore, while studying the alliance strategy, it is also important to analyze the method or contract of the alliance members’ income distribution.
In recent years, some scholars have introduced various contract methods into the cooperation of waste supply chain members regarding the issue of waste recycling and explored the pricing strategies and coordination mechanisms of the government or supply chain members. Wang et al. [45] introduced profit-sharing contracts to solve the strategic inventory problem between suppliers and retailers, thereby improving the overall performance of the supply chain. Zhang and Chen [51] designed wholesale contracts and revenue sharing contracts to solve the problem of information sharing in the supply chain of make-to-stock production. Saha et al. [40] proposed a triple discount mechanism for manufacturers. Panda et al. [39] analyzed revenue subsidy contracts under the influence of corporate social responsibility. Feng et al. [10] proposed two types of coordination contracts, including two pricing contracts and revenue sharing contracts. Lu et al. [17] discussed the option contract. These scholars have used the aforementioned contracts to address different aspects of supply chain coordination.

Although there have been a number of studies on coordination of the interests of the waste recycling supply chain, the existing cost-sharing method or revenue sharing is based on signing a specific contractual agreement, and the two parties share the proceeds proportionally. However, in practice, this often involves factors such as credit and default, making it difficult for both parties to increase profits at the same time, even in violation of the contract and lead to the collapse of the recycling enterprise alliance. The Shapley value method considers factors such as the possibility of participating in the alliance and the marginal contribution and provides a basis for solving the problem of income distribution among supply chain partners via an acceptable distribution principle.

The Shapley value method is essentially a mathematical method to solve the problem of n-person cooperation and the maximum benefit of non-confrontation activities. It is then used in the study of the distribution of enterprise interest in the supply chain, and different ways of using it are derived according to different situations. Lu and Zhu [28] proposed the interval-valued fuzzy Shapley value method combined with a fuzzy analytic hierarchy process (AHP) to ensure the stability of information in the product supply chain and achieve fair profit distribution. Devangan et al. [6] used Shapley value to design buyback contracts with inventory level dependent demand to ensure the fairness and personal reasonableness of the contract. Zheng et al. [54] proposed three coordination mechanisms based on the Shapley value, which promoted cooperation and achieved a fair distribution of residual profits. H. Ding et al. [8] introduced a new modified Shapley value with weighting factor to solve the problem of updating the international project schedule selection model. Sun and Sun [41] used the Shapley value method to solve the problem of management cooperation in the financing alliance of a three-party cooperation infrastructure project. Teng et al. [43] explored the Integrated Project Delivery (IPD) project model, using the improved Shapley value model to assess the marginal contribution of each stakeholder to the alliance in order to establish a fair incentive plan for the IPD project; Teng et al. also noted that compared to cost-oriented, risk-oriented, and equity-based methods, the Shapley value method is the most “rationalized” and “classical” solution in cooperative games. It considers the possibility of participating in alliances and marginal contributions.

Characteristics including the marginal contribution and the high fairness and effectiveness of the Shapley value method make it more applicable for supply chain member cooperation research than other benefit distribution methods. In other
words, it is of theoretical and guiding significance to introduce the Shapley value into enterprise alliance strategy research of CDW recycling. Additionally, in view of the research situation, combined with the key factors affecting the cooperation between CDW recycling enterprises, such as the rights status, the classic Shapley value was revised to closer reflect reality.

Compared with previous studies, this article reflects innovation from the following. First, the Stackelberg game reflects the constraints and mutually beneficial CDW recycling relationships between government and business decision-making, and the internalization of government regulation reflects the trade-off between fiscal expenditure and target benefit (a comprehensive consideration of economic, environmental and social factors) due to regulation. Second, previous studies generally only considered “distributed” and “concentrated” alliances, and this study considered all free alliance cases, and interestingly found that the recycler and the manufacturer alliance, while the retailer’s independent operation is the best. Finally, the coordination mechanism is modified by unequal rights factor, which reflects the relative importance of the enterprise status and makes the mechanism more acceptable.

3. Model and assumption.

3.1. Model description. This study considers a government-regulated closed-loop supply chain of building material products (hereafter referred to as building products), consisting of manufacturers, retailers, contractors (consumers of building materials, hereafter referred to as consumers), recyclers (collection, transportation, classification, preprocessing of CDW, etc., all of the above tasks are simply referred to as “collection”). The building materials mentioned above are used in public construction projects. Public construction projects are projects that use public resources to build and maintain social management facilities to enhance public interest [37]. Compared to ordinary construction projects, their social benefits are relatively obvious. Therefore, this study uses consumer surplus to quantify the impact of such social benefits, which is considered a social welfare index in the profit function. As shown in Fig. 1, the manufacturer produces building material products at unit cost \( c_2 \) and sells them to retailers at price \( \omega \), retailers sell them to public project contractors (consumers) at price \( p \), and recyclers collect building materials and waste generated from construction and demolition activities at cost \( c \) and then sell them to the manufacturer at price \( b \).

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![Figure 1. Closed-loop supply chain of building materials products](image)

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### 3.2. Parameter setup.

| Notation | Definition |
|----------|------------|
| $\alpha$ | Potential market demand for new building products; ($\alpha > 0$) |
| $\beta$ | Sensitivity factor of public construction project contractors (consumers) to new building products; ($\beta > 0$) |
| $D(p)$ | Demand function for new building products |
| $D(p, \eta)$ | The demand function of new building products under government regulation |
| $\eta$ | Government penalizes manufacturer’s products ($\eta > 0$) or subsidies ($\eta < 0$) |
| $c_n$ | The unit cost of producing new building products from new raw materials purchased by manufacturers; ($c_n > 0$) |
| $c_r$ | The unit cost of the manufacturer’s use of CDW to produce new building products; ($c_r > 0$) |
| $\omega$ | The wholesale price of the new building products that the manufacturer provides to the retailer; ($\omega > 0$) |
| $p$ | The retail price of the new building products that the retailer manufacturer provides to the contractor; ($p > 0$) |
| $c$ | Collector’s unit collection cost; ($c > 0$) |
| $b$ | The repurchase price of the CDW paid by the manufacturer to the recycler; ($b > 0$) |
| $\tau$ | The proportion of recycled CDW to the market demand for new building products, referred to as recovery rate; $\tau \in [0, 1]$ |
| $\gamma$ | Environmental benefit coefficient, environmental benefits brought by unit CDW recycling |
| $m$ | The difficulty degree for collecting CDW; ($m \leq 0$) |
| $c_z$ | The unit cost of new building products, as new construction products include new and remanufactured products, so $c_z = \tau c_r + (1 - \tau)c_n = c_n + \tau (c_r - c_n) = c_n - \Delta \tau$ |

3.3. **Assumptions.** The assumptions made throughout the paper are listed as follows:
Assumption 1 The no government intervention condition functions as follows: \( D(p) = \alpha - \beta p \). The government punishes or subsidizes the unit product produced by the manufacturers \([31, 32]\) to protect the environment, increase the income of public construction projects, or improve social welfare. According to different situations, the government can choose to punish \((\eta > 0)\) or subsidize \((\eta < 0)\) the product. Therefore, the demand function can be rewritten as:

\[
D(p, \eta) = \alpha - \beta (p + \eta)
\]

If the government punishes (subsidies) \(\eta\) for the manufacturer’s products, it will cause a difference between the price paid by the consumer and the price received by the seller (retailer). If \(p\) is the price the seller received, then \(p' = p + \eta\) will be the price paid by the customer. It is worth noting that it is irrelevant to punish or subsidize the seller or buyer of the product. Finally, regardless of how it is regulated, the buyer and seller of the product share the burden or benefit of the penalty or subsidy \([31, 32]\).

Assumption 2 The unit cost \((c_n)\) of the manufacturer using new materials to produce new construction products is higher than the unit cost \((c_r)\) of remanufacturing using CDW, indicating that the manufacturer can have cost saving \((\Delta)\), so let \(\Delta = c_n - c_r\).

Assumption 3 Based on government policy \([12]\), public construction projects prioritize the use of recycled CDW for the production of new construction products. When the market demand is not met, new materials are used for production. The recovery rate \((\tau)\) is related to the collection investment \((I)\) of the recycler, \(I = m\tau^2\) lcite \([38]\), where \(m\) is the difficulty factor for collecting CDW.

Assumption 4 There is no distinction between the quality of new construction products made with traditional new materials and waste, so the two products do not have different prices. The real situation is similar to the survey of Chongqing cases, such as recycled concrete bricks.

Assumption 5 In addition to environmental issues and profits, suppose that manufacturers are also concerned with social issues, treating consumer surplus as a social welfare index in their profit function, and consumer surplus refers to consumers (public construction project contractors) willing and able to be commodities or the difference between the total amount paid by the service and the total amount actually paid. If \(\mu \in [0, 1]\) is part of the consumer surplus that manufacturers are concerned with, the consumer surplus under government regulation is:

\[
\mu Cs = \mu \int_{p_{market}}^{p_{max}} D(p, \eta, \tau) dp = \mu \int_p^{\frac{\alpha}{\beta}} [\alpha - \beta(p + \eta)] dp = \frac{\mu(\alpha - \beta(p + \eta))^2}{2}
\]

When \(\mu = 0\), the building product manufacturer is purely profit maximizing, and when \(\mu = 1\), the building product manufacturer completely maximizes the consumer (contractor) welfare \([36, 42]\).

4. Model establishment and Alliance strategy.

4.1. No alliance (Decentralized decision). In this case, the government is the leader of the Stackelberg game, first determining the penalties (subsidies) for the unit product. The manufacturer is the leader of the closed-loop supply chain outside the government and determines the wholesale price \(\omega\) of the building products based on the given penalty (subsidy) \(\eta\). At the same time, the repurchase price \(b\) of
CDW is determined. After the manufacturer’s decision, the retailer (the recycler) determines the retail price \( p \) (the recovery rate \( \tau \) of CDW).

The retailer is denoted as \( R \), the recycler is denoted as \( C \), and the manufacturer is denoted as \( M \). The profits of manufacturers (\( \pi_M \)), retailers (\( \pi_R \)) and recyclers (\( \pi_C \)) are as follows (1) (3):

\[
\pi_M = \omega - cn + \left( \Delta - b \right) \tau \left[ \alpha - \beta \left( p + \eta \right) \right] \quad (1)
\]

\[
\pi_R = \left( p - \omega \right) \left( \alpha - \beta \left( p + \eta \right) \right) \quad (2)
\]

\[
\pi_C = \left( b - c \right) \left( \alpha - \beta \left( p + \eta \right) \right) \tau - \frac{m \tau^2}{2} \quad (3)
\]

The consumer surplus (\( \mu Cs \)) is:

\[
\mu Cs = \frac{\mu (\alpha - \beta \left( p + \eta \right))^2}{2} \quad (4)
\]

CDW Recycling activities will bring environmental benefits. It is assumed that the environmental benefits \( E \) are directly proportional to the recovery rate.

\[
E = \gamma \tau \left[ \alpha - \beta \left( p + \eta \right) \right] \quad (5)
\]

In the process of CDW recycling of public construction projects, the government is faced with economic, environmental and social welfare considerations [46, 48]. The government’s objective function is the sum of social welfare (i.e., profit of manufacturers, retailers, and recyclers, punishment (subsidy), and consumer surplus) and environmental benefits, reflecting economic, social and environmental aspects. The function is denoted as \( \pi_G \):

\[
\pi_G = \pi_M + \pi_R + \pi_C + \mu Cs + \eta \left[ \alpha - \beta \left( p + \eta \right) \right] + E = \frac{\left( \alpha - \beta \left( p + \eta \right) \right) \left( 2p + \alpha \mu - \beta \left( p + \eta \right) \mu + 2(-c + \gamma + \Delta) \tau - 2cn \right) - m \tau^2}{2} \quad (6)
\]

We use the backward induction method to find the optimal solution, then we obtain equation (7). The solution process is shown in Appendix A.

\[
\eta^* = \frac{\left( \beta(c - \Delta)(c - 4\gamma - \Delta) + 4m(2 + \beta \mu)(\alpha - \beta cn) \right)}{\beta(3c - 4\gamma - 3\Delta)(c - \Delta) + 4m(-2 + \beta \mu)} \quad (7)
\]

Substituting \( \eta^* \) back into the functional formula of \( p, \tau, \omega \) and \( b \), we obtain the optimal solution (8)~(11):

\[
b^* = \frac{c + \Delta}{2} \quad (8)
\]

\[
\omega^* = \frac{2\alpha(4m + \beta(c - \Delta)^2) + \beta^2(c^2 + 4\gamma \Delta + \Delta^2 - 2c(2\gamma + \Delta) + 4m(2 + \beta \mu) \alpha c n)}{\beta(3c - 4\gamma - 3\Delta)(c - \Delta) + 4m(-2 + \beta \mu)} \quad (9)
\]

\[
p^* = \frac{2\alpha(4m + \beta(c - \Delta)^2 + \beta(c - \Delta)(c - 4\gamma - \Delta) + 4m(1 + \beta \mu) \alpha c n)}{\beta(3c - 4\gamma - 3\Delta)(c - \Delta) + 4m(-2 + \beta \mu)} \quad (10)
\]

\[
\tau^* = \frac{2(c - \Delta)(\alpha - \beta cn)}{\beta(3c - 4\gamma - 3\Delta)(c - \Delta) + 4m(-2 + \beta \mu)} \quad (11)
\]
Substituting equations (7) ∼ (11) into equations (1) ∼ (6), we obtain equations (12) ∼ (15):

\[
\pi^*_R = \frac{16m^2(\alpha - \beta c_n)^2}{\beta(3c - 4\gamma - 3\Delta)(c - \Delta) + 4m(-2 + \beta \mu)^2} \\
\pi^*_C = \frac{2m(c - \Delta)^2(\alpha - \beta c_n)^2}{\beta(3c - 4\gamma - 3\Delta)(c - \Delta) + 4m(-2 + \beta \mu)^2} \\
\pi^*_M = \frac{4m(8m - \beta(c - \Delta)^2)(\alpha - \beta c_n)^2}{\beta(3c - 4\gamma - 3\Delta)(c - \Delta) + 4m(-2 + \beta \mu)^2} \\
\pi^*_G = \frac{2m(\alpha - \beta c_n)^2}{\beta(3c - 4\gamma - 3\Delta)(c - \Delta) + 4m(-2 + \beta \mu)}
\]

4.2. Alliance (Alliance of some members or Alliance of all members). For the solution of the model in the case of an Alliance, similar to the No alliance (Decentralized decision) solution process, the retailer is denoted as R, the recycler is denoted as C, and the manufacturer is denoted as M. We use the backward induction method to determine the optimal solution. Alliance of some members includes three cases: \{R ∪ C, M\}; \{R ∪ M, C\}; and \{C ∪ M, R\}; Alliance of all members is represented as \{R ∪ C ∪ M\}. Among them, \(U\) indicates that members form alliances, such as \{R ∪ C, M\}, which means that the retailer (R) and the recycler (C) form an alliance, and the manufacturer (M) maintains a separate decision. In the case of \{R ∪ C, M\}, because the alliance lacks the manufacturer, the maximum profit of the alliance is the sum of R and C when there is no alliance [21, 23]. The optimal solutions for each variable and the maximum profit for each alliance are shown in the Appendix A.

4.3. Analysis of results. By analyzing the above results, we obtain the following theorems.

**Theorem 4.1.** Under government regulation, in the case of an alliance or no alliance, the government’s punishment (\(\eta > 0\)) or subsidy (\(\eta < 0\)) for the alliance has the following relationship: \(\eta^*_{CM} < \eta^*_{RCM} < \eta^* = \eta^*_{RC} < \eta^*_{RM} < 0\).

The Proof of all theorems is shown in the Appendix B.

Theorem 4.1 shows that no matter how the members of the supply chain form alliances, the government’s optimal strategy is to subsidize the products, not impose punishment. The CM Alliance will receive the highest subsidy, and the RM Alliance will receive the minimum subsidy. If the retailer joins the alliance, it will reduce the subsidies received from the government. If the manufacturer is aligned with the recycler, the subsidy will increase. Therefore, the optimal strategy should be independent decision-making by retailers and cooperative decision-making between recyclers and manufacturers.

**Corollary 1.** For different national scenarios, the optimal alliance strategy will change when the government punishes (subsidies) in a different way or only considers some of the benefits.

Through Theorem 1, we find that the government will provide different subsidies for different alliances in order to achieve the maximum goal because for a developing country, the government fiscal expenditure (income) will be considered in the objective function. However, with the development of the country, when the state’s financial strength is sufficient or the target changes, for example, in some developed
countries, government fiscal expenditure (income) is no longer included in the objective function category, and a fixed amount of punishment (subsidy) is adopted. The government’s goal is to maximize the sum of supply chain profit, consumer welfare, and environmental benefits, regardless of finance. In this case, the result of the optimal strategy of the alliance will change.

(1) When \( \beta \eta + \beta c_n - \alpha \neq 0 \) (i.e., the government’s penalty \( \eta \neq \frac{\alpha}{\beta} - c_n > 0 \)), and

\[
\frac{2m + (\alpha - \beta c_n - \beta(c - \Delta))(c - \Delta)^2}{\beta(c - \Delta)} \leq \eta < \frac{\alpha}{\beta} - c_n,
\]

the RCM alliance is optimal, followed by the RM alliance, again the CM alliance, and finally the alliance is the worst.

(2) When \( \beta \eta + \beta c_n - \alpha = 0 \) (i.e., the government’s penalty \( \eta = \frac{\alpha}{\beta} - c_n > 0 \)), regardless of which alliance strategy is chosen, the sum of supply chain profits, consumer welfare and environmental benefits is equal, that is, all alliance strategies are equally optimal.

The above results are shown in the Appendix B.

**Theorem 4.2.** For the optimal decision price in the case of alliances or no alliance, the relationship is as follows: retail price \( p^\ast_{CM} > p^\ast_{RC} = p^\ast > p^\ast_{RCM} > p^\ast_{RM} \); wholesale price \( \omega^\ast_{CM} > \omega^\ast = \omega^\ast_{RC} \).

Theorem 4.2 shows that the CM Alliance will set higher decision pricing, and the RM Alliance and No Alliance (Decentralized) will result in lower decision pricing so that the CM Alliance will have higher profits than other alliances. Interestingly, the price \( p \) here is not the price actually encountered by the consumer. The actual price paid by the consumer should be \( p' = p + \eta \). We can calculate and compare the actual price paid by the consumer in the case of the CM Alliance:

\[
p'_{CM} - p^\ast = (p^\ast_{CM} + \eta^\ast_{CM}) - (p^\ast + \eta^\ast) = m(c - \Delta)(c - 4\gamma - \Delta)(-\alpha + \beta c_n) + \frac{m(-2 + \beta \mu)}{(\beta(c - \Delta)(c - 2\gamma - \Delta) + m(-2 + \beta \mu))(\beta(3c - 4\gamma - 3\Delta)(c - \Delta) + 4m(-2 + \beta \mu)} < 0.
\]

The results of the other alliances are equally calculated. Finally, we obtain the lowest price that consumers actually pay under the CM Alliance; meanwhile, consumer welfare under the CM Alliance is also highest. Therefore, the CM alliance under government regulation is more beneficial to enterprises and consumers, which is a win-win situation.

**Theorem 4.3.** For the recovery rate of CDW in the case of alliances and no alliances, the relationship is as follows: \( \tau^\ast_{CM} = \tau^\ast_{RCM} > \tau^\ast = \tau^\ast_{RC} = \tau^\ast_{RM} \).

Theorem 4.3 shows that the CM Alliance and the RCM Alliance have a higher recovery rate of CDW, which will bring higher environmental benefits \( E \). Among them, the recovery rate of the CM Alliance and the RCM Alliance are equal, and the recovery rate of the RC Alliance, RM Alliance, and No Alliance are equal. In addition, the cooperation between manufacturers and recyclers is beneficial for improving the recovery rate of CDW.

**Theorem 4.4.** For the government utility in the case of alliances and no alliances, the relationship is as follows exist: \( \pi^\ast_{gCM} = \pi^\ast_{gRCM} > \pi^\ast_g = \pi^\ast_{gRC} = \pi^\ast_{gRM} \).

Theorem 4.4 shows that the CM Alliance and the RCM Alliance have a higher government utility, that is, the sum of social welfare and environmental benefits is higher. The understanding of Theorem 4 is similar to Theorem 3, it is necessary for the manufacturer and the recycler to form an alliance.
Theorem 4.5. For the maximum profit of each alliance in the case of alliances or no alliances, the following relationships exist: $\pi^*_{CM} > \pi^*_{RCM} > \pi^*_M > \pi^*_{RC} > \pi^*_R > \pi^*_RM > \pi^*_C$.

Theorem 4.5 shows that i) under government regulation, cooperation between recyclers and manufacturers can increase their total profit compared to the case of No Alliance (Decentralized decision); cooperation between recyclers and retailers does not change the total profit; cooperation between manufacturers and retailers will reduce the total profit. ii) The total profit of the alliance of recyclers, manufacturers, and retailers is reduced compared to the condition of an alliance between the manufacturer and the recycler and the retailer making individual decisions. Therefore, the same optimal strategy as theorem 4.1 can be obtained.

Theorem 4.6. The decision variables, alliance profits, and government subsidies ($\eta < 0$) in each alliance are negatively correlated with the recovery difficulty coefficient $m$ and positively correlated with the environmental benefit coefficient $\gamma$.

Theorem 4.6 shows that the government will provide higher subsidies for construction and construction waste, which is difficult to collect ($m$) or recyle, and the waste is remanufactured to yield increased environmental benefits ($\gamma$); this method can also generate higher recovery rates and alliance profits. Based on this method, in the case of technological innovation, if the impact of cost is not considered, the same positive effects as the above subsidies can be obtained through a method by which recyclers can improve their ability to collect waste (i.e., reduce the degree of difficulty of collecting waste $m$) or increase the environmental protection of their own remanufactured products without considering the cost impact (i.e., improve the environmental benefit coefficient $\gamma$). Lu et al. [30] also found similar results.

5. Supply chain coordination based on shapley value. The optimal alliance (CM Alliance) between recyclers and manufacturers can increase the recovery rate of CDW and improve the operation of the recycling market. Therefore, how do we guarantee its stability? For alliances between enterprises, without a reasonable coordination mechanism, the interests of alliance members will be difficult to secure, and they will face the risk of disintegration, ultimately affecting the recycling market and CDW recycling. Therefore, it is urgent to seek a coordination mechanism to distribute the revenue of the optimal alliance.

5.1. Coordination mechanism of Shapley value. The Shapley value method is a mathematical method that is solved by Shapley LS in 1953 to solve the problem of n-person cooperation countermeasures. The distribution of revenue among supply chain partners can be regarded as a multi-person cooperation countermeasure problem, and it can be solved by Shapley value method [18]. The Shapley value of the revenue distribution of each member of the supply chain is:

$$\varphi_i(v) = \sum_{s \in S_i} \omega(|s|)[v(s) - v(s/i)]$$

$$\omega(|s|) = \frac{(n-|s|)!(|s|-1)!}{n!}$$

In the formula, $s$ denotes an alliance composed of several players, $I = \{1, 2, \ldots, n\}$ denotes the set of all players, $s$ is a subset of set $I$, $S_i$ is all subsets containing partner $i$ in set $I$, $|s|$ is the number of elements in the subset $s$, and $n$ is the number of elements in the set $I$. $\omega(|s|)$ is the weighting factor, $v(s)$ is the benefit of the subset $s$, and $v(s/i)$ is the benefit that the alliance can achieve after removing the partner.
i from the subset s. In the CM Alliance, we use the classic Shapley value to coordinate the profit distribution of manufacturers and recyclers (the basis for this step is explained in Appendix B). The results are shown in Table 1.

### Table 1. Calculation of the Shapley value of the recycler and manufacturer

| S   | Recycler’s calculation of Shapley value | Manufacturer’s calculation of Shapley value |
|-----|----------------------------------------|--------------------------------------------|
|     | C           | C ∪ M                                 | M           | C ∪ M                                 |
| v(s) | π_C^*       | π_CM^*                                | π_M^*       | π_CM^*                                |
| v(s/i) | 0           | π_M^*                                | 0           | π_C^*                                |
| v(s) − v(s/i) | π_C^*   | π_CM^* − π_M^*                      | π_M^*       | π_CM^* − π_C^*                      |
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of player \( i \) to participate in the alliance is: \( \lambda_i = \frac{P_i}{\sum_{i=1}^{n} P_i} \). The difference between the actual relative willingness of player \( i \) joining the alliance and the ideal relative willingness is: \( \Delta \lambda_i = \lambda_i - \frac{1}{n} \).

In order to encourage player \( i \) to be willing to join the league, we will give \( i \) the right income incentive, assuming that each player \( i \) can accept the incentive is \( \epsilon \) (\( 0 < \epsilon < 1 \)) then player \( i \)'s actual modified Shapley distribution profit is:

\[
\varphi_i^*(v) = \varphi_i(v) - \Delta \varphi_i(v) = \varphi_i(v) - \Delta \lambda_i \cdot \epsilon \cdot \varphi_N(v)
\]

When \( \Delta \lambda_i < 0 \), then \( \Delta \varphi_i(v) < 0 \), player \( i \) wants to join the league, the relative will is lower than the average level, and the dependence on other players is low, that is, the rights are higher. So, the actual profit should increase by \( \Delta \varphi_i(v) \) from the ideal profit, that is \( \varphi_i^*(v) = \varphi_i(v) + |\Delta \varphi_i(v)| \). Conversely, the case with lower rights is: \( \varphi_i^*(v) = \varphi_i(v) - |\Delta \varphi_i(v)| \).

Based on the existing research \([2, 49]\), through the analysis of the relationship among CDW recycling enterprises, we set the recycler’s dependence on the manufacturer as \( t_1 \) and the manufacturer’s dependence on the recycler as \( t_2 \), then \( t_1 > t_2 \). We performed the calculation of the modified Shapley value under the unequal rights situation as shown in Table 2.

**Theorem 5.2.** Comparing the profit distribution of CM Alliance members before and after modified Shapley values under unequal rights, the relationship is as follows: \( \varphi_i^*(v)_C < \varphi_i(v)_C; \varphi_i^*(v)_M > \varphi_i(v)_M \).

Theorem 5.2 shows that for the profit analysis of CM Alliance members, compared with the classic Shapley value, after modified Shapley value under unequal rights, the profit of the manufacturer is improved, the profit of the recycler is reduced, but the profit is still greatly increased compared with the No Alliance. The modification reflects the manufacturer’s rights advantage in the alliance (i.e., the critical position) and the dependence of the recycler on it, making up for the impact of the manufacturer’s weak relative willingness on the stability of the alliance. The modified Shapley value profit distribution is more easily accepted by alliance members, especially those who are in a critical rights position.

| Player i | Recycler | Manufacturer |
|----------|----------|--------------|
| \( \lambda_i \) | \( \frac{\sqrt{t_1^2}}{\sqrt{t_1^2} + \sqrt{t_2^2}} \) | \( \frac{\sqrt{t_2^2}}{\sqrt{t_1^2} + \sqrt{t_2^2}} \) |
| \( \Delta \lambda_i \) | \( \frac{\sqrt{t_1^2}}{\sqrt{t_1^2} + \sqrt{t_2^2}} - \frac{1}{2} \) | \( \frac{\sqrt{t_2^2}}{\sqrt{t_1^2} + \sqrt{t_2^2}} - \frac{1}{2} \) |
| \( \Delta \varphi_i(v) \) | \( \left( \frac{t_1}{t_1 + t_2} - \frac{1}{2} \right) \cdot \epsilon \cdot \pi_{CM}^* \) | \( \left( \frac{t_2}{t_1 + t_2} - \frac{1}{2} \right) \cdot \epsilon \cdot \pi_{CM}^* \) |
| \( \varphi_i(v) \) | \( \pi_{CM}^* - \pi_{M}^* + \pi_{C}^* \) | \( \pi_{CM}^* - \pi_{C}^* + \pi_{M}^* \) |
| \( \varphi_i^*(v) \) | \( \frac{\pi_{CM}^* - \pi_{M}^* + \pi_{C}^*}{2} - \frac{\pi_{CM}^* - \pi_{C}^* + \pi_{M}^*}{2} \cdot \epsilon \cdot \pi_{CM}^* \) | \( \frac{\pi_{CM}^* - \pi_{C}^* + \pi_{M}^*}{2} - \frac{\pi_{CM}^* - \pi_{M}^* + \pi_{C}^*}{2} \cdot \epsilon \cdot \pi_{CM}^* \) |
Theorem 5.1 and 5.2 show both manufacturers and recyclers are willing to join the CM Alliance and redistribute profits by the modified Shapley value coordination mechanism.

6. Sensitivity analysis. In order to study the optimal alliance strategy of CDW recycling enterprises based on the modified Shapely value coordination mechanism and test the universality of the related theorems, we choose Chongqing, China as an example and obtained relevant data through the literature [15, 24, 29, 47, 52, 53] and a survey. We selected two typical state-owned resource-based enterprises in the main urban area of Chongqing, Heishizi CDW Recycling Plant in Yubei District and Guangyang CDW Disposal Plant in Nan’an District, to analyze their resource activities (The background is shown in AppendixC). Then we combined with those in the literature [2, 22] to study the unequal rights of enterprises. Furthermore, the conditional basis of the model, such as \( \tau \in [0, 1] \), was analyzed so that the model is a meaningful and concise numerical analysis. We make the following assumptions about the relevant parameters of this study: \( \alpha = 70, \beta = 2, \gamma = 20, c_n = 32, \mu = 0.1, m = 850, c = 8, \Delta = 18, \epsilon = 0.2, t_1 = 3, t_2 = 2. \)

Fig. 2 to Fig. 5 show the impact of the collection cost \( c \in (6, 9) \), and cost saving \( \Delta \in (6, 9) \) on each decision variable.

Fig. 2 shows that the government subsidies decline as the collection cost \( c \) increases and rise as the cost of saving \( \Delta \) increases. The subsidy is the highest under the CM Alliance model and the lowest under the RM Alliance model. This numerical result is exactly the same as Theorem 4.1.

Fig. 3 shows that the retail price and the wholesale price decrease with increasing collection cost \( c \) and increase with increasing cost saving \( \Delta \). The price is the highest in the CM Alliance and the lowest in the RC Alliance or No Alliance condition. This is exactly the same as Theorem 4.2.
Fig. 3. Retail price $p$ (Wholesale price $\omega$) comparison between different alliance cases

Fig. 4. shows that the recovery rate $\tau$ (government utility $\pi_g$ which consists of total social welfare and environmental benefits) decreases with increasing collection cost ($c$) and increase with increasing cost saving ($\Delta$). The recovery rate of CDW (The government utility) is higher in the CM Alliance or RCM Alliance and lower in the No Alliance, RC Alliance, and RM Alliance condition. This numerical result is exactly the same as Theorem 4.3 (Theorem 4.4).

Fig. 5 shows that recyclers and manufacturers are willing to join the CM Alliance to achieve higher profits through the Shapley value distribution. In addition, the recycler’s profit slightly decreased after the modified Shapley value distribution under unequal rights, and the manufacturer’s profit after the modification is slightly increased because of the rights advantage of manufacturers and the high dependence of recyclers. This is exactly the same as Theorem 4.7 and 4.8.

7. Managerial implications. The study has a number of management implications.

(1) High efficiency and high acceptance attract new manufacturers and recyclers to join and form a CM alliance. The enthusiasm of enterprises to participate in recycling activities is improved, and the status quo of recycling markets is improved.
Figure 5. Recycler’s (Manufacturer’s) profit $\pi_C$ ($\pi_M$) comparison between different distribution cases

(2) The formation of a CM Alliance further solves the problem of imperfect recycling market so that recyclers do not have to spend large amounts of time and money to establish good relationships with manufacturers. The reliable acquisition channel ensures continuous recycling of CDW.

(3) Through the guarantee of the modified Shapley value coordination mechanism, the recyclers and manufacturers form a CM alliance, which greatly improves the recovery rate. At the same time, the government’s effectiveness has also been improved, which is a beneficial result for developing countries. In different country scenarios, when the government maintains high subsidies to encourage retailers to join the RCM alliance, such fiscal expenditures can be exchanged for greater environmental benefits. For example, in some developed countries, government fiscal expenditure (income) is no longer included in the objective function category, but a fixed amount of punishment (subsidy) is adopted. The government’s goal is to change to the sum of supply chain profit, consumer welfare, and environmental benefits. Under this country scenario, the alliance’s optimal strategy will become the RCM alliance that is optimal in economic, environmental and social.

8. Conclusion. This study analyzes the optimal alliance strategy of CDW resource enterprises under government regulation and uses a modified Shapley value coordination mechanism modified based on the unequal rights factor to rationally distribute the profit of the optimal alliance, and further numerical simulations are carried out using Chongqing’s CDW resource enterprises as an example.

The results show the following:

(1) The optimal alliance strategy is one in which the recycler and the manufacturer form an alliance (CM Alliance) and the retailer makes separate decisions. A CM or RCM Alliance improves environmental benefits and social welfare; a CM Alliance receives higher subsidies, alliance members receive higher profits, and consumers will pay lower actual prices.

(2) The modified Shapley value coordination mechanism can distribute the alliance profits fairly, thus ensuring the long-term stability of the CM alliance. After the classic Shapley value method distributes the profits to CM Alliance members, the profit of both manufacturers and recyclers will increase compared to the situation in which the two operate independently, and both parties will be more willing to choose alliances. Compared to the classic Shapely value, according to
modified Shapley value under unequal rights, the profit of the manufacturer is improved and the profit of the recycler is reduced, but the profit is still greatly increased compared to the No Alliance condition. The modification reflects the advantage of manufacturer’s rights in the alliance (i.e., the critical position) and the dependence of the recycler on this alliance, making up for the impact of the manufacturer’s weak relative willingness on the stability of the alliance. Modified Shapley value profit distribution is more easily accepted by alliance members, especially those who are in a critical rights position.

Future research will consider the following aspects. (1) Multiple competitive supply chains or multi-channel recycling, such as retailer recycling or manufacturer recycling. (2) The company has a profit distribution that limits the situation of alliances, such as multi-step Shapley values with hierarchical utility, while considering the correction of the effects of multiple factors. (3) Recycling quality uncertainty or product quality differences. (4) Demand uncertainty or consumer preferences.

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Appendix A. The solution process of equation (4.7). We use the backward induction method to find the optimal solution. For \( \pi_R \) (equation (4.2)) we have \( d^2 \pi_R / dp^2 = -2 \beta < 0 \); so, \( \pi_R \) is concave in \( p \). Let \( dp_R / dp = 0 \), we obtain \( p = \frac{\alpha - \beta \gamma - \beta \eta}{2 \beta} \). For \( \pi_C \) (equation (4.3)) we have \( d^2 \pi_C / d \tau^2 = -m < 0 \); so, \( \pi_C \) is concave in \( \tau \). Let \( d \pi_C / d \tau = 0 \), we obtain \( \tau = \frac{(b-c) \alpha - \beta \gamma - \beta \eta}{2 \beta} \). Solving the equations of \( p \) and \( \tau \) simultaneously, we obtain \( p = \frac{-\alpha + \beta \gamma - \beta \eta}{2 \beta}, \tau = \frac{-b \alpha - b \beta \gamma - b \beta \eta - c \beta \omega - c \beta \omega}{2m} \).

With substituting this \( p \) and \( \tau \) into equation (4.1), we obtain the manufacturer’s profit \( \pi_M \). In order to guarantee a maximum, Hessian matrix of \( \pi_M \) should be negative definite, so:

\[
H_{\pi_M} = \begin{bmatrix}
\frac{\partial^2 \pi_M}{\partial \eta^2} & \frac{\partial^2 \pi_M}{\partial \eta \partial \omega} \\
\frac{\partial^2 \pi_M}{\partial \omega \partial \eta} & \frac{\partial^2 \pi_M}{\partial \omega^2}
\end{bmatrix}
\]

then \( H_{\pi_M} = \begin{bmatrix}
-2m \beta - (b-c) \beta (b-\Delta) & (b-c) \beta (\alpha - \beta (\eta + \omega)) + \beta (b-\Delta) (\alpha - \beta (\eta + \omega)) \\
(b-c) \beta (\alpha - \beta (\eta + \omega)) + \beta (b-\Delta) (\alpha - \beta (\eta + \omega)) & (\alpha - \beta (\eta + \omega))^2
\end{bmatrix}
\]

when \( H_{\pi_M} < 0 \), \( \eta \) is concave in \( \eta \). Let \( d \pi_C / d \eta = 0 \), we obtain equation (4.7).

The optimal solutions for each variable and the maximum profit for each alliance. To ensure the concaveness of the function, the following values can be obtained: when \( \beta (c-\Delta) (c-2 \gamma - \Delta) + m(-2 + \beta \mu) < 0 \), \( -4m + \beta (c-\Delta)^2 < 0 \), \( \pi_{\text{RM}} \) is a concave function. When \( \beta (c-\Delta) (c-2 \gamma - \Delta) + m(-2 + \beta \mu) < 0 \), \( \pi_{\text{RCM}} \) is a concave function. When \( \beta (c-\Delta) (c-2 \gamma - \Delta) + m(-2 + \beta \mu) > 0 \), \( \pi_{\text{G}} \) is a concave function. When \( \alpha - \beta \gamma - \beta \eta > 0 \), recovery rate \( \tau \in [0,1] \). The optimal solutions for each variable and the maximum profit for each alliance are shown in the Table 3.

Appendix B.

Proof of Theorem 4.1. Based on the value of the previous optimal solution and the concaveness of the function, it is known that \( \beta (c-\Delta) (c-2 \gamma - \Delta) + m(-2 + \beta \mu) < 0 \)

\[
\eta_{\text{CM}} - \eta_{\text{RCM}} = \frac{\beta (c-\Delta) (c-2 \gamma - \Delta) + m(-2 + \beta \mu)}{2m (\alpha - \beta \gamma - \beta \eta)} < 0
\]

\[
\eta_{\text{RCM}} - \eta_{\text{RM}} = \left( \frac{\beta (c-\Delta) (c-2 \gamma - \Delta) + m(-2 + \beta \mu)}{8m (\alpha - \beta \gamma - \beta \eta)} \right) \left( \alpha - \beta \gamma - \beta \eta \right) < 0
\]

\[
\eta_{\text{RM}} - \eta_{\text{RM}} = \beta (3c - 4 \gamma - 3 \Delta) (c-\Delta) + m(-2 + \beta \mu) < 0
\]

Proof of Corollary 1. When \( \frac{2m + (\alpha - \beta \gamma - \beta \eta - \beta (c-\Delta))(c-\Delta)^2}{\beta (c-\Delta)} \leq \eta \), the recovery rate of RCM Alliance \( \tau \leq 1 \). When \( \eta \leq \frac{\alpha}{\beta} - c_n \), the recovery rate of All alliances \( \tau \geq 0 \).

So, let

\[
\eta \in \left[ \frac{2m + (\alpha - \beta \gamma - \beta (c-\Delta))(c-\Delta)^2}{\beta (c-\Delta)}, \frac{\alpha}{\beta} - c_n \right].
\]

(1) When \( \beta \gamma + \beta c_n - \alpha \neq 0 \) (i.e., the government’s penalty \( \eta \neq \frac{\alpha}{\beta} - c_n > 0 \), in the NO Anlliance, the profits of manufacturers (\( \pi_M \)), retailers (\( \pi_R \)) and recyclers...
Table 3. The maximum profit for each alliance

| \(RU/C\) | \(R \cup M\) |
|-----------------|-----------------|
| \(\eta^*\) \(= \frac{(\beta(c-\Delta)(c-\Delta)+4m(1+2\beta)c_\alpha)}{\beta(\beta(c-\Delta)(c-\Delta)+4m(1+2\beta)c_\alpha)}\) | \(= \frac{(\beta(c-\Delta)(c-\Delta)+4m(1+2\beta)c_\alpha)}{\beta(\beta(c-\Delta)(c-\Delta)+4m(1+2\beta)c_\alpha)}\) |
| \(\omega^*\) \(= \frac{2\alpha(\beta(c-\Delta)^2-4m)}{\beta(\beta(c-\Delta)(c-\Delta)+4m(1+2\beta)c_\alpha)}\) | \(= \frac{2\alpha(\beta(c-\Delta)^2-4m)}{\beta(\beta(c-\Delta)(c-\Delta)+4m(1+2\beta)c_\alpha)}\) |
| \(b^*\) \(= \frac{\pi_C}{\omega}\) | \(= \frac{\pi_C}{\omega}\) |
| \(p^*\) \(= \frac{2\alpha(\beta(c-\Delta)^2-4m)}{\beta(\beta(c-\Delta)(c-\Delta)+4m(1+2\beta)c_\alpha)}\) | \(= \frac{2\alpha(\beta(c-\Delta)^2-4m)}{\beta(\beta(c-\Delta)(c-\Delta)+4m(1+2\beta)c_\alpha)}\) |
| \(\tau^*\) \(= \frac{\pi_C}{\omega}\) | \(= \frac{\pi_C}{\omega}\) |
| \(\pi_C^M\) \(= \frac{2m(\alpha+\beta\eta+\beta c_\alpha)}{\beta(\beta(c-\Delta)^2+4m(1+2\beta)c_\alpha)^2}\) | \(= \frac{2m(\alpha+\beta\eta+\beta c_\alpha)}{\beta(\beta(c-\Delta)^2+4m(1+2\beta)c_\alpha)^2}\) |
| \(\pi_C^R\) \(= \frac{4m^2(\alpha+\beta\eta+\beta c_\alpha)}{\beta(\beta(c-\Delta)^2)^2}\) | \(= \frac{4m^2(\alpha+\beta\eta+\beta c_\alpha)}{\beta(\beta(c-\Delta)^2)^2}\) |
| \(\pi_C^\omega\) \(= \frac{m(c-\Delta)^2}{2(\beta(-8m+\beta(c-\Delta)^2)^2)}\) | \(= \frac{m(c-\Delta)^2}{2(\beta(-8m+\beta(c-\Delta)^2)^2)}\) |

\((\pi_C)\) are as follows

\[
\pi_M = \frac{m(-\alpha + \beta\eta+\beta c_n)^2}{\beta(-8m + \beta(c-\Delta)^2)^2}; \quad \pi_R = \frac{4m^2(-\alpha + \beta\eta+\beta c_n)^2}{\beta(-8m + \beta(c-\Delta)^2)^2};
\]

\[
\pi_C = \frac{m(c-\Delta)^2}{2(-8m+\beta(c-\Delta)^2)};
\]

We use the backward induction method to find the optimal solution. Finally, we obtain the optimal solution:

\[
\omega^* = \frac{(4m - \beta(c-\Delta)^2)}{\beta(-8m+\beta(c-\Delta)^2)}; \quad b^* = \frac{c+\Delta}{2};
\]

\[
p^* = \frac{(6m - \beta(c-\Delta)^2)}{\beta(-8m+\beta(c-\Delta)^2)}; \quad \tau^* = \frac{(c-\Delta)(\alpha - \beta\eta - \beta c_n)}{-8m + \beta(c-\Delta)^2};
\]

Then we obtain the optimal profit function, consumer welfare, and environmental benefits.

\[
\pi_M^* = \frac{m(-\alpha + \beta\eta+\beta c_n)^2}{\beta(-8m + \beta(c-\Delta)^2)^2}; \quad \pi_R^* = \frac{4m^2(-\alpha + \beta\eta+\beta c_n)^2}{\beta(-8m + \beta(c-\Delta)^2)^2};
\]

\[
\pi_C^* = \frac{m(c-\Delta)^2}{2(-8m+\beta(c-\Delta)^2)};
\]

\[
\mu C_s^* = \frac{2m^2\mu(-\alpha + \beta\eta+\beta c_n)^2}{(-8m + \beta(c-\Delta)^2)^2}; \quad E^* = \frac{2m\gamma(c-\Delta)(-\alpha + \beta\eta+\beta c_n)^2}{(-8m + \beta(c-\Delta)^2)^2};
\]
Similarly, we can obtain the optimal solution in the case of RC, RM, CM and RCM Alliance. For the comparison of all alliance profits, we obtain

$$\pi^*_{RCM} - \pi^*_{RM} = \frac{m}{\beta(c-\Delta)(\alpha-\beta c_n)} \left( \beta(c-\Delta)^3 + m(-c-12\gamma + 2\Delta + 2\beta(c-\Delta) \mu) \right) > 0$$

$$\pi^*_{RCM} - \pi^*_{RM} = \frac{m}{\beta(c-\Delta)(\alpha-\beta c_n)} \left( \beta(c-\Delta)^3 + m(-c-12\gamma + 2\beta(c-\Delta) \mu) \right) > 0$$

$$\pi^*_{RCM} - \pi^*_{RM} = \frac{m}{\beta(c-\Delta)(\alpha-\beta c_n)} \left( \beta(c-\Delta)^3 + m(-c-12\gamma + 2\beta(c-\Delta) \mu) \right) > 0$$

$$\pi^*_{RCM} - \pi^*_{RM} = \frac{m}{\beta(c-\Delta)(\alpha-\beta c_n)} \left( \beta(c-\Delta)^3 + m(-c-12\gamma + 2\beta(c-\Delta) \mu) \right) > 0$$

For the comparison of consumer welfare, we obtain

$$(\mu C^*)_{RCM} - (\mu C^*)_{RM} = \frac{m^2 \mu(-\alpha+\beta \eta + \beta c_n)^2}{\beta(c-\Delta)^2} - \frac{m^2 \mu(-\alpha+\beta \eta + \beta c_n)^2}{(4m-\beta(c-\Delta)^2)^2} > 0$$

Similarly, based on these optimal solutions, we can obtain all the relationships in the case of alliances or no alliances. The results can be summarized as follows.

a) For the sum of the maximum profit of the supply chain in the case of alliances or no alliances, there are the following relationships: $\pi^*_{RCM} > (\pi^*_{RM} + \pi^* R) > (\pi^* M + \pi^* R + \pi^* c)$

b) For the maximum profit of each alliance in the case of alliances or no alliances, there are the following relationships: $\pi^*_{RCM} > \pi^*_{RM} > \pi^* M > \pi^* R > \pi^* c$

c) For the recovery rate in the case of alliances or no alliances, there are the following relationships: $\tau^*_{RCM} > \tau^*_{RM} > \tau^* c M > \tau^* r M > \tau^* c$

d) For the consumer welfare in the case of alliances or no alliances, there are the following relationships: $\mu C^*_{RCM} > \mu C^*_{RM} > \mu C^* M > \mu C^* R > \mu C^* c$

(2) When $\eta \neq \frac{\alpha}{\beta} - c_n > 0$, we obtain $\pi^*_{RCM} - \pi^*_{RM} = O; (\mu C^*)_{RCM} - (\mu C^*)_{RM} = 0; E^*_{RCM} - E^*_{RM} = 0$. Then we can obtain all the relationships in the case of alliances or no alliances.

---

**Proof of Theorem 4.2.**

$$p \ast_{CM} - p^* = \frac{(c-\Delta)(\alpha-\beta c_n)}{\beta(c-\Delta)^2 + m(-c-12\gamma + 2\beta(c-\Delta) \mu)} > 0$$

$$p \ast - p^*_{RCM} = \frac{(c-\Delta)(\alpha-\beta c_n)}{(3\beta(c-\Delta)(c-2\gamma - \Delta + m(-2\beta + \mu)))((3\beta(c-\Delta)(c-2\gamma - \Delta + m(-2\beta + \mu))) > 0$$

$$p \ast - p^*_{RM} = \frac{m}{\beta(c-\Delta)(\alpha-\beta c_n)} \left( \beta(c-\Delta)^3 + m(-c-12\gamma + 2\beta(c-\Delta) \mu) \right) > 0$$

$$\omega \ast_{CM} - \omega^* = \frac{(c-\Delta)(\alpha-\beta c_n)}{(3\beta(c-\Delta)(c-2\gamma - \Delta + m(-2\beta + \mu)))((3\beta(c-\Delta)(c-2\gamma - \Delta + m(-2\beta + \mu))) > 0$$

---

**Proof of Theorem 4.3.**

$$\tau \ast_{RCM} - \tau^* = \frac{(c-\Delta)(\alpha-\beta c_n)}{\beta(c-\Delta)^2 + m(-c-12\gamma + 2\beta(c-\Delta) \mu)} > 0$$

---

**Proof of Theorem 4.4.**

$$\pi^*_{g_{RCM}} - \pi^*_{g} = \frac{m(-c-\Delta)(\alpha-\beta c_n)^2}{\beta(c-\Delta)^2 + m(-c-12\gamma + 2\beta(c-\Delta) \mu)} > 0$$

---

**Proof of Theorem 4.5.**

$$\pi^*_{CM} - \pi^*_{RCM} = \frac{m^2(\alpha-\beta c_n)^2}{\beta(3\beta(c-\Delta)^2 + m(-2\beta + \mu))} > 0$$

$$\pi^*_{RCM} - \pi^*_{M} = \frac{m(\alpha-\beta c_n)^2}{\beta(3\beta(c-\Delta)^2 + m(-2\beta + \mu))} > 0$$

$$\pi^*_{M} - \pi^*_{RC} = \frac{m(\alpha-\beta c_n)^2}{\beta(3\beta(c-\Delta)^2 + m(-2\beta + \mu))} > 0$$

$$\pi^*_{RC} = \pi^*_{R} + \pi^* C$$
Table 4. Calculation of the Shapley value of the retailer

| s       | R      | R ∪ C   | R ∪ M   | R ∪ C ∪ M |
|---------|--------|---------|---------|-----------|
| v(s)    | πr3   | πr3 + πc3 | πrm4   | πrcm7  |
| v(s/i)  | 0      | πc3     | πm3     | πcm5   |
| | | | | |
| | | | | |

\[ \omega([s]) = \frac{\pi^{\star}}{3} \frac{\pi c3}{6} \frac{\pi m4}{6} \frac{\pi cm7 - \pi cm5}{3} \]

Retailer's Shapley value distribution

\[
\frac{m^2(c - \Delta)(c - 4\Delta)(\beta(7c - 12\gamma - 7\Delta)(c - \Delta) + 8m(2 + \beta \mu))(c - \Delta)6(2 + \beta \mu)}{3(\beta(3c - 4\gamma - 3\Delta)(c - \Delta) + 4m(2 + \beta \mu))^2} > 0
\]

\[
\pi^* R - \pi^* RM = \frac{4m^2(c - \Delta)^2(\alpha - \beta \gamma)^2}{(\beta(3c - 4\gamma - 3\Delta)(c - \Delta) + 4m(2 + \beta \mu))^2} > 0
\]

\[
\pi^* RM - \pi^* C = \frac{2m(8m - 3\beta(c - \Delta)^2)(\alpha - \beta \gamma)^2}{\beta(3c - 4\gamma - 3\Delta)(c - \Delta) + 4m(2 + \beta \mu))^2} > 0
\]

**Proof of Theorem 4.6.** In the range of values of \( m \) and \( \gamma \), we can obtain by calculation:

\[
\frac{\partial \pi^* R}{\partial m} > 0, \frac{\partial \omega}{\partial m} < 0, \frac{\partial \pi^* R}{\partial \gamma} < 0, \frac{\partial \pi^* M}{\partial m} > 0, \frac{\partial \pi^*}{\partial m} < 0, \frac{\partial \pi^* C}{\partial m} < 0, \frac{\partial \pi^* M}{\partial \gamma} > 0, \frac{\partial \pi^*}{\partial \gamma} < 0; \]

\[
\frac{\partial \pi^* R}{\partial \gamma} < 0, \frac{\partial \omega}{\partial \gamma} > 0, \frac{\partial \pi^* R}{\partial \gamma} > 0, \frac{\partial \pi^* M}{\partial \gamma} > 0, \frac{\partial \pi^*}{\partial \gamma} > 0, \frac{\partial \pi^* C}{\partial \gamma} > 0, \frac{\partial \pi^* M}{\partial \gamma} > 0, \frac{\partial \pi^*}{\partial \gamma} > 0
\]

**The basis for this step that we use the classic Shapley value.** If the classic Shapley value is to be used, then this interest activity should be non-confrontational, that is, the increase in the number of people in the cooperation will not lead to a reduction in benefits, so that the cooperation of all individuals will bring the greatest benefit. If \( x_i \) is used to represent the income that member \( i \) in \( I \) should receive from the maximum benefit \( v(I) \) of the cooperation. Obviously, the success of this cooperation must meet the following conditions.

\[
\sum_{i=1}^{n} x_i = v(I) \quad i = 1, 2, 3, \ldots, n
\]

Based on this, it is explained from the perspective of Shapley value that retailer R will not participate in the alliance. If the retailer participates in the alliance, its Shapley value is shown in Table 4.

When the retailer joins the alliance, the Shapley value distribution profit is reduced compared to the profit when operating separately, and their difference is:

\[
\frac{m^2(c - \Delta)(c - 4\Delta)(\beta(7c - 12\gamma - 7\Delta)(c - \Delta) + 8m(2 + \beta \mu))(c - \Delta)6(2 + \beta \mu)}{3(\beta(3c - 4\gamma - 3\Delta)(c - \Delta) + 4m(2 + \beta \mu))^2} - \frac{16m^2(a - 3\Delta)^2}{\beta(3c - 4\gamma - 3\Delta)(c - \Delta) + 4m(2 + \beta \mu))^2} - \frac{m^2(a - \Delta)(c - 4\Delta)(\beta(7c - 12\gamma - 7\Delta)(c - \Delta) + 8m(2 + \beta \mu))(c - \Delta)6(2 + \beta \mu)}{3(\beta(3c - 4\gamma - 3\Delta)(c - \Delta) + 4m(2 + \beta \mu))^2} > 0
\]

**Proof of Theorem 5.1.** Based on the value of the previous optimal solution and the concaveness of the function, the calculation shows that:
\[ \frac{\pi_{CM} - \pi_C^* + \pi_C^*}{\pi_M^*} = \frac{\pi_{CM} - \pi_C^* + \pi_C^*}{\pi_M^*} = \frac{m(\alpha - \beta c_n)^2}{4\beta} \left( \frac{4m - \beta(c - \Delta)^2}{(\beta(c - \Delta)(c - 2\gamma - \Delta) + m(-2 + \beta \mu)^2} \right) > 0. \]

In addition, the situation of the recycler and the manufacturer is similar and positive, and will not be described here. Therefore, retailers will not choose to join the alliance, even if the total profit of the alliance (such as the RCM Alliance) is higher than the sum of the individual profits of the individual operations, but this is the result of cooperation between the recycler and the manufacturer. The addition of the retailer will reduce the profit of the CM Alliance, and its marginal contribution is negative, so the above retailer’s profit difference is negative, which is reasonable. According to Theorem 1 and Theorem 5, we know that the CM alliance profits formed by recyclers and manufacturers are optimal, and then they do not want retailers to join. Here, from the perspective of Shapley value, we also know that retailers will not form alliances with recyclers and manufacturers. In short, based on the position of personal reason, we can know the actual situation of alliance formation: the alliance that can be formed by recycler C is C or CM, and there is no RC or RCM; similarly, the alliance that manufacturer M can form is M, CM. Based on this, we use the classical Shapley value method.

Proof of Theorem 5.2. Known as \( t_1 > t_2 \), that is \( \left( \frac{t_1}{t_1 + t_2} - \frac{1}{2} \right) \cdot \epsilon \cdot \pi_{CM}^* > 0 \), and \( \left( \frac{t_2}{t_1 + t_2} - \frac{1}{2} \right) \cdot \epsilon \cdot \pi_{CM}^* < 0 \), so,

\[ \phi_i^*(v) = \phi_i(v)_C - \left( \frac{t_1}{t_1 + t_2} - \frac{1}{2} \right) \cdot \epsilon \cdot \pi_{CM}^* < \phi_i(v)_C \quad \phi_i^*(v)_M = \phi_i(v)_M - \left( \frac{t_2}{t_1 + t_2} - \frac{1}{2} \right) \cdot \epsilon \cdot \pi_{CM}^* > \phi_i(v)_C \]

Appendix C. An introduction to the background of Chongqing in the numerical analysis section. The two CDW recycling plants were completed and put into use in 2014. The annual disposal capacity of CDW recycling in Yubei District is 800,000 tons, and that in Nan’an District is 600,000 tons. Taking recycled concrete bricks as an example, the economic cost (including labor, fuel, equipment, etc.) of using new materials to produce approximately 1.9 million square meters of concrete bricks is approximately 428.3 million yuan, and if we recycle 1.5 million tons of CDW (including collection and transportation, pretreatment, product remanufacturing, residual material processing, etc.) the cost to produce this amount is 342.98 million yuan. In terms of environmental benefits, the environmental costs (including energy consumption, emissions management, etc.) for the production of concrete bricks using new materials and waste remanufacturing are approximately 221.43 million yuan and 131.83 million yuan; therefore, resource-based activities can bring a positive environmental benefit of 89.6 million yuan. The above data are only summary data. Regarding the detailed data, the economic cost of 342.98 million yuan includes 18.79 million yuan for pretreatment, 321.98 million yuan for remanufacturing, and 2.21 million yuan for residual material processing. The transportation distance, entrance fee, price of recycled building materials and other parameters can be obtained from the policy documents and cost information issued by the Chongqing Municipal Government. Based on the example of Chongqing, the model of this study was applied to carry out numerical simulations of the optimal
alliance strategy for CDW recycling enterprises. The processing volume (demand), cost, and environmental benefits in the survey data were unitized.

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