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DOI: 10.2478/eces-2023-0050 ECOL CHEM ENG S. 2023;30(4):595-615

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RECYCLING STRATEGY OF GREEN CLOSED-LOOP SUPPLY CHAIN UNDER URBAN AND RURAL LOW-CARBON PLANNING

Abstract: The low-carbon ecological city aims to harmonise sustainable urban development with low-emission planning approaches. Emissions from business production processes are central to low-carbon planning. This paper explores three closed-loop supply chain recycling models - manufacturer, retailer, and third-party - considering carbon trading and emission reduction technology investment. Respective Stackelberg game models are developed incorporating carbon emission reduction costs, recycling costs, carbon trading price, emission intensity, and recycling price. The influence of these variables on carbon emission reduction and profit is examined through numerical analysis. Results indicate the government's free carbon quota does not impact per-unit carbon reduction or manufacturer profit, nor optimal recycling mode selection. Under specific remanufacturing emission intensity and production cost saving conditions, carbon quota trading can substantially incentivise manufacturers to invest in emission reduction and recycling. With carbon trading and emission reduction technology investment, manufacturer recycling optimises economic and environmental benefits when remanufactured products provide high production cost savings. This fosters sustainable development supporting low-carbon planning.

Keywords: urban-rural low-carbon planning, carbon trading mechanisms, remanufacturing recycling, sustainable development, Stackelberg game

Introduction

The Five-Sphere Integrated Plan emphasises the importance of ecological progress in urban and rural areas, as well as economic, political, cultural, and social development. China's Guangdong Province practices this spirit of urban and rural development and has become a model province for low-carbon ecological urban planning [1-3]. With the initiation of China's significant decision to robustly develop remanufacturing, as outlined in 'Made in China 2025', enterprises are urged to focus not only on the production and sales within the forward supply chain, but also on the recycling and remanufacturing aspects of the reverse supply chain. The goal is to achieve sustainable development characterised by low energy consumption and low emissions, a substantial undertaking in the context of urban and rural low-carbon planning [4-6].

Several manufacturing enterprises, including Xiaomi, IBM, and Apple, have begun to invest in remanufacturing and low-carbon production, aspiring to establish their own green, closed-loop supply chain models [7]. From an environmental resource's perspective,

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remanufactured products significantly reduce costs, material use, and energy consumption, and lessen waste emissions and pollution compared to new products [8].

Currently, major corporations are actively developing cost-effective and efficient recycling channels. BMW, for instance, has set up a waste recycling warehouse in Munich; retailers recycle used wine bottles; and third-party recycling companies, like Air Recycling, assist businesses in recycling waste products, with all of these methods achieving impressive recycling efficiency. At present, urban and rural low-carbon policies can be categorised into four types based on relevant policies issued by various countries and scholarly research: carbon quota trading, carbon tax, carbon subsidy, and carbon penalty [9]. Carbon trading policy, one of the low-carbon initiatives that the National Education Commission significantly emphasises, encourages, promotes, and widely applies, has been proven by some scholars to play a critical role in achieving carbon emission reduction goals. The research shows that carbon emission trading brings more flexibility to manufacturing enterprises and enables enterprises to increase their profits [10].

In the context of the current stage of green and sustainable development, low-carbon city construction and planning is a top priority. A key practical issue at present is how enterprises can make recycling, remanufacturing, and carbon emission reduction decisions under the carbon trading policy. Thus, studying more efficient and greener closed-loop supply chain recycling modes is of immense significance [11].

In fact, the recycling and remanufacturing of waste products represent significant components of a green, closed-loop supply chain. Studying the impact of competition between manufacturers and retailers on recycling rates found that competition can reduce recycling rates [12]. Applying the Stackelberg game model to their study, it considers not only traditional recycling models, but also online recyclers for mixed-channel recycling, with the aim of improving recycling and remanufacturing efficiency [13]. The Stackelberg leader-follower game model is leveraged to shape the government as the leader, with manufacturers, remanufacturers, and recyclers as followers. They concluded that government subsidies can incentivise recycling and remanufacturing, and that remanufacturing costs influence closed-loop supply chain decisions [14, 15]. Study the impact of information sharing on multi-tier supply chain indices to generate different levels of performance [16, 17].

Some papers have also considered the impact of carbon trading policies on the closed-loop supply chain. For example, considering the carbon emission cost of the supply chain, it is found that carbon price is negatively correlated with the total cost of emission reduction, while carbon allowances are directly proportional to carbon emissions [18]. There are also studies that examine the impact of carbon trading mechanisms and carbon taxes on corporate decision-making in the current global economic and environmental context. They found that, especially when implementing carbon tax systems, volatile carbon trading prices were more conducive to the expected profits of the supply chain than stable carbon trading prices [19]. The same study found that carbon trading mechanisms are effective in the long term in the current global economic and environmental context. In particular, the adoption of a carbon tax system will affect the overall profits of the supply chain [20]. Therefore, in a carbon trading environment, raising the price of carbon trading will reduce the total carbon emissions of the supply chain [21]. In the study of resource coordination and production scheduling optimisation mechanism of manufacturing enterprises, the impact of manufacturers' emission reduction decisions and closed-loop supply chain profits is considered [22, 23]. In addition, some scholars have studied

low-carbon strategies from the perspective of ecological environment [24] and the important role of low-carbon landscapes in rural development [25], illustrating the importance of low-carbon development in urban and rural areas.

A review of the existing literature reveals gaps in research that also considers policies for carbon reduction technology implementation, recycling, remanufacturing, and carbon trading [26], as well as the role of factors such as information and social media [27]. Therefore, this paper classifies the methods used by manufacturers to obtain carbon reduction rights as: free carbon allowances granted by the government, carbon emissions after the application of carbon reduction technologies by manufacturers, and carbon emission rights obtained from the carbon trading market. These methods are used in the Stackelberg game [28].

This paper combines carbon trading cost, carbon emission reduction technology implementation cost and waste recycling and remanufacturing cost, compares various recycling modes, conducts numerical simulation analysis, and examines the impact of carbon trading price, carbon emission intensity, waste recycling price and unit production cost saving on the environment and economy. The purpose of the study is to provide a theoretical basis for the government to improve the carbon trading policy. In addition, it provides a reference model for urban and rural planning to build a green closed-loop supply chain, further promote sustainable development, and support low-carbon urban and rural planning.

Problem description and research hypothesis

Parameter symbol

This article uses the following parameters to illustrate the research question:

α - represents the largest market demand,

β - represents price sensitivity coefficient,

γ - the carbon emission intensity of unit remanufactured products before carbon emission reduction ($0 \le \gamma \le 1$),

Δ - the units production cost saved for remanufacturing,

θ_j - the recovery rate of waste products of participant j in each recycling mode of closed-loop supply chain ($0 \le \theta_j \le 1$),

λ - represents the cost factor of emission reduction,

π_j^i - for i recycling mode of participation main body j profits, among them, $i \in (1,2,3)$ is M, R, T recovery mode. $j \in (1,2,3)$ are manufacturers, retailers, third party recyclers three supply chain participants,

τ - represents the carbon emission reduction per unit product,

b - represents the unit recovery price of waste products recovered from consumers,

C_L - the cost factor of recovery activities,

C_n - the units production cost of the new product,

C_r - the units production cost of the remanufactured product,

D - the product demand in the market,

e - the carbon emission per unit of new products before carbon emission reduction,

e_g - the total amount of free carbon quota,

f - represents the unit recovery price of waste products recovered by the manufacturer through indirect recycling,

p - retail prices for new and remanufactured products,

p_c - the market trading price of carbon emission rights,

w - wholesale prices for new and remanufactured products.

Problem description

In this study, we construct three distinct closed-loop supply chain recycling models, as illustrated in Figures 1-3. The solid line represents the forward supply chain, which extends from manufacturers to retailers to consumers, while the dotted line signifies the reverse supply chain. The recycling agent and channel differ across the various recycling modes. In these configurations, manufacturers must consider aspects such as the carbon trading market mechanism, the free carbon quota provided by the government, and their independent investments in carbon emission reduction. The analysis is conducted with manufacturers positioned as leaders and retailers and third-party recyclers as followers.

Model 1: In this mode, the reverse supply chain sees the manufacturer directly recovering waste products from consumers at a price denoted as b. In alignment with China's urban and rural low-carbon planning policy, the manufacturer allocates a specific amount of funds towards the research and development of carbon emission reduction technology, engages in carbon emissions trading within the carbon trading market, and benefits from the carbon emissions quota allotted by the government. This configuration is referred to as the M mode (Fig. 1).

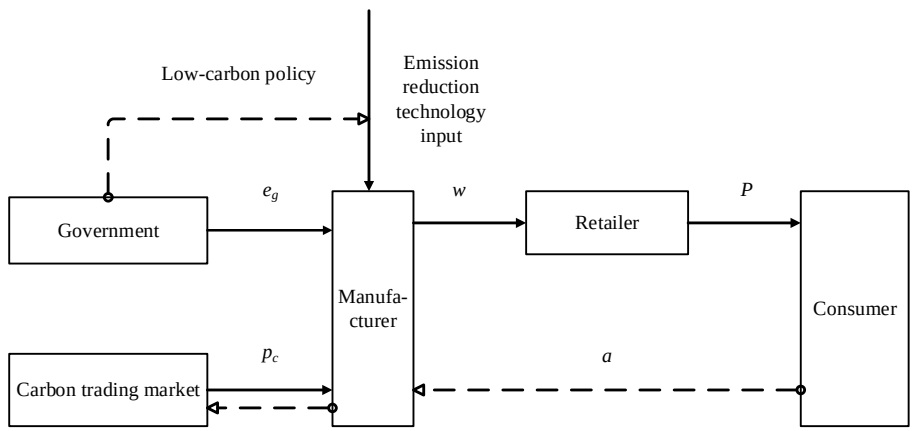


Fig. 1. Manufacturer recycling mode (M mode)

Model 2: In this configuration, the reverse supply chain acquires waste products from consumers at a price denoted as b, and subsequently resells them to manufacturers at a price f for remanufacturing. Concurrently, in accordance with China's urban and rural low-carbon planning policy, manufacturers invest a specific sum of money towards the research and development of carbon emission reduction technology, participate in carbon

emissions trading within the carbon trading market, and receive the carbon emissions quota distributed by the government. This arrangement is referred to as the *R* mode (Fig. 2).

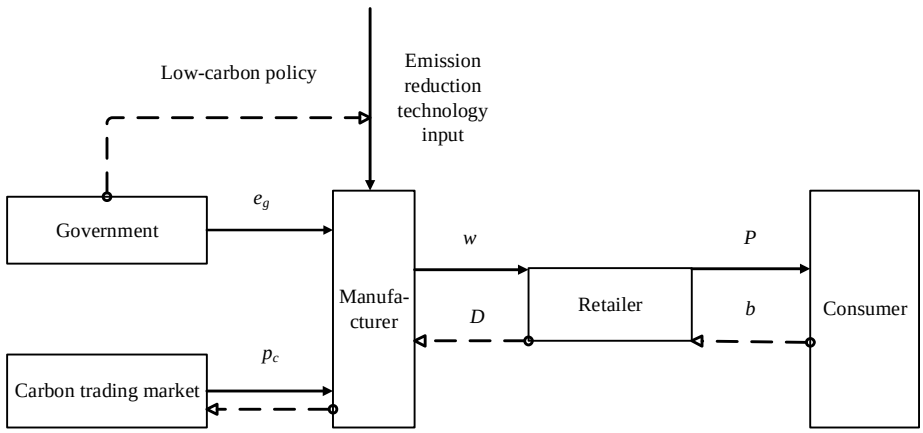


Fig. 2. Retailer recycling mode (*R* mode)

Model 3: In this approach, the reverse supply chain obtains waste products from consumers at a price marked as *b*, then resells these items to the manufacturer at a price indicated as *f* for remanufacturing. Concurrently, in alignment with China's urban and rural low-carbon planning policy, the manufacturer invests a certain amount of funds in research and development of carbon emission reduction technology, trades carbon emission rights within the carbon trading market, and benefits from the carbon emission quota provided by the government. This configuration is termed the *T* mode (Fig. 3).

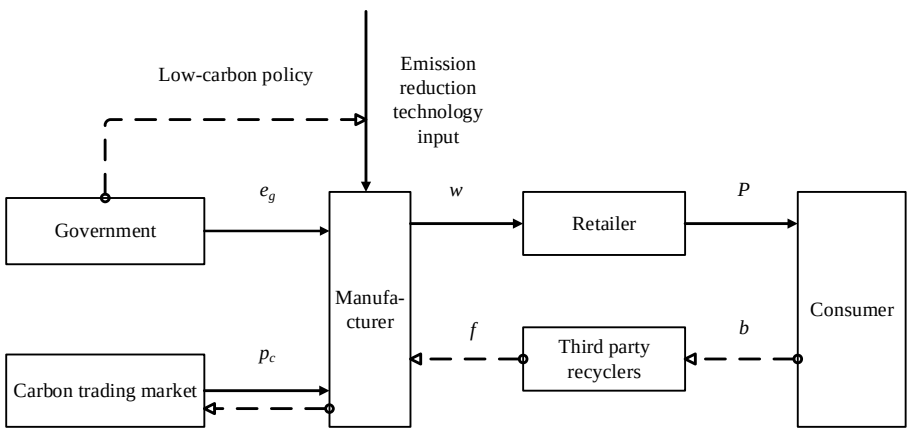


Fig. 3. Recycling mode of third-party recyclers (*T* mode)

Research hypothesis

(1) We assume that new products and remanufactured products share identical information, including quality, appearance, performance, and price, rendering consumers unable to distinguish between the two. This study posits that every component of internal and external waste products must be disassembled and recycled, and these functional parts should be repurposed in the manufacture of new products. The remanufacturing process strictly adheres to the original design and international standards, thereby ensuring that remanufactured products are not considered 'second-hand goods', but rather brand-new products. This eliminates consideration for repairing or refurbishing waste products. Consequently, new products and remanufactured products can seamlessly substitute for each other. Market demand is treated as a linear function of price, $D = \alpha - \beta p$, $\alpha, \beta > 0$, and $\alpha > \beta p$.

(2) We assume that the research environment consists of a singular manufacturer, a single retailer, and a single third-party recycler. Each stakeholder has no competitors and operates under complete rationality.

(3) We assume that all recycled waste products retain their utility and can be remanufactured. The costs and carbon emissions associated with producing remanufactured products are lower than those of new products, implying that the difference, that is $\Delta = C_n - C_r > 0$, and the price of recycling from consumers is lower than the price of recycling from retailers, that is $f > b$.

(4) It is assumed that all entities engaged in recycling bear certain costs for the process, which include expenditures related to establishing channels and advertising. Therefore, we assume that the total cost associated with recycling waste products (excluding the cost of waste product recycling) is denoted by $C_{(L)} = C_L \theta_j^2$.

(5) It is assumed that only the carbon emissions from the manufacturer's production process are considered in the study, excluding those from the recycling process. Thus, with the implementation of a carbon emission reduction policy, the carbon emissions from manufacturing each unit of a new product is $e - \tau$, while the carbon emissions from the remanufactured product amount to $\gamma e - \tau$.

(6) If the manufacturer's carbon emissions fall below the carbon allowance, the surplus can be sold to generate additional revenue. Conversely, if the manufacturer's emissions exceed the carbon quota, the manufacturer must procure additional carbon credits from the trading market. The free carbon allowance is strictly limited to use within a single cycle and cannot be carried over to the next cycle.

(7) Drawing from existing research, it's been concluded that the cost of the manufacturer's carbon emissions reduction technology increases convexly in relation to the reduction of emissions per unit of product. Therefore, this paper postulates that the cost function for carbon emissions reduction is $C_{(\tau)} = \frac{1}{2}\lambda\tau^2$ ($0 < \tau < e$), When the emission reduction τ tends to e, the cost of carbon emission reduction will be very large.

Model development and solution

Stackelberg game

The Stackelberg game is a two-stage fully informational dynamic game, and the time of the game is sequential. The main idea is that both parties choose their own strategy according to the other party's possible strategy to ensure that their interests under the other party's strategy are maximised, so as to achieve Nash equilibrium.

M recovery mode

In the *M* mode, a two-stage dynamic game is solved using the backward induction method. The manufacturer first sets the wholesale price for new and remanufactured products, establishes the waste product recovery rate, and determines the carbon reduction capacity per unit of product. Subsequently, the retailer sets the retail price, given the optimal wholesale price and level of emission reduction. In this mode, the profit functions for both the manufacturer and the retailer are as follows:

$$\begin{aligned}\max \pi_1^1 &= (w - C_n)D + (\Delta - b)D\theta_1 - C_L\theta_1^2 - \frac{1}{2}\lambda\tau^2 \\ &+ e_g p_c - D(1-\theta_1)(e-\tau)p_c - D\theta_1(\gamma e - \tau)p_c\end{aligned} \tag{1}$$

$$\max \pi_2^1 = (p - w)D \tag{2}$$

In the second stage of the game, we compute the second partial derivative of π_2^1 with respect to p, $\frac{\partial^2 \pi_2^1}{\partial p^2} = -2\beta < 0$. Substituting $D = \alpha - \beta p$ into equation (2), we then calculate the first partial derivative of π_2^1 with respect to p and set it equal to zero, that is $\frac{\partial \pi_2^1}{\partial p} = 0$. Following this, the optimal retail price p for the products can be determined as follows:

$$p = \frac{\alpha + \beta w}{2\beta} \tag{3}$$

Transitioning to the first stage of the game, we substitute p into equation (1). The Hessian matrix of π_2^1 with respect to the product wholesale price w and carbon emission reduction per unit product τ is given by:

$$H(\pi_1^1) = \begin{pmatrix} \frac{\partial^2 \pi_2^1}{\partial w^2} & \frac{\partial^2 \pi_2^1}{\partial w \tau} \\ \frac{\partial^2 \pi_2^1}{\partial \tau w} & \frac{\partial^2 \pi_2^1}{\partial \tau^2} \end{pmatrix} = \begin{pmatrix} -\beta & -\frac{pc\beta}{2} \\ -\frac{pc\beta}{2} & -\lambda \end{pmatrix} \tag{4}$$

Given that $-\beta < 0$, and when the beta lambda $\beta\lambda - \frac{pc^2\beta^2}{4} > 0$, we have a negative definite matrix, indicating that π_1^1 is a strictly concave function of w, τ. This ensures the existence of optimal values for the product's wholesale price w and carbon emissions per unit product τ that maximises π_1^1 to obtain the optimal solution, the w, τ, first order partial

derivatives, and makes it equal to zero. Specifically, we have $\frac{\partial \pi_1^1}{\partial w}=0$, $\frac{\partial \pi_1^1}{\partial \tau}=0$, $\frac{\partial \pi_1^1}{\partial \theta_1}=0$. Solving these equations simultaneously, we obtain the optimal values for the product wholesale price *w*, carbon emissions per unit product τ and recovery rate θ_1 respectively:.

$$w=\frac{\alpha}{\beta}+\frac{4C_L\lambda(\beta C_n+p_c\beta e-\alpha)}{8C_L\lambda\beta-\beta^2\lambda[\Delta-b+p_ce(1-\gamma)]^2-2C_L{p_c}^2\beta^2} \tag{5}$$

$$\tau=\frac{2C_Lp_c(\alpha-\beta C_n-p_c\beta e)}{8C_L\lambda-\beta\lambda[\Delta-b+p_ce(1-\gamma)]^2-2C_L{p_c}^2\beta} \tag{6}$$

$$\theta_1=\frac{\lambda(\alpha-\beta C_n-p_c\beta e)[\Delta-b+p_ce(1-\gamma)]}{8C_L\lambda-\beta\lambda[\Delta-b+p_ce(1-\gamma)]^2-2C_L{p_c}^2\beta} \tag{7}$$

Substituting the above optimal solutions into equation (3), we can derive the optimal retail price set by the retailer:

$$p=\frac{\alpha}{\beta}+\frac{2C_L\lambda(\beta C_n+p_c\beta e-\alpha)}{8C_L\lambda\beta-\beta^2\lambda[\Delta-b+p_ce(1-\gamma)]^2-2C_L{p_c}^2\beta^2} \tag{8}$$

Ultimately, by plugging the above optimal solutions into the profit function equations (1) and (2) for each supply chain participant, the expressions for π_1^1 and π_2^1 can be formulated as follows:

$$\pi_1^1=\frac{C_L\lambda(\alpha-\beta C_n-p_c\beta e)^2}{8C_L\beta\lambda-\beta^2\lambda[\Delta-b+p_ce(1-\gamma)]^2-2C_L{p_c}^2\beta^2}+e_gp_c \tag{9}$$

$$\pi_2^1=\frac{4{C_L}^2\lambda^2(\alpha-\beta C_n-p_c\beta e)^2}{\beta\{8C_L\lambda-\beta\lambda[\Delta-b+p_ce(1-\gamma)]^2-2C_L{p_c}^2\beta\}} \tag{10}$$

Lemma 1: Under the manufacturer's recycling model:

(1) $\frac{\partial p}{\partial\lambda}>0$, $\frac{\partial w}{\partial\lambda}>0$, $\frac{\partial\tau}{\partial\lambda}<0$, $\frac{\partial\theta_1}{\partial\lambda}<0$, $\frac{\partial\pi_j^1}{\partial\lambda}<0$.

(2) $\frac{\partial p}{\partial C_L}>0$, $\frac{\partial w}{\partial C_L}>0$, $\frac{\partial\tau}{\partial C_L}<0$, $\frac{\partial\theta_1}{\partial C_L}<0$, $\frac{\partial\pi_j^1}{\partial C_L}<0$.

(3) $\frac{\partial p}{\partial\Delta}<0$, $\frac{\partial w}{\partial\Delta}<0$, $\frac{\partial\tau}{\partial\Delta}>0$, $\frac{\partial\theta_1}{\partial\Delta}>0$, $\frac{\partial\pi_j^1}{\partial\Delta}>0$.

(4) $\frac{\partial p}{\partial\gamma}>0$, $\frac{\partial w}{\partial\gamma}>0$, $\frac{\partial\tau}{\partial\gamma}<0$, $\frac{\partial\theta_1}{\partial\gamma}<0$, $\frac{\partial\pi_j^1}{\partial\gamma}<0$.

(5) $\frac{\partial p}{\partial b}>0$, $\frac{\partial w}{\partial b}>0$, $\frac{\partial\tau}{\partial b}<0$, $\frac{\partial\theta_1}{\partial b}<0$, $\frac{\partial\pi_j^1}{\partial b}<0$.

Lemma 1 delineates the impact of carbon-related and recycling and remanufacturing-related coefficients on optimal decision-making and profit, as follows:

(1) The recycling rate of waste products and the carbon emission reduction per unit product, both set by manufacturers, decrease as the carbon emission reduction cost factor increases. A higher cost factor indicates that executing the carbon emission reduction policy would necessitate a larger investment. Consequently, this results in an

increase in both wholesale and retail prices, a decrease in demand, and a reduction in profits for both manufacturers and retailers.

(2) Both the waste product recycling rate and the carbon emission reduction per unit product, as determined by the manufacturer, decrease as the recycling cost coefficient increases. An increase in recycling cost consequently reduces profit.

(3) The greater the unit production cost saved by remanufactured products in comparison to new products, the more manufacturers and retailers are inclined towards recycling and remanufacturing. Furthermore, an increase in remanufactured products can enhance carbon emission reduction. If manufacturers continually improve their remanufacturing capacity and technology, they can attain higher profits and further carbon emission reduction.

(4) The lower the emission intensity of remanufactured products compared to new products, the more favourable it is to recycle waste products and increase carbon emission reduction. Moreover, lower carbon emissions contribute to environmentally sustainable development.

(5) The higher the per-unit recovery price of waste products from consumers, the lower the recovery rate of waste products becomes, consequently increasing the cost for manufacturers.

R recovery mode

In R mode, we use the backward induction method to solve the two-stage dynamic game. Initially, the manufacturer determines the wholesale price of both new and remanufactured products, as well as the carbon reduction capacity per unit product. Subsequently, upon gaining knowledge of the optimal wholesale price w and carbon reduction capacity τ, the retail price p of the corresponding products and the waste product recovery rate θ_2. Within this mode, the profit functions for the manufacturer and retailer are as follows:

$$\begin{aligned}\max \pi_1^2 &= (w - C_n)D + (\Delta - f)D\theta_2 - \frac{1}{2}\lambda\tau^2 \\ &+ e_g p_c - D(1-\theta_2)(e-\tau)p_c - D\theta_2(\gamma e - \tau)p_c\end{aligned} \tag{11}$$

$$\max \pi_2^2 = (p - w)D + (f - b)D\theta_2 - C_L\theta_2^{\,2} \tag{12}$$

At the second stage in the game, first of all ask π_2^2 on p and θ_2 second order partial derivatives, and $D = \alpha - \beta p$ plug type (12), have π_2^2 Hessian matrix of the:

$$H(\pi_2^2) = \begin{pmatrix} \dfrac{\partial^2 \pi_2^2}{\partial p^2} & \dfrac{\partial^2 \pi_2^2}{\partial p \theta_2} \\ \dfrac{\partial^2 \pi_2^2}{\partial \theta_2 p} & \dfrac{\partial^2 \pi_2^2}{\partial \theta_2^{\,2}} \end{pmatrix} = \begin{pmatrix} -2\beta & -(f-b)\beta \\ -(f-b)\beta & -2C_L \end{pmatrix} \tag{13}$$

Because $-\beta < 0$, and when $4\beta C_L - (f-b)^2\beta^2 > 0$, shows the negative definite matrix, namely the existence of optimal p and θ_2 make π_2^2 to obtain the optimal solution.

Applying the method of backward induction, we calculate the first partial derivatives of π_2^2 on p and θ_2 respectively, and equate them to zero. That is, we solve for, $\frac{\partial \pi_2^2}{\partial p}=0$, $\frac{\partial \pi_2^2}{\partial \theta_2}=0$. This gives us the optimal retail price p and recovery rate θ_2 for both new and remanufactured products, which are obtained as follows:

$$p=\frac{\alpha(2C_L-(f-b)^2\beta+2\beta C_L w)}{\beta(4C_L-(f-b)^2\beta)} \tag{14}$$

$$\theta_2=\frac{(f-b)(\alpha-\beta w)}{4C_L-(f-b)^2\beta} \tag{15}$$

In the first stage of the game, similarly, we substitute the previously derived values of p and θ_2 into π_1^2. We then compute the first-order partial derivatives of π_1^2, with respect to w, τ and set them equal to zero. That is, we solve $\frac{\partial \pi_1^2}{\partial w}=0$, $\frac{\partial \pi_1^2}{\partial \tau}=0$. This process yields the unique optimal solutions for the product wholesale price w and the carbon reduction capacity of the unit product τ which are as follows:

$$w=\frac{\alpha}{\beta}+\frac{\lambda[4C_L-(\mathrm{f}-b)^2\beta](\beta C_n+p_c\beta e-\alpha)}{8C_L\lambda\beta-2\beta^2\lambda(\mathrm{f}-b)[\Delta-b+p_c e(1-\gamma)]-2C_L{p_c}^2\beta^2} \tag{16}$$

$$\tau=\frac{C_L p_c(\alpha-\beta C_n-p_c\beta e)}{4C_L\lambda-\beta\lambda(\mathrm{f}-b)[\Delta-b+p_c e(1-\gamma)]-C_L{p_c}^2\beta} \tag{17}$$

After substituting the derived values for w, τ into equations (14) and (15), we can obtain the optimal retail price p and recovery rate θ_2 can be obtained as follows:

$$p=\frac{\alpha}{\beta}+\frac{\lambda C_L(\beta C_n+p_c\beta e-\alpha)}{4C_L\lambda\beta-\beta^2\lambda(\mathrm{f}-b)[\Delta-b+p_c e(1-\gamma)]-C_L{p_c}^2\beta^2} \tag{18}$$

$$\theta_2=\frac{\lambda(\mathrm{f}-b)(\alpha-\beta C_n-p_c\beta e)}{8C_L\lambda-2\beta\lambda(\mathrm{f}-b)[\Delta-b+p_c e(1-\gamma)]-2C_L{p_c}^2\beta} \tag{19}$$

Lastly, by incorporating the aforementioned optimal solutions into the profit function equations (11) and (12) for each supply chain participant, the expressions for π_1^2 and π_2^2 can be derived as follows:

$$\pi_1^2=\frac{\lambda C_L(\alpha-\beta C_n-p_c\beta e)^2}{8C_L\lambda\beta-2\beta^2\lambda(\mathrm{f}-b)[\Delta-b+p_c e(1-\gamma)]-2C_L{p_c}^2\beta^2}+e_g p_c \tag{20}$$

$$\pi_2^2=\frac{\lambda^2 C_L[4C_L-(\mathrm{f}-b)^2\beta](\alpha-\beta C_n-p_c\beta e)^2}{\beta\{8C_L\lambda-2\beta\lambda(\mathrm{f}-b)[\Delta-b+p_c e(1-\gamma)]-2C_L{p_c}^2\beta\}^2} \tag{21}$$

Lemma 2: Retailer recycling model has:

(1) $\frac{\partial p}{\partial \lambda}>0$, $\frac{\partial w}{\partial \lambda}>0$, $\frac{\partial \tau}{\partial \lambda}<0$, $\frac{\partial \theta_2}{\partial \lambda}<0$, $\frac{\partial \pi_j^2}{\partial \lambda}<0$.

(2) $\frac{\partial p}{\partial C_L}>0$, $\frac{\partial w}{\partial C_L}>0$, $\frac{\partial \tau}{\partial C_L}<0$, $\frac{\partial \theta_2}{\partial C_L}<0$, $\frac{\partial \pi_j^2}{\partial C_L}<0$.

(3) $\frac{\partial p}{\partial \Delta}<0$, $\frac{\partial w}{\partial \Delta}<0$, $\frac{\partial \tau}{\partial \Delta}>0$, $\frac{\partial \theta_2}{\partial \Delta}>0$, $\frac{\partial \pi_j^2}{\partial \Delta}>0$.

(4) $\frac{\partial p}{\partial \gamma}>0$, $\frac{\partial w}{\partial \gamma}>0$, $\frac{\partial \tau}{\partial \gamma}<0$, $\frac{\partial \theta_2}{\partial \gamma}<0$, $\frac{\partial \pi_j^2}{\partial \gamma}<0$.

(5) $\frac{\partial p}{\partial b}>0$, $\frac{\partial w}{\partial b}>0$, $\frac{\partial \tau}{\partial b}<0$, $\frac{\partial \theta_2}{\partial b}<0$, $\frac{\partial \pi_j^2}{\partial b}<0$.

Lemma 2 outlines the impact of carbon-related parameters and the correlation coefficients of recycling and remanufacturing on optimal decision-making and profitability as follows:

(1) The recovery rate of waste products and the carbon emission reduction per unit product are inversely related to the cost coefficient of carbon emission reduction. If the cost coefficient of carbon emission reduction increases, manufacturers will reduce both the rate of carbon emission reduction and waste product recovery, subsequently leading to an increase in wholesale and retail prices of the products. Consequently, the demand for products will decline, adversely affecting the profits of both manufacturers and retailers.

(2) Both the waste product recovery rate and the carbon emission reduction per unit product decrease in response to an increase in the recovery cost coefficient. The rise in recovery cost consequently leads to an increase in both wholesale and retail prices, which in turn diminishes product demand and reduces the profits for both manufacturers and retailers.

(3) The greater the unit production cost savings realised by remanufacturing compared to new product manufacturing, the more pronounced the benefits of remanufacturing become. Concurrently, remanufacturing contributes to enhanced carbon emission reduction. The profit gained from the surge in demand can entirely counterbalance the losses incurred due to price reduction, thus boosting the profits of both manufacturers and retailers.

(4) The lower the emission intensity of remanufactured products relative to new products, the more advantageous it becomes to recycle waste products and escalate carbon emission reduction, consequently leading to amplified cost savings.

(5) The higher the price that retailers pay to recycle waste products, the less inclined they become to recycle. This reduction in the recycling rate will, in turn, augment the manufacturers' costs.

T recovery mode

In T Mode, the backward induction method is utilised to solve the two-stage dynamic game. Initially, the manufacturer determines the whole sale price w of the product and the carbon emission reduction τ per unit of product. Subsequently, the retailer establishes the retail price p of the product, while the third-party recycler sets the recovery rate θ_3 for waste products. The Stackelberg game model in this mode can be expressed as follows:

$$\max \pi_1^3 = (w - C_n)D + (\Delta - f)D\theta_3 - \frac{1}{2}\lambda\tau^2 + e_g p_c - D(1-\theta_3)(e-\tau)p_c - D\theta_3(\gamma e - \tau)p_c \tag{22}$$

$$\max \pi_2^3 = (p - w)D \tag{23}$$

$$\max \pi_3^3 = (f - b)D\theta_3 - C_L\theta_3^2 \tag{24}$$

First, we compute the reaction function. The optimal recovery rate θ_3 can be obtained from equation $\frac{\partial \pi_3^3}{\partial \theta_3} = 0$ in equation (24):

$$\theta_3 = \frac{(f-b)(\alpha - \beta w)}{4C_L} \tag{25}$$

The optimal retail price p can be obtained by equation $\frac{\partial \pi_2^3}{\partial p} = 0$ in equation (23):

$$p = \frac{\alpha + \beta w}{2\beta} \tag{26}$$

Similarly, it can be determined that there is a unique optimal solution for π_1^3 with respect to w, τ. By substituting the above-obtained values for θ_3 and p into π_1^3, and then setting the first order partial derivatives of π_1^3, with respect to w, τ equal to zero, that is, $\frac{\partial \pi_1^3}{\partial w} = 0$, $\frac{\partial \pi_1^3}{\partial \tau} = 0$, we can find the optimal values for the wholesale price w and the carbon emissions reduction per unit product τ can be obtained respectively:

$$\mathrm{w} = \frac{\alpha}{\beta} + \frac{2\lambda C_L(\beta C_n + p_c\beta e - \alpha)}{4C_L\lambda\beta - \beta^2\lambda(\mathrm{f}-b)[\Delta - f + p_c e(1-\gamma)] - C_L p_c{}^2\beta^2} \tag{27}$$

$$\tau = \frac{C_L p_c(\alpha - \beta C_n - p_c\beta e)}{4C_L\lambda - \beta\lambda(\mathrm{f}-b)[\Delta - f + p_c e(1-\gamma)] - C_L p_c{}^2\beta} \tag{28}$$

After substituting the calculated values for w and τ into equations (25) and (26), we can find the optimal retail price p and recovery rate θ_3 as follows:

$$p = \frac{\alpha}{\beta} + \frac{\lambda C_L(\beta C_n + p_c\beta e - \alpha)}{4C_L\lambda\beta - \beta^2\lambda(\mathrm{f}-b)[\Delta - f + p_c e(1-\gamma)] - C_L p_c{}^2\beta^2} \tag{29}$$

$$\theta_3 = \frac{\lambda(\mathrm{f}-b)(\alpha - \beta C_n - p_c\beta e)}{8C_L\lambda - 2\beta^2\lambda(\mathrm{f}-b)[\Delta - f + p_c e(1-\gamma)] - 2C_L p_c{}^2\beta^2} + e_g p_c \tag{30}$$

Lastly, by plugging the previously derived optimal solutions into the profit function equations (22), (23), and (24) of each participant in the supply chain, we can express π_1^3, π_2^3 and π_3^3 in the following manner:

$$\pi_1^3 = \frac{\lambda C_L(\alpha - \beta C_n - p_c\beta e)^2}{8\beta C_L\lambda - 2\beta^2\lambda(\mathrm{f}-b)[\Delta - f + p_c e(1-\gamma)] - 2C_L p_c{}^2\beta^2} + e_g p_c \tag{31}$$

$$\pi_2^3 = \frac{\lambda^2 C_L{}^2(\alpha - \beta C_n - p_c \beta e)^2}{\beta\{4C_L\lambda - \beta\lambda(\mathrm{f}-b)[\Delta - f + p_c e(1-\gamma)]^2 - C_L p_c{}^2\beta\}^2} \tag{32}$$

$$\pi_3^3 = \frac{\lambda^2 C_L(\mathrm{f}-b)^2(\alpha - \beta C_n - p_c \beta e)^2}{4\{4C_L\lambda - \beta\lambda(\mathrm{f}-b)[\Delta - f + p_c e(1-\gamma)]^2 - C_L p_c{}^2\beta\}^2} \tag{33}$$

Lemma 3: Under the recycling model involving third-party recyclers, the following observations can be made:

(1) $\frac{\partial p}{\partial \lambda} > 0$, $\frac{\partial w}{\partial \lambda} > 0$, $\frac{\partial \tau}{\partial \lambda} < 0$, $\frac{\partial \theta_1}{\partial \lambda} < 0$, $\frac{\partial \pi_j^3}{\partial \lambda} < 0$;

(2) $\frac{\partial p}{\partial C_L} > 0$, $\frac{\partial w}{\partial C_L} > 0$, $\frac{\partial \tau}{\partial C_L} < 0$, $\frac{\partial \theta_1}{\partial C_L} < 0$, $\frac{\partial \pi_j^3}{\partial C_L} < 0$;

(3) $\frac{\partial p}{\partial \Delta} < 0$, $\frac{\partial w}{\partial \Delta} < 0$, $\frac{\partial \tau}{\partial \Delta} > 0$, $\frac{\partial \theta_1}{\partial \Delta} > 0$, $\frac{\partial \pi_j^3}{\partial \Delta} > 0$;

(4) $\frac{\partial p}{\partial \gamma} > 0$, $\frac{\partial w}{\partial \gamma} > 0$, $\frac{\partial \tau}{\partial \gamma} < 0$, $\frac{\partial \theta_1}{\partial \gamma} < 0$, $\frac{\partial \pi_j^3}{\partial \gamma} < 0$;

(5) $\frac{\partial p}{\partial b} > 0$, $\frac{\partial w}{\partial b} > 0$, $\frac{\partial \tau}{\partial b} < 0$, $\frac{\partial \theta_1}{\partial b} < 0$, $\frac{\partial \pi_j^3}{\partial b} < 0$;

Lemma 3 illustrates the impact of carbon interdependency, as well as the correlation between recycling and remanufacturing, on optimal decision-making and profit as follows:

(1) In alignment with Lemma 1 and Lemma 2, the recovery rate of waste products and the carbon emission reduction per unit product both decrease as the carbon emission reduction cost factor increases for third-party recyclers.

(2) The recovery rate of waste products and the carbon emission reduction per unit product both diminish as the recovery cost coefficient increases. The escalation in recovery costs leads to a surge in wholesale and retail prices, which subsequently reduces the profits of manufacturers and retailers.

(3) When the unit production cost of remanufactured products is higher compared to new products, manufacturers and third-party recyclers are more inclined towards recycling waste products for remanufacturing. In addition, remanufacturing can enhance carbon emission reduction. An increase in demand, which generates additional profit, can entirely compensate for any losses due to reduced prices, leading to an overall increase in the profits across the supply chain.

(4) Lower emission intensity from remanufactured products compared to new ones encourages waste product recycling and boosts carbon emission reduction. This process increases cost savings and subsequently enhances the profits of both manufacturers and retailers.

(5) Higher recycling prices paid by third-party recyclers to recycle waste products can hamper the expansion of recycling and remanufacturing operations within the closed-loop supply chain, thus posing challenges to green and sustainable development.

Comparative analysis of three green closed-loop supply chain recovery modes

The Stackelberg game model was employed to carry out a detailed analysis of the recycling and remanufacturing modes within a green closed-loop supply chain. Key indicators including retail price, wholesale price, carbon emission reduction per unit

product, waste product recovery rate, and manufacturer profit were examined for optimal conditions. The aim was to compare and analyse these indicators to establish the most optimal recycling and remanufacturing mode.

Contrast 1: The optimal retail price relationship is established as: $p^3 > p^2 > p^1$. This study presumes that product demand follows the functional relationship: $D = \alpha - \beta p$, thereby resulting in the demand relationship: $D^3 < D^2 < D^1$.

Proof:

$$p^1 - p^2 = \frac{2C_L\lambda(\beta C_n + p_c\beta e - \alpha)}{8C_L\beta\lambda - \beta^2\lambda[\Delta - b + p_c e(1-\gamma)]^2 - 2C_L {p_c}^2\beta^2} - \frac{C_L\lambda(\beta C_n + p_c\beta e - \alpha)}{4C_L\beta\lambda - \beta^2\lambda(f-b)[\Delta - b + p_c e(1-\gamma)] - C_L {p_c}^2\beta^2}$$

When the numerators are identical, the denominator is smaller in the manufacturer's recycling model; consequently, the retail price in the manufacturer's recycling model is smaller, leading to $p^1 - p^2 < 0$. Similar to the above comparison, the next inequality, $p^2 - p^3 < 0$, is obtained. Therefore, based on these inequalities, it can be deduced that the retail price is highest under the recycling mode led by third-party recyclers.

Contrast 2: The relationship among the optimal wholesale prices set by the manufacturer is such that $w^3 > w^2 > w^1$. The comparison proceeds in a manner similar to the previous inequality.

Contrast 3: The relationship among the optimal manufacturer's carbon emission reductions per unit product is as follows: $\tau^3 < \tau^2 < \tau^1$.

Contrast 4: The optimal recycling rate of waste products in the reverse closed-loop supply chain follows the relationship: $\theta_3^3 < \theta_2^2 < \theta_1^1$.

Contrast 5: The relationship of the manufacturer's profit in the optimal case is: $\pi_1^3 < \pi_1^2 < \pi_1^1$.

The above comparisons lead us to conclude that the manufacturer's recycling mode exhibits the highest recovery rate. This suggests that manufacturers are more motivated to recycle a larger amount of waste products, reducing production costs through recycling and remanufacturing processes. Furthermore, recycling and remanufacturing also serve as effective strategies for reducing carbon emissions. The functional components extracted during the recycling and disassembly processes can be repurposed in the production process, resulting in reduced raw material costs and lower carbon emissions. The wholesale price directly mirrors the unit cost savings. With the decrease in wholesale price, the retail price also falls, thereby transferring the marginal profit earned from recycling to the consumers. This not only boosts consumer demand significantly, but also enhances consumer awareness of low carbon solutions, leading to increased acceptance of remanufactured products. Ultimately, it enhances the profits of both manufacturers and retailers. Remanufactured products, with their lower carbon emissions and reduced production costs, have a significant role to play and substantial market demand in the context of urban and rural low-carbon planning. The manufacturer recycling mode optimises the recycling and remanufacturing processes within the green closed-loop supply chain, maximising environmental and economic benefits. Given China's increasing focus on energy saving and emission reduction, and businesses' growing consciousness about low carbon environmental protection and maintaining a green and healthy corporate image, it is

recommended that manufacturers prioritise independent recycling and remanufacturing modes.

Results and discussion

Building upon the primary model analysis and solution results conducted earlier in this paper, we will now proceed to a numerical simulation analysis of these results. In this study, we utilise Matlab2021b software to explore the changes in carbon emission reduction and manufacturers' profits under three different recycling modes. This allows us to examine the relationship between parameters more intuitively using graphical representations. Refer to the study of Lin et al. [29] for our simulations, we have set certain parameters as follows, $\alpha = 100$, $\beta = 4$, $C_n = 10$, $f = 3$, $C_L = 25$, $\lambda = 20$, $e = 2$, $e_g = 100$.

The impact of carbon trading price on carbon emission reduction and profits

In this section, we examine the impact of the carbon trading price p_c on the carbon emission reduction capacity of a unit product and the manufacturer's profit. Assuming that the carbon emission intensity satisfies $\gamma = 0.5$, $\Delta = 5$, $b = 2$, we reference the average carbon trading price from various carbon trading pilot programs carried out in recent years in China, in accordance with the established national carbon emission trading system. By combining these with the parameters set for this study, we ascertain an approximate reasonable range for the carbon trading price to be used in this paper. Consequently, when the carbon trading price p_c varies between 0 and 2.4, we study the ensuing changes in the emission reduction per unit product and the manufacturer's profit.

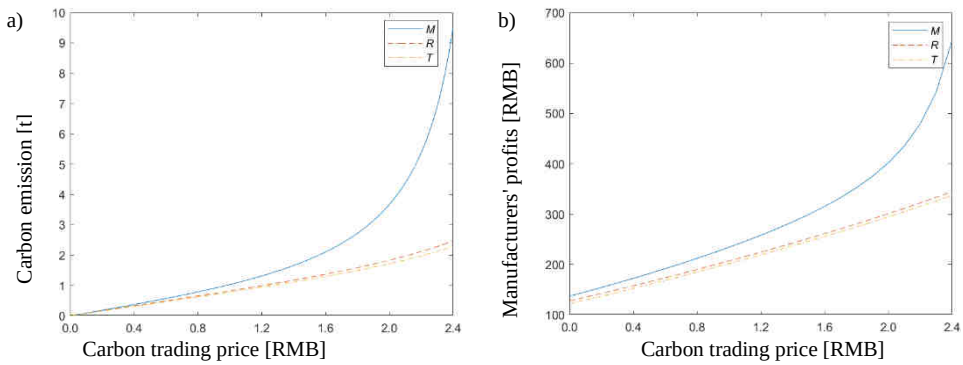


Fig. 4. a) The impact of carbon trading price on carbon reduction, b) the impact of carbon trading price on manufacturers' profits ($0 < p_c < 2.4$) (RMB - Renminbi or Chinese Yuan)

The relationship between carbon emission reduction per unit product and carbon trading price is shown in Figure 4a. As can be seen from the figure, the variation trend of carbon emission reduction per unit product of manufacturers under the three recycling modes is basically the same. When $0 < p_c < 2.4$, the carbon emission reduction per unit product also escalates with the rise in the carbon trading price. The production unit of a new product releases a fixed amount of carbon. However, under the carbon trading policy, the carbon emitted necessitates payment based on quantity.

Results discussion: therefore, a surge in the carbon trading price will cause the production cost of the unit product to rise. To assure the maximisation of their own interests, manufacturers will undertake control measures to emit less carbon. Comparatively, among the three recycling modes, the manufacturer recycling mode results in the highest carbon emission reduction per unit product.

The relationship between manufacturer's profit and carbon trading price is shown in Figure 4b. It can be seen from the figure that the change trend of manufacturer's profit curve under the three recycling modes is basically the same. When $0 < p_c < 2.4$, the manufacturer's profit gradually escalates with the rise in the carbon trading price. It is noteworthy that the manufacturer recycling mode results in both the highest profit and the highest carbon emission reduction. Therefore, from the perspectives of the environment and profit, the manufacturer recycling mode emerges as the first choice.

Results discussion: at a lower carbon trading price, the manufacturer will not invest more in carbon emission reduction costs, and the government will allocate fewer free carbon quotas to encourage low carbon emission reduction. Consequently, manufacturers can boost their profits by enhancing carbon emission reduction. Therefore, within a reasonable range, the higher the carbon trading price, the better the implementation of carbon emission reduction policies.

The impact of carbon intensity on carbon emission reduction and profits

In this section, we turn our focus towards understanding how carbon intensity γ influences the carbon emission reduction per unit product and the manufacturer's profits, and consequently, the choice of recycling mode. For this, we set $p_c = 1$, $\Delta = 5$, $b = 2$ is set. Meanwhile, $0 < \gamma < 1$ can be known from the above parameter assumptions. Therefore, when the carbon emission intensity changes between 0 and 1. Thus, when the carbon intensity fluctuates between 0 and 1, we study the resulting changes in carbon emission reduction per unit product and the manufacturer's profit.

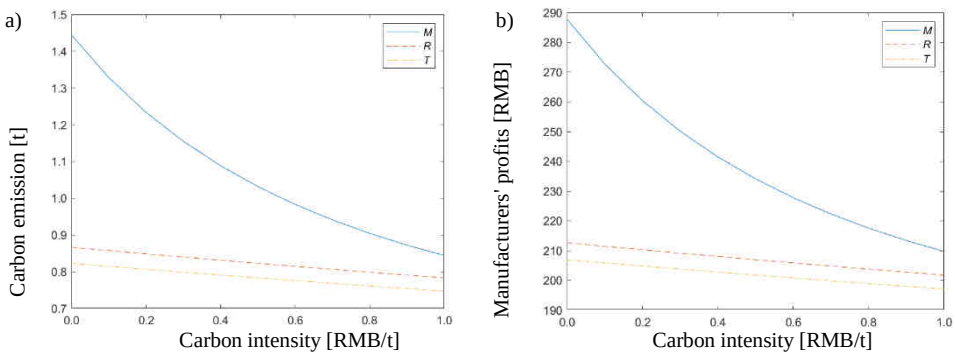


Fig. 5. a) The impact of carbon emission intensity on carbon reduction, b) the impact of carbon emission intensity on manufacturers' profits ($0 < \gamma < 1$)

The relationship between carbon emission reduction per unit product and carbon emission intensity is illustrated in Figure 5a. It can be seen from the figure that the change trend of carbon emission reduction per unit product under the three recycling modes is

basically the same. When $0<\gamma<1$, the carbon emission reduction per unit product gradually decreases with the increase of carbon emission intensity.

Results discussion: this implies that the influence of carbon emission intensity on carbon emission reduction remains unchanged under different recycling modes. Upon comparison of the three different recycling modes, it becomes evident that the manufacturer's recycling mode offers the highest carbon emission reduction per unit product.

The relationship between the manufacturer's profit and carbon emission intensity is illustrated in Figure 5b. It can be seen from the figure that the change trend of manufacturer's profit under the three recycling modes is basically the same. When $0<\gamma<1$, the carbon emission intensity of remanufactured products compared with that of new products is inversely proportional to the manufacturer's profit.

Results discussion: comparing the three different recycling modes, it is clear that the manufacturer's recycling mode is the most advantageous considering both unit carbon emission reduction and manufacturer's profit. This not only ensures the highest profit for the manufacturer but also helps achieve a higher carbon emission reduction target. Lower carbon emission intensity will facilitate the expansion of recycling and remanufacturing scales; thus, fewer carbon emissions will further promote the low-carbon emission reduction plans of urban and rural governments.

The impact of recycling prices on carbon reduction and profits

This section concentrates on how the recycling price *b*, which needs to be paid to consumers for recycling waste products, influences the carbon reduction capacity per unit product and the manufacturer's profit, consequently affecting the selection of the recycling mode. For this scenario, we set $p_c=1$, $\gamma=0.5$, $\Delta=5$. Since the parameter $f=3$ is set before in this paper, and $b<f$ is assumed above, the changes of carbon emission reduction per unit product and manufacturer's profit are studied when the recovery price changes between 0 and 3.

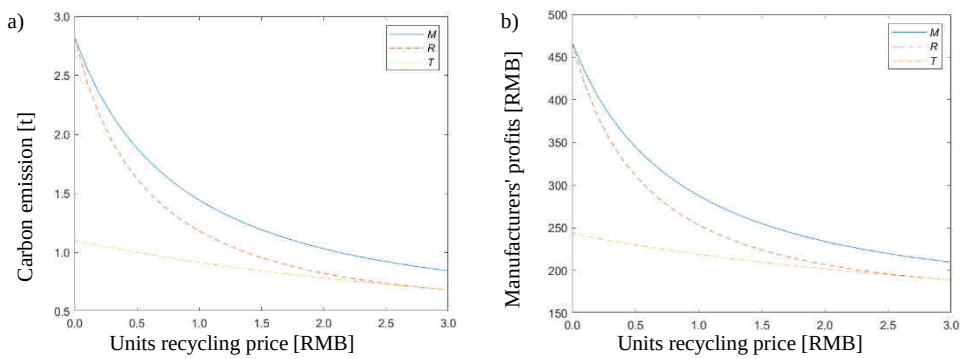


Fig. 6. a) The impact of recycling price on carbon reduction, b) the impact of recycling price on manufacturers' profits ($0<b<3$)

The relationship between carbon emission reduction per unit product and the recycling price is depicted in Figure 6a. The figure indicates that, for $0<b<3$, carbon emission

reduction per unit product gradually diminishes with an increase in the recycling price across all three recycling modes, indicating that the effect of recycling price on carbon emission reduction remains constant across different recycling modes.

Results discussion: by comparing the three different recycling modes, it is apparent that within the range of $0<b<3$, the manufacturer recycling mode yields the highest carbon emission reduction per unit product.

The relationship between the manufacturer's profit and the recovery price is depicted in Figure 6b. The figure shows that, across all three recovery modes, when $0<b<3$, the manufacturer's profit gradually decreases with the increase in recovery price. A lower recovery price would further incentivise supply chain participants to recycle and remanufacture, thus greatly reducing production costs.

Results discussion: from a comparative standpoint, it is evident that the manufacturer's recycling mode results in the highest profit and the highest carbon emission reduction, thereby achieving an optimal scenario.

The impact of unit production cost savings on carbon reduction and profits

In this section, we examine how the unit production cost savings of remanufactured products relative to new products influence the carbon reduction capacity per unit product and the manufacturer's profits, thereby affecting the choice of recycling mode. Here, the parameters $p_c=1$, $\gamma=0.5$, $b=2$ is set, because the parameter $C_n=10$ is assumed in the preceding text, and $C_n>\Delta$ it is evident that remanufactured products have certain production costs. Consequently, we obtain an approximate reasonable range of 0 to 7. Therefore, we study the change in carbon emission reduction per unit product and manufacturer's profits when the saved unit production cost varies between 0 and 7.

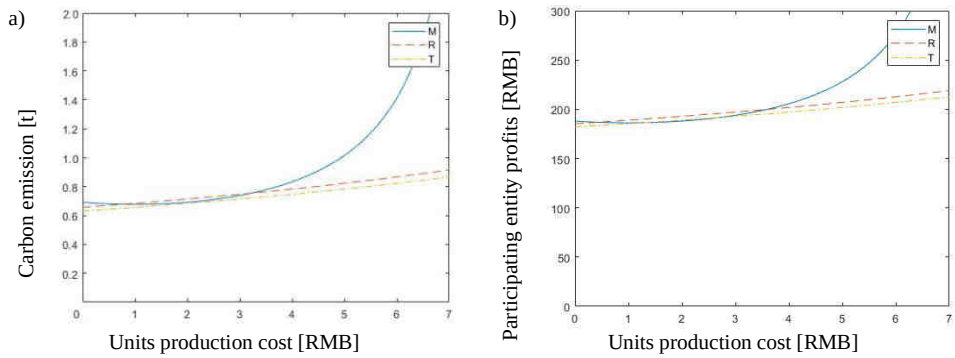


Fig. 7. a) The impact of saved unit production cost on carbon reduction, b) the impact of saved unit production cost on manufacturers' profits ($0<\Delta<7$)

The relationship between the carbon emission reduction per unit product and unit production cost savings is depicted in Figure 7a. As evident from the figure, under all three recycling modes, as the unit production cost savings increase from 0 to 7, the carbon emission reduction per unit product correspondingly escalates. This means that the influence of saved unit production costs on carbon emission reduction remains consistent across different recycling modes.

Results discussion: comparing the three different recycling modes, it is evident that in the $0<\Delta<0.8$ and $3.2<\Delta<7$, he carbon emission reduction per unit product is highest under the manufacturer's recycling mode, followed by the retailer's recycling mode and the third-party recycler's recycling mode. However, in the $0.8<\Delta<3.2$ range, the retailer's recycling mode boasts the highest carbon reduction.

The relationship between the manufacturer's profit and the saved unit production cost is illustrated in Figure 7b. The figure reveals that under all three recovery modes, the manufacturer's profit progressively increases as the saved unit production cost expands from 0 to 7. Comparing the three different recycling modes, it is apparent that the manufacturer's profit under the retailer recycling mode is highest when $0.4<\Delta<3.6$, the manufacturer's profit under the retailer recycling mode is the highest, but when $0<\Delta<0.4$ and $3.6<\Delta<7$, the manufacturer's profit is higher under the manufacturer's recycling mode than the other two modes. Thus, the saved unit production cost significantly impacts the carbon emission reduction, profit, and the selection of the optimal recovery mode.

Results discussion: when $0.8<\Delta<3.2$, the retailer′s recovery mode has the best economic and environmental benefits, and when $0<\Delta<0.4$ and $3.6<\Delta<7$. Moreover, the optimal scenario under the manufacturer's recycling mode tends to outperform that under the retailer's recycling mode. In any other cases, a win-win situation of both economic and environmental benefits cannot be attained.

In summary, when the unit production cost saved by the remanufactured product is minimal, meaning that the remanufactured product barely reduces the production cost, the manufacturer recycling mode can achieve a balanced outcome for both the environment and economy. However, under this mode, the manufacturer's profit is modest, and the level of carbon emission reduction is not high. As the remanufacturing technology advances to a stage where it can save a moderate amount of production costs, the retailer recycling model becomes a more viable option. Yet, as the production technology continues to mature, and the remanufactured product can significantly save on costs, enterprises should independently select the manufacturer's recycling mode, which can lead to optimal conditions. At this stage, both carbon emission reduction and the manufacturer's profit are considerably higher compared to when the unit production cost savings were lower. This implies that the incorporation of carbon emission reduction technology and recycling and remanufacturing models can not only boost the manufacturers' profits but also enhance environmental benefits. Therefore, if manufacturers aim to reap higher profits under the carbon trading policy, they should adopt technological measures to create remanufactured products that yield more unit production cost savings.

Conclusion

This study makes several key contributions to research on recycling and remanufacturing in sustainable low-carbon city development. First, it proposes a Stackelberg game-theoretic model to analyse three critical recycling channels - manufacturer, retailer, and third-party. The model incorporates carbon emission policies and remanufacturing cost effects, providing new insights compared to existing literature. Second, the analysis indicates the manufacturer channel is optimal when remanufacturing costs are substantially lowered, highlighting the importance of cleaner production technologies. Third, the study offers policy guidance on regulating carbon pricing,

incentivising enterprises, increasing consumer acceptance, and integrating sustainability into urban planning.

However, there are some limitations that provide avenues for future research. The model could be extended by incorporating consumer preferences, information asymmetry between actors, and hybrid recycling structures. Exploring these factors under varied policy scenarios would further advance knowledge on optimising closed-loop supply chains. Moving forward, empirical analysis and real-world case studies of low-carbon cities would help translate the theoretical findings into practical implementation.

Overall, this research makes key strides in using game-theoretic techniques to examine recycling and remanufacturing for sustainable urban development. The modelling approach and policy insights contribute to the growing knowledge on building green, eco-friendly cities. With further extensions and empirical validation, the framework can support strategies to achieve national carbon neutrality goals and promote low-carbon planning in cities.

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