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Pricing and financing strategies of dual channel closed-loop supply chain considering capital-constrained manufacturer

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Abstract: With the rise of the 'internet + recycling' model, the manufacturer actively constructs a dual channel closed-loop supply chain model and faces serious capital constraints, and the manufacturer's financing strategy is particularly important. Based on this, this paper uses Stackelberg theory to construct a dual channel closed-loop supply chain game model composed of the manufacturer and the retailer. Furthermore, in view of the fact that the manufacturer has capital constraints, the optimal financing and pricing strategies of supply chain enterprises are studied in two financing models: bank loan and retailer financing. Finally, using case study to verify the model results, it is found that the retailer financing can bring higher economic profit and recovery rate. In the retailer financing mode, when interest rate is low, the raising interest rate will 'harm others and itself', while when interest rate is high, the raising interest rate will 'benefit others and harm itself'. [Received: 6 June 2022, Accepted: 4 January 2023]

Keywords: capital-constrained; dual channel closed-loop supply chain; financing strategy; pricing strategy.

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Di Wu received his BS in Mathematics and Applied Mathematics from the Northwestern Polytechnical University, and MSM in Management Science and Engineering from the Xi'an University of Technology. In 2020, he received his PhD degree with the Supply Chain Integration and Service Innovation Institute from Xi'an University of Technology and stayed in this school as a Lecturer. He has been engaged in dual-channel closed-loop supply chain research field since 2016 and has published ten related papers in this field.

Haiqing Hu was admitted to Xi'an Jiaotong University for a Doctorate in Applied Economics in 1999, mainly engaged in research on corporate finance and obtained his Doctorate in Applied Economics in 2005. In 2002, he received his Doctorate from Tokushima University in Japan, mainly engaged in relevant research in the field of information economics. He is currently the Dean of the School of Economics and Management of Xi'an University of Technology, and has been engaged in scientific research and teaching for many years. He has published nearly 100 high-level papers in English, Japanese and Chinese in core journals.

1 Introduction

In the digital economy environment, the 'recycling revolution' caused by the rapid development of the dual channel closed-loop supply chain based on 'internet + recycling' has attracted much attention (Wang et al., 2018, Wu et al., 2019). The dual channel closed-loop supply chain refers to the supply chain model composed of both traditional offline recycling channels and online recycling channels based on internet technology (Wu et al., 2020). On the one hand, with its high level of recovery price, recovery service and recovery efficiency, the dual channel closed-loop supply chain based on online recycling stimulates consumers' recycling enthusiasm, significantly increases the total volume of product recycling and reduced production cost, thereby promoting enterprises' economic profit and sustainable competitive advantage (Giri et al., 2017; Zuo et al., 2020). According to the data released by China's largest online recycling platform Aihuishou, compared with traditional offline recycling channels, the recovery price of waste electronic products per unit in online recycling channels is on average 10% to 15% higher, and the monthly recovery volume reaches 1 million pieces. After GEM, a Chinese traditional manufacturing enterprise launched its online recycling platform recycling Ge, its product recycling links have been reduced from the 6–7 to 4, and the recovery volume has increased by 60% compared with the original. On the other hand, professional recycling enterprises usually disassemble and decompose waste products in online recycling channels, which makes enterprises obtain more resources while reducing harmful emissions to the ecological environment (Wang et al. 2020; Chen et al. 2022). For the above reasons, enterprises from different countries such as China, the USA (Fortuna and Diyamandoglu, 2015; Zissis et al., 2018) and Australia (Corder et al., 2014) have been actively constructing a dual channel closed-loop supply chain model with parallel online and offline recycling channels in recent years.

However, although the construction of online recycling channels by manufacturing enterprises is conducive to increasing economic profits and obtaining sustainable competitive advantages, it also greatly increases the recovery cost and economic burdens of enterprises (Gu et al., 2019; Sherafati et al., 2020). This is due to the fact that online recycling channels often have high early-stage investment and surge in operation and maintenance costs in actual operation, resulting in a shortage of funds for the manufacturer, and uncertain risks for other supply chain members. Specifically, the high initial investment is due to the fact that the manufacturer needs to solve and coordinate various problems such as equipment, technology, personnel, and upstream and downstream partners in the supply chain in the process of constructing online recycling channels in the early stage, so it needs to invest high initial funds (Feng et al., 2017; Ramzan et al., 2020). The surge in operation and maintenance costs is due to the fierce competition in the online recycling market. Enterprises need to invest a lot of money in advertising cost, the cost of constructing offline stores, and the labour cost of hiring couriers to pick up goods on site, in order to occupy the market first (Qu et al., 2019). Once the manufacturer is unable to obtain financing after the shortage of funds, it is bound to affect the production, wholesale, retail, and recycling activities in the upstream and downstream of the closed-loop supply chain, and bring uncertainty risks to other enterprises (He et al., 2021; Li et al., 2022). Therefore, how to solve the dilemma of insufficient funds faced by the manufacturer after constructing online recycling channels has become an important issue to improve the manufacturer's profit, promote the stability of upstream and downstream enterprises, and enhance the overall sustainable competitiveness of closed-loop supply chain.

In order to solve the problem of insufficient funds after constructing online recycling channels, the manufacturer usually needs to choose between two financing strategies: bank loan and retailer financing (Jin et al., 2019; Yang et al., 2019; Huang et al., 2020). In the bank loan or retailer financing model, the manufacturer loans from the bank or the retailer based on its funding gap, and repay the principal and interest to the bank or the retailer at their respective interest rate after transaction (Lin and He, 2019; Babagolzadeh et al., 2020). Since the manufacturer's choice of financing model will affect its own wholesale price and recovery rate, it will also have an important effect on the decision and profit of other supply chain members, such as the retailer. In addition, based on the previous literature analysis of decision issues related to dual-channel supply chains and capital constraints, we find that the competition intensity between channels and interest rate have an important effect on the decision-making and profits of upstream and downstream enterprises in the supply chain. In summary, this paper focuses on the influence of channel competition intensity and interest rate on the optimal financing and pricing strategies of supply chain enterprises when the manufacturer has capital constraints in dual channel closed-loop supply chain. The questions to be answered in this study are as follows:

1 What are the characteristics of dual channel closed-loop supply chain? How to characterise the demand and recovery function the dual channel closed-loop supply chain model?

2 How to characterise the revenue function of each enterprise in dual channel closed-loop supply chain? When the manufacturer has capital constraints, how will the choice of bank loan and retailer financing affect the enterprise revenue function?

3 When channel intensity competition or interest rate changes, how should the manufacturer and the retailer adjust their optimal pricing and recovery rate decisions? How will their optimal profit change? Will the above factors affect the manufacturer's financing strategy?

The main contributions of this paper can be summarised as follows:

1 Aiming at the dual channel closed-loop supply chain model composed of the manufacturer and the retailer, this paper describes, analyses and integrates its characteristics in the process of production, wholesale, retail and recycling. Based on the above research, this paper more accurately puts forward the demand function and recovery function of the manufacturer and the retailer in this model, which makes the model closer to reality and improves the effectiveness of the model results.

2 Based on the in-depth analysis of the two financing models of bank loan or retailer financing when the manufacturer faces capital constraints, this paper proposes decision models of dual channel closed-loop supply chain in the two models by using Stackelberg game theory. While laying the foundation for the subsequent related research on model solution and analysis, this paper also enriches and promotes the research process of the model of dual channel closed-loop supply chain in the field of capital constraints.

3 Through theoretical derivation and numerical analysis, this paper analyses and verifies the effects of channel competition intensity and interest rate on the optimal financing model selection, pricing, recovery rate and profit of enterprises in two models of bank loan and retailer financing. At the same time, according to the above results, and comprehensively considering the economic profit and environmental performance of enterprises, this paper provides management suggestions for the manufacturer and the retailer, which further enhances the practical guiding significance of the research conclusions to reality.

The rest of the paper is structured as follows. Section 2 reviews the relevant literature and puts forward the research gap. Section 3 constructs, solves and analyses the model based on the description of the problem. Section 4 uses case study to analyse and verify the influence of channel competition intensity and interest rate on enterprise optimal decision and profit, and put forward management enlightenment. Section 5 gives the conclusion of this paper.

2 Literature review

2.1 Dual channel closed-loop supply chain

On the basis of the rapid development of modern information technology, manufacturing enterprises give full play to the optimisation and integration role of internet technology in the allocation of social resources to construct dual channel closed-loop supply chain structure where online and offline recycling channels coexist. Up to now, in the research on dual channel closed-loop supply chain, scholars mainly focus on issues such as consumer preferences, model selection and service level, and conduct in-depth analysis on pricing and coordination strategies of the manufacturer, the retailer, and the recycler.

Feng et al. (2017) constructs a pricing model for the recycling centre and the third-party recycler under centralised and decentralised decision based on the offline and online dual recycling channel model, and designs a revenue distribution contract to coordinate enterprise profit in the decentralised decision-making model. Finally, through numerical analysis, he points out that consumers' preference for online channels will affect the acceptance of contracts by different recyclers. Chu et al. (2018) studies the pricing and coordination decisions of the third-party recycling platform serving multiple electronic equipment manufacturing enterprises by constructing a Stackelberg game model, and designs two pricing contracts to coordinate supply chain system, and points out that the total profit of supply chain system in the third-party platform recycling model is better than that of a single retailer or manufacturer. Li et al. (2019) studies the pricing decision problems of dual channel closed-loop supply chain including an online recycling model under the situation of random demand, obtains optimal pricing and recycling volume decision, and points out that the online and offline hybrid recycling model can help reduce the transfer price, force the recycler to increase the recovery price and thus increase the total recovery volume. Miao et al. (2020) points out that Huawei has taken the lead in implementing a hybrid recycling model including manufacturer's offline recycling and retailer's online recycling, and greatly improved the recycling efficiency of waste mobile phones. Based on the comparison of the two recycling models, a hybrid recovery network model of contract coordination is constructed, and the optimal recycling distribution ratio in the two models is determined through simulation analysis. Wu et al. (2020) studies the pricing and service level coordination strategy model of the dual-channel reverse supply chain for the decision problem of the recycling service level provided by the recycling centre to consumers, and coordinate the profit of recycling enterprises under decentralised decision by introducing revenue cost sharing contract.

2.2 Capital constraints

In closed-loop supply chain, the manufacturer or the recycler needs to invest a lot of money in platform construction, manpower deployment, sorting and processing facilities to construct online recycling channels, which causes them to face long-term insufficient funds and affects production and operation efficiency. Therefore, how to provide scientific and effective financing strategies for closed-loop supply chain enterprises facing capital constraints has become an important issue to be solved urgently. At present, scholars mainly study capital constraints of supply chain enterprises from two aspects: external financing and internal financing.

External financing refers to the financing services provided to enterprises by financial institutions outside supply chain system. Internal financing refers to the way enterprises seek financing from upstream and downstream enterprises in supply chain by means of delayed payment and other methods. In addition to the above research, some scholars also conduct research on financing strategy based on the comparison of the two financing models. For the retailer with the ability to provide customised services and capital constraints, Dang et al. (2021) proposes and compares two financing modes, bank financing and 3PL financing, and points out that the choice of financing mode depends on the proportion of profit sharing of customised services. In order to solve the capital problem of the retailer affected by demand interruption, Zhao et al. (2022) builds decision models under four financing strategies: bank-bank, supplier-supplier, bank-supplier, and supplier-bank, for the supply chain mode composed of the bank, the supplier, and the retailer. The results show that bank-bank, and bank-supplier financing modes can significantly reduce the bankruptcy probability of the retailer. Different from the above studies, which mainly consider the existence of capital constraints of the retailer, some scholars also conduct research on the capital constraints of other supply chain members, such as the manufacturer. For the supply chain composed of the manufacturer, the supplier and the e-business platform, Qin et al. (2021) builds three financing strategies: platform financing mode, supplier credit financing mode, and mixed financing mode when the manufacturer has capital constraints. Qin uses a numerical example to verify the model and points out that the selection of financing mode is affected by the usage fees charged by the platform. Zhang and Chen (2022), aiming at the closed-loop supply chain system consisting of a supplier and an original equipment manufacturer, build a decision model in three financing modes: pure bank loan, full delay–in-payment with bank loan and partial delay-in-payment with bank loan when the manufacturer has capital constraints. The research shows that the total remanufacturing volume is always the highest in full delay-in-payment with bank loan mode. The above-mentioned studies are all at the single channel level, and some scholars also consider the issue of corporate capital constraints from the perspective of dual channels. Ma and Meng (2022) propose four financing strategies: bank credit financing strategy, retailer credit financing strategy, mixed financing strategy of bank credit and equity financing (MF-BE) and mixed financing strategy of retailer credit and equity financing (MF-RE) for the dual channel closed-loop supply chain mode in which the manufacturer is responsible for online direct sales and offline wholesale, and the retailer is responsible for offline retail and offline recycling, taking into account the financing strategy selection problem when the manufacturer has capital constraints. The research indicates that equity financing ratio negatively affects the retailer's profit under MF-RE strategy, while positively affects the retailer's profit under MF-BE strategy.

2.3 Research gaps

Table 1 compares the similarities and differences between the models in the above literature and the models designed in this paper from the aspects of supply chain structure, enterprise members, leaders, and financing strategies. Among them, as the most important reference of this paper, the mode built in Ma and Meng (2022) and the mode built in this research are both dual channel supply chain modes. However, unlike Ma and Meng (2022), which only studies single offline recycling channels, this paper considers the coexistence of online and offline recycling modes in reverse channels. This kind of innovation in research objects expands the research in this field to a new level, which is also the core advantage of this paper compared with Ma and Meng (2022). In addition, the limitations of the above literature are mainly reflected in the following aspects:

1 There is currently no research on financing strategy choice of enterprises in renewable resource industry

2 There is currently no research on financing and pricing strategies of dual-channel closed-loop supply chain enterprises based on online recycling

3 The existing studies do not consider the competition intensity between different channels as the main parameters that affect the choice of financing strategy

4 The existing studies mostly consider the situation that the retailer has capital constraints, and do not take the manufacturer with capital constraints as the main object.

However, in the reality of dual-channel closed-loop supply chain management, the above problems are faced by enterprise managers and need to be solved urgently. The research done in this paper can well solve them.

Table 1 Comparison of the models in this study and in the above studies

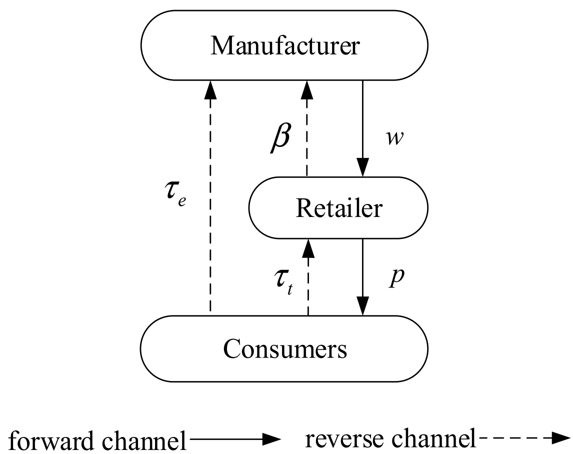
Related research	*Supply chain members*	*Leader*	*Reverse recovery model*	*Dual-channel model*	*Online recycling model*	*Pricing decision*	*Financing strategies*
Ma and Meng (2022)	manufacturer and retailer	manufacturer	√	√	×	√	√
Dang et al. (2021)	manufacturer and retailer	manufacturer	×	×	×	√	√
Zhao et al. (2022)	supplier, retailer and bank	retailer	×	×	×	√	√
Qin et al. (2021)	manufacturer, supplier and retailer	manufacturer	×	×	×	√	√
Zhang and Chen (2022)	manufacturer and supplier	manufacturer	×	×	×	√	√
Feng et al. (2017)	recycling centre and third-party recycler	recycling centre	√	√	√	√	×
Chu et al. (2018)	Manufacturer and third-party recycling platform	manufacturer	√	√	√	√	×
Li et al. (2019)	recycling centre and third-party recycler	recycling centre	√	√	√	√	×
Miao et al. (2020)	manufacturer and retailer	manufacturer	√	√	√	√	×
Wu et al. (2020)	recycling centre and third-party recycler	recycling centre	√	√	√	√	×
This research	Manufacturer and retailer	manufacturer	√	√	√	√	√

3 Mathematical models

3.1 Problem description

The dual channel closed-loop supply chain studied in this paper includes a manufacturer and a retailer. In the forward channel, the manufacturer first produces new products at the unit cost of cm, then sells the products to the retailer at the wholesale price of w, and finally the retailer sells the products to consumers at the retail price of p. Different from the forward channel, the reverse channel contains two types of recycling models at the same time. In the traditional recycling model, the retailer operates offline recycling channels at the total cost of I_t, and recycles waste products from consumers at the recovery rate of τ_t, and then resells waste products to the manufacturer at the price of β. At the same time, in the online recycling channel introduced by the manufacturer, the manufacturer operates the online recycling channel at the cost of I_m, and directly recycles the consumers' waste products at the recovery rate of τ_e. In this supply chain model, the manufacturer and the retailer have not only upstream and downstream cooperation, but also competition in different channels. Similar to the research of Wu et al. (2020), in this supply chain model, the decision process of the manufacturer and the retailer follows the Stackelberg game model, and the manufacturer has advantages over the retailer in terms of enterprise scale and policy support, so they occupy a dominant position. Figure 1 depicts the structure of the dual channel closed-loop supply chain.

Figure 1 The structure of the dual-channel closed loop supply chain



The significance of operating reverse channels is not only that the proper disposal of waste products can reduce environmental pollution, but also that the parts and components obtained from dismantling waste products are more conducive to reducing the cost of new products produced by the manufacturer. The unit cost of the manufacturer producing new products with raw materials is c_m, while the unit production cost of the manufacturer using waste products obtained through recycling channels can reduce to c_t. However, the construction of online recycling channels has also seriously increased the operating cost of the manufacturer, resulting in a sharp increase in their financial expenditures. Facing the problem of insufficient funds, the manufacturer needs to ease financial pressure through financing. It can either choose to finance from the retailer within the supply chain at the interest rate of r_i, or apply for loans from the commercial bank outside the supply chain at the interest rate of r_j.

3.2 Model assumptions

The main assumptions of this model are as follows:

- The information owned by each participating enterprise in the supply chain is symmetrical.
- The participants in the supply chain are completely rational, that is, they all make decisions with the goal of maximising their own profits, without considering the influence of irrational act factors such as the fairness concerns of enterprise decision makers on decisions.
- The waste products considered in the model in this paper have the same brand, type and loss degree before being recycled by the manufacturer and the retailer.
- Due to the introduction of online recycling channels, advanced payment, and inventory backlog of waste products, the manufacturer has the problem of insufficient funds, while the retailer has sufficient funds to provide the manufacturer with financing service in the supply chain.
- Although the manufacturer faces the problem of insufficient funds in the process of opening online recycling channels, it still insists on not outsourcing the recycling channels to the retailer. On the one hand, although there are short-term capital constraints, scholars such as Wu et al. (2020) and Miao et al. (2020) point out in their studies that opening online recycling channels will certainly make the manufacturer profitable in the long run. On the other hand, efficient operation of online recycling channels can also help the manufacturer to output environmental performance, directly contribute to sustainable development strategies, and enhance the social reputation of the enterprise in the government and the masses.
- Based on the research of Wu et al. (2020), there is no difference in function, quality and appearance between new products and remanufactured products produced by the manufacturer, and consumers have the same degree of acceptance of both. Therefore, the demand functions of new products and remanufactured products are consistent and linear, namely:

$$D = \varphi - \alpha p \tag{1}$$

- Based on the research of Savaskan and Wassenhove (2006) and Huang et al. (2013), in the dual channel closed-loop supply chain model with recycling channel competition, the costs for the manufacturer and retailer to operate recycling channels are:

$$Im = C_L \left(\tau e^2 + \theta \tau t^2 \right) / (1 - \theta^2), It = C_L \left(\tau t^2 + \theta \tau e^2 \right) / (1 - \theta^2) \tag{2}$$

For convenience, we summarise the notations used in the paper in Table 2.

Table 2 Notations used in the models

Notation	*Description*	*Notation*	*Description*
w	Wholesale price of products in the sales channel	r_i	Interest rate in internal financing model ($r_i > 0$)
p	Retail price of products in the sales channel	r_j	Interest rate in the bank loan model ($r_j > 0$)
β	The unit price of waste products recovered from the retailer by the manufacturer is a fixed value	c_m	The unit production cost of the manufacturer using original materials to produce new products ($c_m > 0$)
θ	Competition intensity between online and offline recycling channels ($0 < \theta < 1$)	c_t	The unit production cost of the manufacturer using the recycled waste products to produce new products ($c_m > c_t > 0$)
φ	Basic volume of the sales market	Δ	The unit cost saved by the manufacturer through recycling and remanufacturing production mode, $\Delta = c_m – c_t$
C_L	Cost factor of recovery scale	I_m	Cost of the manufacturer operating the recycling channel
α	Sensitive factor of sales volume affected by retail price in sales market ($\alpha > 0$)	It	Cost of the retailer operating the recycling channel
τ_t	Recovery rate of waste products recovered through traditional channels	D	Market demand for new products
τ_e	Recovery rate of waste products recovered through online channels	Π_m	The manufacturer's profit
f	Manufacturer's initial capital ($f > 0$)	Π_t	The retailer's profit

3.3 *Model formulation*

Below, firstly, for the manufacturer without capital constraints, a decision model is constructed for dual channel closed-loop supply chain, and the optimal pricing, recovery rate decision, and optimal profit of the manufacturer and the retailer are obtained. Next, the optimal decision and profit of the manufacturer and the retailer are obtained in the two models of bank loan and internal financing of the supply chain selected by the manufacturer. Finally, the decision variables and objective functions in the game model in the three models of no capital constraints, bank loan and internal financing are comprehensively compared in order to discover internal laws and extract management enlightenment with practical guiding significance.

3.3.1 No capital constraints

In this model, the enterprises in the whole dual channel closed-loop supply chain have sufficient funds and do not need financing service. Since the manufacturer occupies the dominant position in the game relative to the retailer, the manufacturer first determines its optimal new product wholesale price w and the optimal recovery rate τ_e in the online recycling channel. After observing the manufacturer's decision, the retailer optimises its own optimal new product retail price p and the optimal recovery rate τ_t of offline recycling channels. According to the reverse induction method of Stackelberg game theory, we need to construct and analyse the retailer's profit function first. The retailer's profit function is:

$$\begin{aligned}\Pi_t(\tau_t, p) &= D(p-w) + D\beta\tau_t - I_t \\ &= (\varphi-\alpha p)(p-w) + (\varphi-\alpha p)\beta\tau_t - C_L\left(\tau_t^2+\theta\tau_e^2\right)/(1-\theta^2)\end{aligned} \tag{3}$$

Theorem 1: In the non-capital constraint model, when $4C_L/(1-\theta^2) > \alpha\beta^2$, the retailer has the following optimal retail price p^* and offline recovery rate τ_t^* to maximise its profit:

$$p^* = \left[\alpha\beta^2\varphi(\theta^2-1) + 2C_L(w\alpha+\varphi)\right]/\alpha\left[\alpha\beta^2(\theta^2-1)+4C_L\right] \tag{4}$$

$$\tau_t^* = \beta(\theta^2-1)(w\alpha-\varphi)/\left[\alpha\beta^2(\theta^2-1)+4C_L\right] \tag{5}$$

Proof of Theorem 1: We first construct the Hessian matrix of $\Pi_t(p, \tau_t)$ as follows:

$$\begin{bmatrix}\partial^2\Pi_t/\partial p^2 & \partial^2\Pi_t/\partial p\partial\tau_t \\ \partial^2\Pi_t/\partial\tau_t\partial p & \partial^2\Pi_t/\partial\tau_t^2\end{bmatrix} = \begin{bmatrix}-2\alpha & -\alpha\beta \\ -\alpha\beta & -2C_L/\left(1-\theta^2\right)\end{bmatrix} \tag{6}$$

From the above, the first-order principle sub-formula of the Hessian matrix is $-2\alpha < 0$, and the second-order principle sub-formula is $4\alpha C_L/(1-\theta^2)-\alpha^2\beta^2$. Therefore, we only need to make $4\alpha C_L/(1-\theta^2)- \alpha^2\beta^2 > 0$, that is, $4C_L/(1-\theta^2) > \alpha\beta^2$, and we can make the Hessian Matrix a negative definite matrix, and then there is a set of optimal p^* and τ_t^*, making $\Pi_t(p, \tau_t)$ have a maximum.

Therefore, we solve the first-order partial derivatives of Π_t to p and τ_t^* respectively, and we can obtain $\partial\Pi_t/\partial p = -\alpha p-\alpha (p-w) + \varphi-\alpha\beta\tau_t$ and $\Pi_t/\partial\tau_t = \beta(\varphi-\alpha p)-2C_L\tau_t/(1-\theta^2)$. Then respectively set $\partial\Pi_t/\partial p = 0$ and $\partial\Pi_t/\partial\tau_t = 0$ and combine them, the optimal retail price of the retailer can be solved as

$$p^* = \left[\alpha\beta^2\varphi(\theta 2-1) + 2C_L(w\alpha+\varphi)\right]/\left[\alpha\beta^2(\theta^2-1)+4CL\right] \tag{7}$$

the optimal offline recovery rate is

$$\tau_t{}^* = \beta(\theta^2-1)(w\alpha-\varphi)/\left[\alpha\beta^2(\theta^2-1)+4C_L\right] \tag{8}$$

This ends the proof.

After obtaining the retailer's optimal decision (7) (8), we construct the manufacturer's profit function and substitute (7) (8), and we can get:

$$\begin{aligned}\Pi_m(\tau_e, w) &= D(w-c_m) + D\Delta\tau_e + D(\Delta-\beta)\tau_t - I_m \\ &= (\varphi-\alpha p^*)\left[w-c_m+\Delta\tau_e+(\Delta-\beta)\tau_t^*\right] - C_L\left(\tau_e^2+\theta\tau_t^{*2}\right)/(1-\theta^2)\end{aligned} \tag{9}$$

Theorem 2: In the non-capital constraint model, the manufacturer has the following optimal wholesale price w^* and online recovery rate τ_e^* to maximise its profit:

$$w^* = \frac{\alpha c_m\left[-\alpha\beta^2(\theta^2-1)-4C_L\right]+\varphi\left[\alpha(\theta^2-1)\left(-2\beta\Delta-\Delta^2+\beta^2+\beta^2\theta\right)-4C_L\right]}{\alpha\left[\alpha\left(\beta^2\theta-2\beta\Delta-\Delta^2\right)(\theta^2-1)-8C_L\right]} \tag{10}$$

$$\tau_e^* = \Delta(\theta^2-1)(\varphi-\alpha c_m)\Big/\left[\alpha\left(\beta^2\theta-2\beta\Delta-\Delta^2\right)(\theta^2-1)-8C_L\right] \tag{11}$$

Proof of Theorem 2: We first construct the Hessian Matrix of $\Pi_m(\tau_e, w)$ as follows:

$$\begin{bmatrix} \partial^2\Pi_m/\partial\tau_e^2 & \partial^2\Pi_m/\partial\tau_e\partial w \\ \partial^2\Pi_m/\partial w\partial\tau_e & \partial^2\Pi_m/\partial w^2 \end{bmatrix}$$

$$= \begin{bmatrix} -2C_L/(1-\theta^2) & -2\alpha\Delta C_L/\left(\alpha\beta^2\theta^2-\alpha\beta^2+4C_L\right) \\ \dfrac{-2\alpha\Delta C_L}{\alpha\beta^2\theta^2-\alpha\beta^2+4C_L} & \dfrac{2C_L\left[-\beta\alpha^2(2\Delta-\beta\theta)(\theta^2-1)-8\alpha C_L\right]}{\left(\alpha\beta^2\theta^2-\alpha\beta^2+4C_L\right)^2} \end{bmatrix} \tag{12}$$

From the above, the first-order principle sub-formula of the Hessian matrix is $-2C_L/(1-\theta^2) < 0$, and the second-order principle sub-formula is $4\alpha C_L^2[\alpha(\theta^2-1)(\theta\beta^2-2\beta\Delta-\Delta^2)-8C_L]/(\theta^2-1)(\alpha\beta^2\theta^2-\alpha\beta^2 + 4C_L^2)^2$. Therefore, we only need to make $4\alpha C_L^2[\alpha(\theta^2-1)(\theta\beta^2-2\beta\Delta-\Delta^2)\text{-}8C_L]/(\theta^2-1(\alpha\beta^2\theta^2-\alpha\beta^2 + 4C_L^2)^2 > 0$, that is, $\alpha(\theta^2-1)(\theta\beta^2-2\beta\Delta-\Delta^2) < 8C_L$, and we can make the Hessian matrix a negative definite matrix. Since Hessian matrix is a negative definite matrix, $\Pi_m(w, \tau_e)$ is a concave function, then there is a set of optimal w and τ_e^* that makes $\Pi_m(w, \tau_e)$ have a maximum.

Therefore, we solve the first-order partial derivatives of Π_m to w and τ_e respectively, set $\partial\Pi_m/\partial_w$ and $\partial\Pi_m/\partial\tau_e$ to 0 respectively, then combine them, and we can obtain the manufacturer's optimal wholesale price w^* as (10) and online recovery rate τ_e^* as (11).

This ends the proof.

Since (10) and (11) are completely composed of parameters and do not contain other decision variables, they are the final solution of the manufacturer's optimal decision. Substituting (10) (11) into (3)(7)(8)(9), we can obtain the optimal decision and the maximum profit of the manufacturer and the retailer when the decision is taken in the model of non- capital constraint.

Theorem 3: In the no capital constraints mode, the competition intensity of online and offline recycling channels θ positively affects the manufacturer's optimal wholesale price w^* and optimal retail price p^*, while negatively affects the optimal online recovery rate τ_e^* and optimal offline recovery rate τ_t^*.

Proof of Theorem 3: According to the proof of Theorem 2, in order to make the manufacturer have a maximum value, it is necessary to meet $\alpha(\theta^2-1)$ $(\theta\beta^2-2\beta\Delta-\Delta^2) < \beta C_L$. Therefore, it can be seen that the denominator part $a[\alpha(\theta^2-1)$ $(\theta\beta^2-2\beta\Delta-\Delta^2)-8C_L] < 0$ of (10)(11) is always valid. Since in the molecular part of (10), the coefficient of θ is $\varphi\alpha\beta^2$ $(\theta^2-1) < 0$ is always valid. Therefore, it can be seen that with the increase of θ, w^* increases monotonously, that is, the competition intensity of online and offline recycling channels θ positively affects the manufacturer's optimal wholesale price w^*. In the molecular part of (11), with the increase of θ, the molecular part of (11) increases monotonously as a whole, so (11) decreases monotonously as a whole, that is, the competition intensity of online and offline recycling channels θ negatively affects the optimal online recovery rate τ_e^*.

According to the proof of Theorem 1, in order to make the retailer have a maximum value, it is necessary to meet $4\alpha C_L/(1-\theta^2)-\alpha\beta^2 > 0$. Therefore, we can see that the denominator $\alpha^2\beta(\theta^2-1) + 4\alpha C_L > 0$ of (7) (8) is always valid. Since in the molecular part of (7), with the increase of θ, the molecular part of (7) increases monotonously as a whole, so (7) increases monotonously as a whole, that is, the competition intensity of online and offline recycling channels θ positively affects the optimal retail price p^*. In the molecular part of (8), due to $wa-\varphi < 0$, with the increase of θ, the molecular part of (7) decreases monotonously as a whole, so (7) decreases monotonously as a whole, that is, the competition intensity of online and offline recycling channels θ negatively affects the optimal offline recovery rate τ_t^*.

This ends the proof.

Theorem 3 shows that with the increase of the competition intensity of online and offline recycling channels, the wholesale price and retail price in the positive sales channel will continue to increase, which will significantly inhibit the sales market. In addition, the increase in the competition intensity will also lead to the continuous reduction of the optimal online recovery rate of the manufacturer and the optimal offline recovery rate of the retailer. Although the reduction of the optimal recovery rate can effectively reduce the cost of the manufacturer and the retailer to operate the recovery channel, it will also have a negative impact on the normal operation of the recovery channel, which is not conducive to the normal development of renewable resources industry and environmental protection.

3.3.2 Bank loan

In this model, the manufacturer has a shortage of capital due to the newly opened online recycling channel, and needs to borrow from the bank at the interest rate of r_j, and then pay additional interest to the bank in proportion after transaction. Assuming that the manufacturer's initial capital is f, the difference $Dc_m + D\beta\tau_t + I_m-f$ between the expenditure part of the manufacturer's profit function (9) and f is the loan limit that the manufacturer needs to seek from the bank. In addition, although the manufacturer has insufficient funds in this model, because its scale and technical level are far beyond the retailer, the manufacturer still occupies the dominant position in the game model with the retailer. The manufacturer first determines the amount of loan from the bank, the optimal wholesale price w of new products, and the optimal recovery rate τ_e in the online recovery channel. After observing the manufacturer's decision, the retailer optimises its own optimal decision p and τ_t. According to the reverse induction method, we first construct the retailer's profit function Π_t as:

$$\begin{aligned}\Pi_t(\tau_t, p) &= D(p-w) + D\beta\tau_t - I_t \\ &= (\varphi-\alpha p)(p-w) + (\varphi-\alpha p) \\ &\quad \beta\tau_t - C_L\left(\tau_t^2+\theta\tau_e^2\right)/(1-\theta^2)\end{aligned} \tag{13}$$

Since the profit function is consistent with the profit function (3), according to Theorem 1, we can obtain the optimal decision of the retailer in this model is p^* of (7) and τ_t^* of (8). Next, we construct the profit function of the manufacturer's loan from the bank Π_m, substitute p^* and τ_t^* into it, and we can get:

$$\begin{aligned}\prod_m(\tau_e, w) &= D(w-c_m) + D\Delta\tau_e + D(\Delta-\beta)\tau_t \\ &\quad -I_m - r_j\left(Dc_m + D\beta\tau_t + I_m - f\right) \\ &= (\varphi-\alpha p)\left(w-c_m+\Delta\tau_e+\Delta\tau_t-\beta\tau_t\right) \\ &\quad -I_m - r_j\left[(\varphi-\alpha p)(c_m+\beta\tau_t)+I_m-f\right]\end{aligned} \tag{14}$$

Theorem 4: When the manufacturer has insufficient funds and borrows from the bank, and when $\alpha(\theta^2-1)\,G < 8C_L(1+r_j)$, the manufacturer has the following optimal wholesale price w^* and online recovery rate τ_e^* to maximise its profit:

$$w^* = \frac{\varphi\left\{\alpha(\theta^2-1)\left[G+\beta^2(1+r_j)\right]-4C_L(1+r_j)\right\} - \alpha c_m\left[\alpha\beta^2(\theta^2-1)+4C_L\right](1+r_j)^2}{\alpha\left[\alpha(\theta^2-1)G-8C_L(1+r_j)\right]} \tag{15}$$

$$\tau_e^* = \Delta(\theta^2-1)\left(\varphi-ac_m-ac_mr_j\right)\Big/\left[\alpha(\theta^2-1)G-8C_L(1+r_j)\right] \tag{16}$$

In which:

$$G = -2\beta\Delta - \Delta^2 + \beta^2 r_j^2(\theta+2) + \beta^2\theta + 2\beta r_j(\beta+\beta\theta-\Delta) \tag{17}$$

Proof of Theorem 4: We first construct the Hessian matrix OF $\Pi_m(\tau_e, w)$ as follows:

$$\begin{bmatrix} \partial^2\Pi_m/\partial\tau_e^2 & \partial^2\Pi_m/\partial\tau_e\partial w \\ \partial^2\Pi_m/\partial w\partial\tau_e & \partial^2\Pi_m/\partial w^2 \end{bmatrix} = \begin{bmatrix} -2C_L(1+r_j)/(1-\theta^2) & \dfrac{-2\alpha\Delta C_L}{\alpha\beta^2\theta^2-\alpha\beta^2+4C_L} \\ \dfrac{-2\alpha\Delta C_L}{\alpha\beta^2\theta^2-\alpha\beta^2+4C_L} & \dfrac{2C_L\left\{-\beta\alpha^2\left[2\Delta-\beta\theta-\beta r_j(\theta+2)\right](\theta^2-1)-8\alpha C_L\right\}}{\left(\alpha\beta^2\theta^2-\alpha\beta^2+4C_L\right)^2} \end{bmatrix} \tag{18}$$

From the above, the first-order principle sub-formula of the Hessian matrix is $-2C_L/(1-\theta^2) < 0$, and the second-order principle sub-formula is $4\alpha C_L^2\{\alpha(\theta^2-1)G-8C_L(1+r_j)\}/(\theta^2-1)(\alpha\beta^2\theta^2-\alpha\beta^2+4C_L^2)^2$. Therefore, we only need to make $4\alpha C_L^2\{\alpha(\theta^2-1)G-8C_L(1+r_j)\}/(\theta^2-1)(\alpha\beta^2\theta^2-\alpha\beta^2+4C_L^2)^2 > 0$, that is, $\alpha(\theta^2-1)G < 8C_L(1+r_j)$, we can make the Hessian matrix negative definite matrix, and then there is a set of optimal w and τ_e^* that makes $\Pi_m(w, \tau_e)$ have a maximum.

Therefore, we solve the first-order partial derivatives of Π_m to w and τ_e respectively, set $\partial\Pi m/\partial w$ and $\partial\Pi m/\partial\tau e$ to 0 respectively, then combine them, and we can obtain the manufacturer's optimal wholesale price w^* as (15) and online recovery rate τ_e^* as (16).

This ends the proof.

Substituting the manufacturer's optimal decisions (15) (16) into (3) (4) (5) (14), we can obtain the manufacturer's and the retailer's optimal decision and maximum profit when taking the decision in the model that the manufacturer has insufficient funds and borrows from the bank.

Theorem 5: In the bank loan mode, the competition intensity of online and offline recycling channels θ positively affects the manufacturer's optimal wholesale price w^* and optimal retail price p^*, while negatively affects the optimal online recovery rate τ_e^* and optimal offline recovery rate τ_t^*.

Proof of Theorem 5: According to the proof of Theorem 4, in order to make the manufacturer have a maximum value, it is necessary to meet $\alpha(\theta^2-1)\, G < 8C_L(1 + r_j)$. Therefore, it can be seen that the denominator part $\alpha(\theta^2-1)\, \mathrm{G}-8C_L(1 + r_j) < 0$ of (15) (16) is always valid. Because in G the coefficient of θ is greater than 0 is always valid, and at the same time, in the molecular part of (15), the coefficient of G is less than 0. Therefore, for (15) as a whole, the coefficient of θ is always greater than 0. That is, with the increase of θ, w^* increases monotonously, and the competition intensity of online and offline recycling channels θ positively affects the manufacturer's optimal wholesale price w^*. In the molecular part of (16), with the increase of θ, the molecular part of (16) increases monotonously as a whole, so (16) decreases monotonously as a whole, that is, the competition intensity of online and offline recycling channels θ negatively affects the optimal online recovery rate τ_e^*.

As the profit function of the retailer in 3.3.2 and in 3.3.1 is the same, similarly to the proof of Theorem 3, it is easy prove the competition intensity of online and offline recycling channels θ positively affects the optimal retail price p^*, while negatively affects the optimal offline recovery rate τ_t^*.

This ends the proof.

Theorem 6: In the bank loan mode, the bank interest rate r_j negatively affects the optimal online recovery rate τ_e^*.

Proof of Theorem 6: According to the proof of Theorem 4, in order to make the manufacturer have a maximum value, it is necessary to meet $\alpha(\theta^2-1)G < 8C_L(1 + r_j)$. Therefore, it can be seen that the denominator part $\alpha(\theta^2-1)G-8C_L(1 + r_j) < 0$ of (16) is always valid. In the molecular part of (16), the coefficient of rj is greater than 0 is always valid. Therefore, for (16) as a whole, the coefficient of r_j is always less than 0. That is, with the increase of r_j, τ_e^* decreases monotonously, and the bank interest rate r_j negatively affects the optimal online recovery rate τ_e^*.

This ends the proof.

Both Theorem 5 and Theorem 6 show that in the bank financing mode, the competition intensity of online and offline recovery channels and bank interest rate will have a significant impact on enterprise decision-making. Among them, similar to the situation without capital constraints, the increase in channel competition intensity will not only have a negative impact on the product sales market, but also inhibit the recovery rate in online and offline recovery channels, which is not conducive to the development of renewable resources industry. In addition, the bank's increase in interest rate will also force the manufacturer to reduce channel operating cost by reducing online recycling rate, damaging the overall interest of the entire dual channel reverse supply chain.

3.3.3 Internal financing

In this model, the manufacturer chooses internal financing in the supply chain in case of insufficient funds, that is, borrows from the retailer. After the whole transaction is completed, the interest is paid to the retailer at the rate of r_i. Compared with external financing mainly based on bank loan, enterprises in the supply chain have a better understanding of each other's actual business information, which is conducive to making loans at a faster speed and with a higher amount. Similar to the assumption in 3.2, the manufacturer's funding gap is $Dc_m + D\beta\tau_t + I_m - f$, and it needs to seek loans from the retailer at this amount. According to the reverse induction method, we first construct the retailer's profit function Π_t as:

$$\begin{aligned}\Pi_t(\tau_t, p) &= D(p-w) + D\beta\tau_t - I_t + r_i\left(Dc_m + D\beta\tau_t + I_m - f\right)\\ &= (\varphi - \alpha p)(p - w + \beta\tau_t) - I_t + r_i\left[(\varphi-\alpha p)(c_m + \beta\tau_t) + I_m - f\right]\end{aligned} \tag{19}$$

Theorem 7: In the model where the manufacturer has insufficient funds and finances from the retailer, when $4C_L(\theta r_i - 1)/(\theta^2 - 1) > \alpha\beta^2(r_i + 1)^2$, the retailer has the following optimal retail price p^* and the offline recovery rate τ_t^* to maximise its profit:

$$\begin{aligned}p^* = {}&\varphi\alpha\beta^2(\theta^2-1)(r_i+1)^2 + 2C_L(1-\theta r_i)\left(\alpha w + \varphi - \alpha c_m r_i\right)/\alpha\left[\alpha\beta^2\right.\\ &\left.(\theta^2-1)(r_i+1)^2 + 4C_L(1-\theta r_i)\right]\end{aligned} \tag{20}$$

$$\tau_t^* = \beta(\theta^2-1)(r_i+1)\left(\alpha w - \varphi - \alpha c_m r_i\right)/\left[\alpha\beta^2(\theta^2-1)(r_i+1)^2 + 4C_L(1-\theta r_i)\right] \tag{21}$$

Proof of Theorem 7: We first construct the Hessian matrix of $\Pi_t(p, \tau_t)$ as follows:

$$\begin{bmatrix} \partial^2\Pi_t/\partial p^2 & \partial^2\Pi_t/\partial p\partial\tau_t \\ \partial^2\Pi_t/\partial\tau_t\partial p & \partial^2\Pi_t/\partial\tau_t^2 \end{bmatrix} = \begin{bmatrix} -2\alpha & -\alpha\beta - \alpha\beta r_i \\ -\alpha\beta - \alpha\beta r_i & 2C_L(\theta r_i - 1)/(1-\theta^2) \end{bmatrix} \tag{22}$$

From the above, the first-order principle sub-formula of the Hessian matrix is $-2\alpha < 0$, and the second-order principle sub-formula is $4C_L\alpha(\theta r_i - 1)/(\theta^2-1) - \alpha^2\beta^2(r_i + 1)^2$. Therefore, we only need to make $4C_L\alpha(\theta r_i - 1)/(\theta^2-1) - \alpha\beta^2(r_i + 1)^2 > 0$, that is, $4C_L(\theta r_i - 1)/(\theta^2-1) > \alpha\beta^2(r_i + 1)^2$, the Hessian Matrix can be made a negative definite matrix, and then there is a set of optimal p* and τt* that makes $\Pi_t(p, \tau_t)$ have a maximum.

Therefore, we solve the first-order partial derivatives of Π_t to p and τ_t respectively, set $\partial\Pi_t/\partial p = 0$ and $\partial\Pi_t/\partial\tau_t = 0$ respectively, and then combine them. We can obtain the optimal retail price p^* of the retailer as (20), and the optimal offline recovery rate τ_t^* as (21).

This ends the proof.

After obtaining the retailer's optimal decision (20) (21), we construct the manufacturer's profit function and substitute (20) (21), and we can get:

$$\begin{aligned}\Pi_m(\tau_e, w) &= D(w - c_m) + D\Delta\tau_e + D(\Delta-\beta)\tau_t^* - I_m\\ &\quad - r_i\left(Dc_m + D\beta\tau_t^* + I_m - f\right)\\ &= (\varphi - \alpha p^*)\left[w - c_m + \Delta\tau_e + (\Delta-\beta)\tau_t^*\right]\\ &\quad - I_m - r_i\left[(\varphi-\alpha p^*)(c_m + \beta\tau_t^*) + I_m - f\right]\end{aligned} \tag{23}$$

Theorem 8: In the model where the manufacturer has insufficient funds and finances from the retailer, when $N(1 + r_i)/(\theta^2-1) > \alpha\Delta^2(\theta r_i - 1)^2$, the manufacturer has the following optimal wholesale price w^* and online recovery rate τ_e^* to maximise its profit:

$$w^* = \left\{\varphi\left[(1+r_i)(\theta r_i - 1)M + H\right] + \alpha c_m K\right\}/\alpha H \tag{24}$$

$$\tau_e^* = -\Delta(\theta^2 - 1)(\varphi - ac_m)(\theta r_i - 1)^2 / H \tag{25}$$

in which

$$\begin{aligned} H = {} & 8C_L(1+r_i)(\theta r_i - 1)^2 - \alpha(\theta^2 - 1) \\ & \left[-2\beta\Delta - \Delta^2 + \beta^2\theta + 2r_i\left(\beta\Delta\theta - 2\beta\Delta + 2\beta^2\theta + \Delta^2\theta\right)\right] \\ & -\alpha(\theta^2 - 1)\left[r_i^2\left(6\beta^2\theta - \Delta^2\theta^2 - 2\beta\Delta + 4\beta\Delta\theta\right)\right. \\ & \left. +2\beta\theta r_i^3(2\beta + \Delta) + \beta^2\theta r_i^4\right] \end{aligned} \tag{26}$$

$$\begin{aligned} K = {} & -\alpha(\theta^2 - 1)\left[\beta^2 + r_i\left(2\beta\Delta + \Delta^2 + 3\beta^2 - 2\beta^2\theta\right)\right] \\ & + r_i^2\left(3\beta^2 - 7\beta^2\theta - 2\Delta^2\theta + 4\beta\Delta - 2\beta\Delta\theta\right) \\ & + r_i^3\left(\beta^2 - 9\beta^2\theta + 2\beta\Delta - \beta\Delta\theta + \Delta^2\theta^2\right) \\ & - \beta\theta r_i^4(5\beta + 2\Delta) - \beta^2\theta r_i^5 - 4C_L(1 + 3r_i + 2r_i^2)(\theta r_i - 1)^2 \end{aligned} \tag{27}$$

$$M = \alpha\beta^2(\theta^2 - 1)(1 + r_i)^2 + 4C_L(1 - \theta r_i) \tag{28}$$

$$N = -8C_L(1 - \theta r_i)^2 + \alpha\beta(\theta^2 - 1)(1 + r_i)\left(\beta\theta - 2\Delta + 2\beta\theta r_i + 2\Delta\theta r_i + \beta\theta r_i^2\right) \tag{29}$$

Proof of Theorem 8: We first construct the Hessian matrix of $\Pi_m(\tau_e, w)$ as follows:

$$\begin{bmatrix} \partial^2\Pi_m/\partial\tau_e^2 & \partial^2\Pi_m/\partial\tau_e\partial w \\ \partial^2\Pi_m/\partial w\partial\tau_e & \partial^2\Pi_m/\partial w^2 \end{bmatrix} = \begin{bmatrix} -2C_L(1+r_i)/(1-\theta^2) & -2\alpha\Delta C_L(1-\theta r_i)/M \\ -2\alpha\Delta C_L(1-\theta r_i)/M & 2\alpha C_L N/M^2 \end{bmatrix} \tag{30}$$

From the above, the first-order principle sub-formula of the Hessian matrix is $-2C_L(1 + r_i)/(1-\theta^2) < 0$, and when $N(1 + r_i)/(\theta^2-1) > \alpha\Delta^2(\theta r_i-1)^2$, the second-order principal sub-formula is always greater than 0. Therefore, we only need to set $N(1 + r_i)/(\theta^2-1) > \alpha\Delta^2(\theta r_i-1)^2$ to make the Hessian Matrix a negative definite matrix, and then there is a set of optimal w and τ_e^* that makes $\Pi_m(w, \tau_e)$ have a maximum.

Therefore, we solve the first-order partial derivatives of Π_m to w and τ_e respectively, set $\partial\Pi m/\partial w$ and $\Pi m/\partial\tau e$ ∂ to 0 respectively, and then combine them. We can obtain the manufacturer's optimal wholesale price w* as (24) and the online recovery rate τ_e^* as (25).

This ends the proof.

Substituting the manufacturer's optimal decisions (24) (25) into (19) (20) (21) (23), it can be obtained that the manufacturer's and the retailer's optimal decision and the maximum profits when the decision is taken.

Thus far, we obtain the optimal strategies of each enterprise in the dual channel closed-loop supply chain in the two models of bank loan and retailer financing when the manufacturer has capital constraints. And we can see that when each enterprise takes its optimal pricing and recovery rate decision, it can achieve the only realisation of its optimal profit. In addition, when facing such management issues in reality, the enterprise also needs to make new decisions on financing model selection, pricing, and recovery rate under the change and effect of different parameters. For example, when the interest rate in the two models of bank loan and retailer financing are equal, how should the manufacturer choose the financing model? How will the choice of the manufacturer affect the profits of the retailer and the supply chain system? When the competition intensity between the recycling channels operated by the manufacturer and retailer changes, what changes will happen to the manufacturer' s choice of financing model? When the interest rates of the two financing models are not equal, how will they affect enterprise decision and profit? The above are all management issues that directly affect enterprise profit and are of great practical significance and enlightenment. However, because the expression of the final solution result of the model is too complicated, we cannot obtain some meaningful management enlightenment through intuitive analysis of them. Therefore, we need to use case study method in the next section to further analyse the model results and obtain more valuable management suggestions.

4 Case study and discussion

In this section, we will use numerical analysis to verify the results in Section 3 and provide management suggestions related to recovery price and recovery rate for the enterprise in dual channel closed-loop supply chain. Specifically, we will separately verify the competition coefficient θ between different recycling channels and the interest rate r of the financing model, and the influence of the changes of these two parameters on the decision and profit of the enterprise and the supply chain system. Under the constraints of Nomenclature, similar to the study of Wu et al. (2020), we assume $\beta = 200$, $c_m = 50$, $c_t = 40$, $\Delta = c_m - c_t = 10$, $\varphi = 500$, $C_L = 200$, $\alpha = 1$, $f = 1000$. In addition, in order to distinguish, we add subscript j to all the decision variables and objective functions in the bank loan model, and subscript i to the above notations in the retailer financing model.

4.1 Analysis of channel competition intensity

In this section, we study the influence of changes of the competition intensity θ on the choice of the manufacturer's financing model, assuming that the interest rates of bank loan and retailer financing are equal to $r_i = r_j = 0.2$ and remain unchanged. On the one hand, channel competition intensity is reflected in the continuous increase of channel competition intensity caused by the manufacturer and the retailer competing for the recycling market and optimising their own profit after the manufacturer introduces online recycling channels. On the other hand, channel competition intensity can also reflect the actual differences in the process of the enterprise operating online and offline recycling channels in the recycling market for different waste products. For example, in China, because the government only grants limited enterprises permission to dismantle waste mobile phones, the competition intensity of online and offline channels for recycling waste TV set market is much higher than that for waste mobile phone market. Specifically, we assume that channel competition intensity θ gradually increases from 0.2 to 0.6 at the rate of 0.1, and use Mathematica software to obtain the optimal decision and profit of the manufacturer, the retailer, and the whole supply chain system in the two financing models, as shown in Table 3 and Table 4. At the same time, we draw line chart of the influence of θ on enterprise decision and profit, as shown in Figure 2 and Figure 3.

Table 3 The influence of θ on decision and profit in the bank loan model

θ	w_j	p_j	τ_{tj}	τ_{ej}	Π_{mj}	Π_{tj}	Π_j
0.1	58.02	76.04	0.59	0.74	8,584.27	4,917.36	13,501.63
0.2	58.71	76.54	0.56	0.70	8,411.56	4,637.51	13,049.07
0.3	59.50	77.15	0.52	0.65	8,196.51	4,347.83	12,544.34
0.4	60.36	77.86	0.47	0.58	7,950.59	4,067.09	12,017.68
0.5	61.24	78.62	0.40	0.50	7,684.49	3,809.23	11,493.72
0.6	62.11	79.41	0.33	0.41	7,407.58	3,583.43	10,991.01

Table 4 The influence of θ on decision and profit in the retailer's financing model

θ	w_i	p_i	τ_{ti}	τ_{ei}	Π_{mi}	Π_{ti}	Π_i
0.1	59.06	71.92	0.85	0.87	10,728.60	6,401.86	17,130.46
0.2	60.11	72.63	0.82	0.82	10,464.60	5,943.77	16,408.37
0.3	61.32	73.55	0.77	0.75	10,118.40	5,452.21	15,570.61
0.4	62.60	74.63	0.69	0.67	9,714.53	4,968.22	14,682.75
0.5	63.85	75.79	0.61	0.57	9,277.16	4,522.82	13,800.98
0.6	65.01	76.99	0.50	0.46	8,828.18	4,136.18	12,964.36

On the one hand, Figure 2 and Figure 3 show that with the increase of competition intensity between channels θ, in the two financing models, the manufacture's optimal decision and profit, the retailer's optimal decision and profit, and the total profit of the supply chain system all show the same change trend. Specifically, for the manufacturer, channel competition intensity is positively correlated with its optimal wholesale price w, and negatively correlated with its online recovery rate τe and profit Π_m; for the retailer, channel competition intensity is positively correlated with its optimal retail price p, and negatively correlated with its offline recovery rate τt and profit Π_t; for the whole supply chain system, channel competition intensity is negatively correlated with its total profit Π. This first shows that the intensification of competition between channels will lead to higher wholesale and retail prices, inhibit consumers' purchase enthusiasm and product sales, and cause the adverse result of reducing the total profit of both individual enterprise and supply chain system. Secondly, the high level of channel competition intensity also increases the cost burden of the manufacturer and the retailer operating recycling channels. In order to reduce the recovery cost and the profit loss, the above enterprises have to reduce the recovery rate. It can be seen that the high level of channel competition intensity has a significant inhibitory effect on the recovery rates of online and offline channels, which is not conducive to motivating the manufacturer and the retailer to actively carry out product recovery activities. Finally, compared with the manufacturer, the negative correlation of channel competition intensity on retailer's profit is more significant, and the profit gap between the two enterprises also increases with the increase of competition intensity. This shows that high-level channel competition not only does more harm to the retailers as followers, but also further deepens the profit enterprise acquisition gap between the supply chain enterprises, which is not conducive to the overall stability and coordination of the supply chain system.

On the other hand, from Figure 2 and Figure 3, it can be seen that when interest rates are equal and remain unchanged, there are significant differences in the decisions and profits of the enterprises in the two financing models. Specifically, the manufacturer's wholesale price w, online recovery rate τ_e, and profit Π_m in the retailer financing model are significantly higher than those in bank loan model. The retailer's offline recovery rate τ_t and profit Π_t in retailer financing model are significantly higher than those in bank loan model, and the retail price p is significantly lower than that in bank loan model. The total profit Π of the supply chain system in retailer financing model is significantly higher than that in bank loan model. In bank loan model, the manufacturer's online recovery rate τ_e is always higher than the retailer's offline recovery rate τ_t; in retailer's financing model, when competition intensity is low, the online recovery rate τ_e is higher than the offline recovery rate τ_t, and the opposite result occurs when competition intensity is high. This first shows that whether it is for the manufacturer, the retailer or the supply chain system, retailer financing model can bring higher economic profit than bank loan model. At the same time, it should not be overlooked that consumers can also purchase products at lower retail prices in retailer financing model. There is no doubt that the choice of retailer financing by the manufacturer can ensure that it is optimal for consumers and business participants. Therefore, the manufacturers should further actively seek financial cooperation with the retailer. Secondly, since the online recovery rate of the manufacturer or the offline recovery rate of the retailer in retailer financing model is significantly higher than that in bank loan model, this indicates that the capital exchange within the supply chain is more conducive to enterprises to strengthen the investment and operation of recovery channels, and then greatly contribute to the cause of environmental protection. Finally, when channel competition intensity is low, the online recovery rate is higher than the offline recovery rate, which indicates that the stability and coordination of the supply chain system is more conducive to the manufacturer to develop and operate online recycling channels at a high level. When channel competition intensity increases, in order to reduce the conflict with offline recycling channels operated by the retailer, the manufacturer has to continuously reduce the online recovery rate, thereby reducing the recovery volume and recovery cost.

Figure 2 The change of decision as θ increases (see online version for colours)

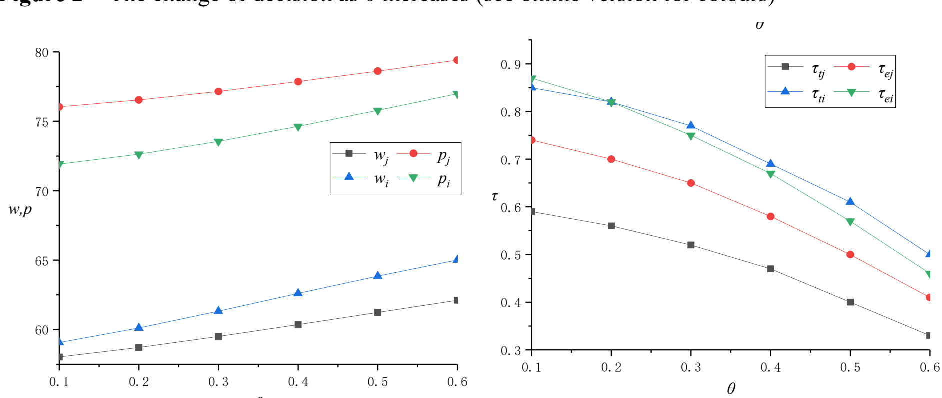
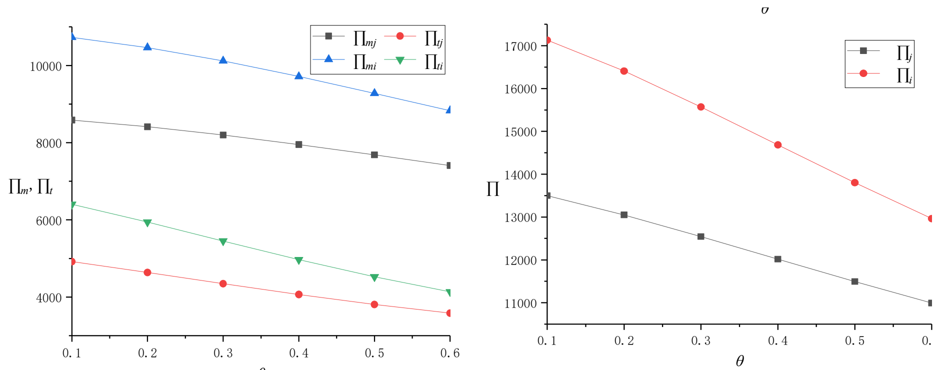


Figure 3 The change of profit as θ increases (see online version for colours)



4.2 *Interest rate analysis*

In this section, we will study and verify the cross influence of the interest rate of bank loan model and retailer financing model on enterprise decision and profit. Whether it is a bank or a supply chain cooperative enterprise willing to provide financing, the change of its interest rate will affect the interest that the manufacturer needs to repay after the transaction is completed, and then affect the profit and optimal decision of the supply chain participating enterprise. In reality, factors such as price changes, policy adjustments and enterprise credit will all have an important influence on interest rate. Specifically, in this section, we assume that $\theta = 0.5$ remains unchanged, and the interest rates of the two financing models both increase from 0.1 to 0.6 at the rate of 0.1. By using Mathematica software to numerically solve the model result in Section 2, we can obtain the optimal decision and profit of each enterprise in the two models of bank loan and retailer financing, as shown in Table 5 and Table 6 respectively. At the same time, we also draw a line chart of the influence of r on enterprise decision and profit, as shown in Figure 4 and Figure 5.

Table 5 The influence of r on decision and profit in bank loan model

r_j	w_j	p_j	τ_{tj}	τ_{ej}	Π_{mj}	Π_{tj}	Π_j
0.1	58.87	77.31	0.43	0.58	8,326.77	4,218.63	12,545.40
0.2	61.24	78.62	0.40	0.50	7,684.49	3,809.23	11,493.72
0.3	63.45	79.83	0.38	0.44	7,105.75	3,431.35	10,537.10
0.4	65.53	80.98	0.36	0.38	6,581.58	3,083.87	9,665.45
0.5	67.49	82.06	0.34	0.34	6,105.38	2,764.99	8,870.37
0.6	69.36	83.09	0.32	0.30	5,672.09	2,472.72	8,144.81

On the one hand, it can be seen from Figure 4 and Figure 5 that the interest rate in the two financing models is positively correlated with the manufacturer's wholesale price w and the retailer's retail price p, while negatively correlated with the manufacturer's online recovery rate τ_e, the retailer's profit Π_t and the total profit of the supply chain system Π. In addition, it can be seen that the interest rate r_j of bank loan model is negatively correlated with the offline recovery rate τ_t, while the interest rate ri of retailer financing model is positively correlated with the offline recovery rate τ_t; the interest rate r_j of bank loan model is negatively correlated with the manufacturer's profit Π_m, while the interest rate r_i of retailer financing model is first positively correlated and then negatively correlated with the manufacturer's profit Π_m. This shows that regardless of financing models, the increase of interest rate will have a negative effect on the profits of the retailer and the supply chain system. It is worth noting that, although intuitively, the increase of interest rate in retailer financing model is conducive to helping the retailer obtain higher interest, in fact, this also leads to a substantial increase in wholesale prices and increases the retailer's operating cost, and then lower profits. From this point of view, when interest rate is low, the retailer's raising interest rate belongs to the behaviour of 'harm others and itself'; when interest rate is high, the retailer's raising interest rate belongs to the behaviour of 'benefit others and harm itself'. Therefore, when the manufacturer chooses retailer financing model, the retailer should lower interest rate as much as possible whether it is to increase the profit of itself or the manufacturer. In addition, the above results also show that the increase of interest rate in bank loan model urges the manufacturer and the retailer to reduce the recovery rate, which is not conducive to their further development of recovery channels. In retailer financing model, although the increase of interest rate can significantly promote the retailer's offline recovery rate, the retailer's total cost increases sharply and profit decreases significantly, which is not conducive to the normal operation of the enterprise.

Table 6 The influence of r on decision and profit in retailer financing model

r_i	w_i	p_i	τ_{ti}	τ_{ei}	Π_{mi}	Π_{ti}	Π_i
0.1	59.94	75.83	0.52	0.62	9,162.57	4,635.73	13,798.30
0.2	63.85	75.79	0.61	0.57	9,277.16	4,522.82	13,799.98
0.3	68.16	75.81	0.69	0.52	9,371.81	4,315.34	13,687.15
0.4	72.92	75.93	0.79	0.48	9,425.30	3,999.62	13,424.95
0.5	78.34	76.24	0.89	0.45	9,410.89	3,558.43	12,969.32
0.6	84.52	76.81	0.99	0.41	9,295.89	2,977.97	12,273.86

On the other hand, it can be seen from Figure 4 and Figure 5 that when the interest rates in the two financing models remain equal, there are significant differences in various decisions and profits of the enterprises. Specifically, the wholesale price w_i, online recovery rate τ_{ei}, offline recovery rate τ_{ti}, manufacturer profit Π_{mi}, retailer profit Π_{ti}, and total supply chain system profit Π_i in retailer financing model are all significantly higher than those in bank loan model, the wholesale price w_j, online recovery rate τ_{ej}, offline recovery rate τ_{tj}, manufacturer profit Π_{mj}, retailer profit Π_{tj} and total supply chain system profit Π_j. At the same time, the retail price p_i in retailer financing model is significantly lower than the wholesale price p_j in bank loan model. This shows that whether it is for the manufacturers or the retailer, retailer financing model can bring higher economic profits to the above enterprises than bank loan model. In this model, the lower retail price stimulates consumers' purchase enthusiasm and greatly increases product sales. Although the retailer's unit product profit decreases slightly, the increase of total sales volume and the interest obtained from the manufacturer can significantly increase the retailer's profit. For the manufacturer, the increase of sales volume and unit profit contribute to the substantial increase of its total profit. At the same time, the research results also show that retailer financing model can bring higher social and environmental benefits than bank loan model. In retailer financing model, the online and offline recovery rates are significantly higher than those in bank loan model. The high level of recovery rate not only helps the enterprise obtain more remanufactured raw materials through the recycling process, which has the effect of resource conservation, but also reduces harmful emissions from the manufacturing and remanufacturing processes to nature, contributing to the cause of global sustainable environmental protection. In summary, both the manufacturer and retailer should actively develop a supply chain finance model based on retailer financing for the purpose of improving economic profits or promoting environmental benefits.

Figure 4 The change of decision as r increases (see online version for colours)

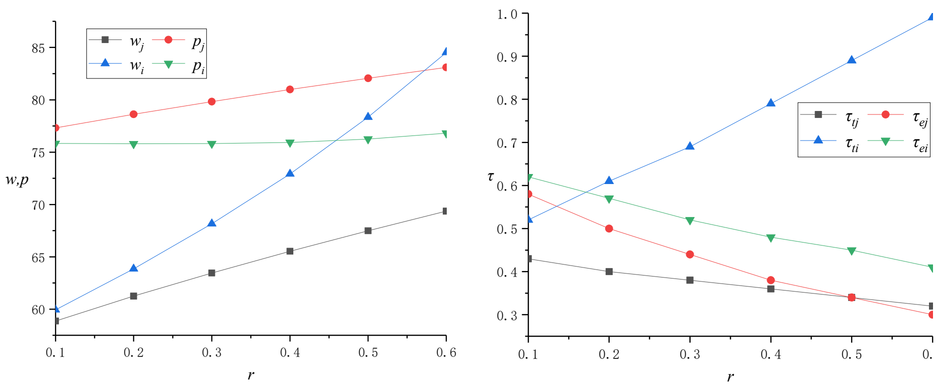
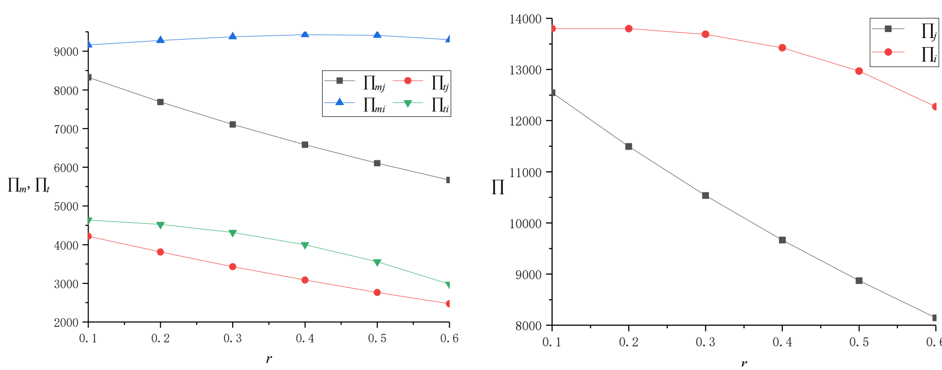


Figure 5 The change of profit as r increases (see online version for colours)



5 Conclusions

In order to solve the problem of financing and pricing strategies when the manufacturer faces capital constraints in constructing online recycling channels, this paper first proposes a dual channel closed-loop supply chain decision model in two financing modes: retailer financing and bank loan. Then, we use Stackelberg game theory to solve the model, and obtain the optimal pricing, recovery rate decision and optimal profit of the manufacturer and retailer in the two financing modes when channel competition intensity and interest rate change. Finally, through case study, we further analyse the optimal decision and profit, and put forward management suggestions for the manufacturer's financing strategy based on the comprehensive consideration of the economic profit and social environmental performance.

According to the research results of the interest rate, we provide the following insights respectively from the three aspects of bank loan, internal financing and their comparison:

1 In the bank loan mode, the interest rate not only negatively affects the manufacturer's recovery rate, but its increase also exhibits the retailer's recovery rate, which is not conducive to the development of recovery channels for enterprises

2 In the internal financing mode, when the interest rate is low, the retailer will increase the interest rate for the manufacturer to 'harm others and itself', while when the interest rate is high, the retailer will increase the interest rate to 'benefit others and harm itself'

3 By comparing the bank loan mode and the internal financing mode, we can find that the retailer financing mode can bring higher economic profit to the manufacturer and the retailer than the bank loan mode. In addition, in the retailer financing mode, the recovery rate of the manufacturer and the retailer is significantly higher than that in the bank loan mode.

This study puts the following suggestions to the manufacturer and the retailer respectively:

1 For the manufacturer, since the economic profit and recovery rate of the supply chain members in the retailer financing mode is significantly higher than that in the bank loan mode, when the manufacturer faces financial pressure, it should seek and strengthen financing cooperation with the retailer through technical cooperation, contract design, information sharing, etc. so as to contribute to environmental protection, and achieve mutual benefit and win-win results in the supply chain while promoting the continuous improvement of product recovery rate

2 For the retailer, it should not set higher interest rate in the retailer financing mode. Although the retailer can obtain higher interest rate at a high level in the short term, the inhibition of the recycling market will continue to damage the overall economic performance of the retailer, the manufacturer and the entire supply chain system, which is not conducive to the long-term sustainable development of the entire renewable resources recycling industry.

In addition, this paper lays a theoretical foundation for future research in this field from the following aspects:

1 The participants in the supply chain decision-making model constructed in this paper include the manufacturer and the retailer. However, in reality, the supplier, as an important participant in reverse logistics, also plays an important role in upstream and downstream financing of the supply chain. Future scholars can incorporate the supplier into financing decision models to observe the impact of its decisions on other enterprises' decisions and profits

2 Based on the models in this paper, it will be an interesting topic to consider the effect of policy factors such as carbon tax and carbon subsidy on enterprise recovery rate and profit in the process of manufacturer production and recovery

3 This paper discusses the manufacturer's self-built online recycling channel model, but in reality, there is also a model in which the manufacturer entrusts a professional third-party enterprise to build online recycling platform. Therefore, it will also be of great significance to bring third-party recycling platform into the research on the decision of dual channel closed-loop supply chain considering capital constraints

4 In recent years, relying on its high-level of subsidies, the trade-in model based on online platform set off a huge wave in both product sales and recycling. Therefore, in closed-loop supply chain based on trade-in model, when the manufacturer faced with capital constraints, how to cooperate with the platform and the retailer to make financing, pricing and subsidy decisions will become a key issue in future research.

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