The Retailer's Capital-constrained Risk-averse Closed-loop Supply Chain Financing Strategy Considering Product Heterogeneity

Chengdong Shi, Yongzheng Yin

***Abstract*—The recycling and remanufacturing of materials is an important method of improving the efficiency of resource utilisation. However, it is often subject to financial constraints that increase the risk of chain breakage in the closed-loop supply chain of recycling and remanufacturing. Furthermore, market uncertainty exacerbates this risk. Consequently, it is necessary to investigate different financing models for the supply chain. In this paper, we utilise a closed-loop supply chain comprising a risk-averse manufacturer, a capital-constrained retailer and a remanufacturer responsible for recycling and remanufacturing as a case study. We employ game theory and mean-variance theory to investigate the financing strategies of the closed-loop supply chain under capital constraints. Firstly, a financing decision model in which the retailer has the ability to obtain bank loans is constructed as a reference model. On this basis, the financing model of commercial credit financing and the combined financing model of equity transfer and bank financing are considered separately in order to explore the impact of the retailer's financing strategy on heterogeneous product pricing and risk-averse supply chain returns. The computational results demonstrate that the manufacturer provides financial support to the remanufacturer by reducing the patent license fee, which enables the remanufacturer to invest more resources in recycling activities and, consequently, enhances the efficiency of resource utilization within the supply chain. The simulation results indicate that the retailer and the remanufacturer prefer the commercial credit financing model, although the combined strategy of equity transfer and bank financing can result in gains. It is also noteworthy that the manufacturer's risk aversion benefits not only the entire supply chain but also consumers.**

***Index Terms*—closed-loop supply chain; financial constraints; commercial credit; third-party remanufacturing**

I. INTRODUCTION

IN 2019, the Ministry of Industry and Information Technology in China revealed that small and medium-sized enterprises (SMEs), which constitute 99% of all enterprises in the country, contribute a substantial 50% to tax revenue and generate over 60% of the gross domestic product (GDP). However, in contrast to well-funded large-scale enterprises, SMEs often encounter difficulties in accessing capital, which can result in challenges such as low credit ratings and a paucity of collateral assets. This can hinder their ability to secure bank loans [1]. In order to address these issues, the Central Bank, in collaboration with eight other ministries and commissions, issued the "Opinions on Regulating the Development of Supply Chain Finance to Support the Stable Circulation and Optimization and Upgrading of the Supply Chain Industrial Chain" in September 2020. The document highlighted the necessity for financial institutions and core enterprises to enhance collaboration and information sharing, thereby deepening the synergistic impact of data and clarifying the direction for the development of supply chain finance. Moreover, the 2022 Government Work Report took a further step by proposing to "endeavour to cultivate a conducive financing environment and further explore solutions to the financing challenges faced by the real economy, particularly for small, medium, and micro enterprises."

The remainder of this paper is structured as follows. Section II outlines the theoretical background by reviewing the relevant literature. Section III presents the assumptions about this supply chain, the associated notation, and the corresponding game model. Section IV utilises parameter analysis and numerical simulations to visualise the theoretical results. Finally, Section V discusses the main findings, theoretical contributions, and management insights.

II. LITERATURE REVIEW

The following section presents a comprehensive review of the literature pertinent to our study, organised according to four key areas: financing methods, financial constraints, patent licensing, and closed-loop supply chains. The research background is presented, and the innovative nature of this study is discussed.

A. Financing Methods

One of the principal methods of supply chain finance is to depend on banks and other financial institutions for financing. The rapid development of information and Internet technology has led to the increasing importance of online supply chain finance in improving supply chain performance from multiple perspectives, including capital and information [2]. As early as September 2018, China Construction Bank launched the "Hui-know-you" online financing platform for capital-constrained small and medium-sized enterprises in the supply chain. The objective was to reduce the cost of enterprise financing, improve the efficiency of financing

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services, and enhance the competitiveness of the supply chain. The impact of commercial credit on business development as a corporate finance tool is particularly significant in the context of short-term financing. Commercial credit has a discernible alleviating effect on financing constraints. It provides enterprises with greater liquidity and greater flexibility in production and operation under different conditions [3]. Jena [4] constructed a game model of a two-channel supply chain and a multi-channel supply chain to analyse the impact of external financing and trade credit supply chain financing schemes on price-sensitive demand and supply chain profits. In their study, Li and Jiang [5] examined the optimal decision-making process in a two-level supply chain comprising suppliers and capital-constrained retailers. In this context, retailers are able to obtain bank credit to fulfil their own ordering decisions through suppliers' credit guarantees.

The other is trade credit between firms within the supply chain. Borrowing and lending activities are conducted through the medium of delayed payments and other financial instruments during the course of business transactions. In particular, suppliers permit retailers with limited financial resources to place orders first and repay at the conclusion of the selling season. From 2019 to 2020, the e-commerce giant Amazon provided more than $1 billion in loans to suppliers in the United States, China, and other countries, thereby supporting their growth [6]. A three-echelon supply chain comprising commercial banks, e-commerce platforms and capital-constrained online retailers was subjected to analysis. In this context, retailers have limited creditworthiness and access to only restricted bank loans, while the remainder require the use of e-commerce platforms to finance their businesses [7].

In the financial markets, capital-constrained MSMEs can address the lack of working capital by selling equity. In contrast to debt financing, equity financing does not require the enterprise to repay the principal and interest to the investors. However, the enterprise is obliged to share the profits and growth of the enterprise with the investors. Equity financing represents a viable solution to the capital constraints faced by MSMEs, offering a means of mitigating the risk of bankruptcy. Consequently, equity financing has been rapidly developing in the financial market. Jiang et al. [8] examined a supply chain comprising a well-capitalised supplier and a capital-constrained small-scale retailer. In the event of a shortage of capital, the retailer's alternative financing options were considered. Yang et al. [9] investigated the impact of external financing on participants' optimal decision-making and the supply chain performance. In a study by Fu et al. [10], the potential benefits to third-party logistics companies of external equity financing support for their supply chains were examined.

B. Financial Constraints

It is inevitable that supply chain financing activities will result in bankruptcy for capital-constrained small and medium-sized enterprises (SMEs). In 2011, Zhejiang Tianshi Electronics Company was unable to repay a 50 million yuan loan to the bank and was consequently declared bankrupt. Consequently, in recent years, numerous scholars have considered the risk inherent in supply chain models. Shen [11] examined a supply chain system comprising a capital-constrained manufacturer and two retailers. The study analysed the risk aversion of the member firms and the impact of the retailer's degree of competition on the manufacturer's decision on financing options. Feng [12] proposed a two-level fresh agricultural product supply chain decision model, in which the supplier is risk-neutral and the retailer is risk-averse. In a study of a mass customisation supply chain, Choi [13] applied mean-variance to portray the risk attitudes of both the manufacturer and the retailers, which were both risk-averse.

C. Patent Licensing

A patent protection system represents an essential institutional guarantee for technology transfer. In this context, patent authorization constitutes a pivotal factor in technology transfer and the formation of genuine productivity. In the first half of 2019, the amount of patented technology licensed in China reached 723.9 billion yuan, representing a year-on-year increase of 23.6%. Zhang [14] examined the relationship between R&D investment and technology licensing in supply chains comprising original equipment manufacturers (OEMs) and contract manufacturers (CMs). Huang and Wang [15] employed a game analysis of technology licensing to investigate the advantages of information sharing among manufacturers, distributors, and third parties in a closed-loop supply chain under three remanufacturing scenarios.

D. Closed-loop Supply Chain

Meanwhile, the significance of remanufacturing used products into new ones has been widely acknowledged in both literature and practice [16]. In a closed-loop supply chain of third-party remanufacturing, the third-party remanufacturer is responsible for recycling used products and remanufacturing the recycled products in order to achieve efficient resource utilisation. Some consumers may choose to participate in the recycling of used products and purchasing remanufactured products independently, motivated by both environmental protection and financial benefits. Remanufacturing, in particular third-party remanufacturing, has emerged as a pivotal strategy for Original Equipment Manufacturers (OEMs) to effectively reconcile economic benefits with environmental impacts [17]. In a study by Wu [18], a game-theoretic model was developed to re-examine the impact of pricing strategy in a closed-loop supply chain. The findings indicated that third-party remanufacturing could result in a win-win-win situation for the supplier, the OEM, and potentially consumers, regardless of the pricing policy.

In the event of a retailer going out of business due to financial constraints, this will inevitably have an impact on the upstream manufacturer in the supply chain, potentially leading to a risk-averse mindset. Against this background, this paper considers the risk aversion of the manufacturer and the financial constraints of the retailer. A closed-loop supply chain model is developed, comprising a manufacturer, a retailer, and a third-party remanufacturer. The study examines the financing decisions faced by the retailer, with a particular focus on bank borrowing, commercial credit financing, and a combination of equity financing and bank loans. Furthermore, the study examines how the retailer makes financing choices with varying degrees of risk aversion and how the manufacturer's risk-averse behaviour affects the overall dynamics of the supply chain.

III. Methodology

A. Model Description

As illustrated in Figure 1, the manufacturer is accountable for the production of the novel products and their subsequent distribution to the retailer. The retailer then sells the products to the consumer. Once consumers have used the new products, they will generate waste products. The remanufacturer collects the used products from consumers and manufactures the remanufactured products. The remanufacturer will then sell the remanufactured products through the retailer. In this process, the remanufacturer is required to pay a patent license fee to the manufacturer and to dispose of used products that cannot be remanufactured.

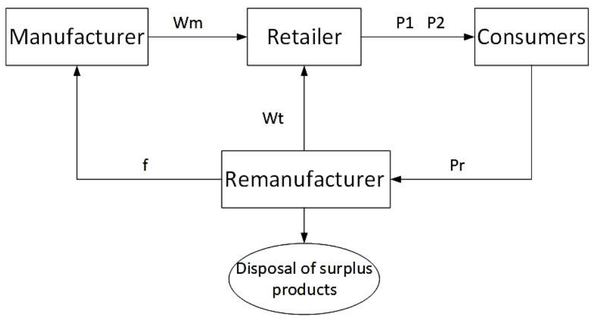

Fig. 1. Supply chain structure diagram.

B. Model Assumptions and Parameter Interpretation

In order to construct and quantitatively evaluate the profit functions of the manufacturer, retailer, and remanufacturer, we assume that the closed-loop supply chain model, which incorporates the retailer's capital constraint, satisfies the following conditions: These conditions serve to specify the variables and parameters utilized in the model.

Assumption 1. The manufacturer and remanufacturer have access to sufficient capital, whereas the retailer is constrained by financial limitations. These constraints can be addressed by seeking commercial credit from other chain members, obtaining off-chain equity financing, or securing bank loans. For the sake of simplicity, it is assumed that the exchange of information between the firms involved in this study is perfectly symmetric.

Assumption 2. Drawing on the literature [19], the demand functions for new and remanufactured products as $D_1 = Q - \frac{p_1 - p_2}{1-\theta} + \varepsilon$, $D_2 = \frac{\theta p_1 - p_2}{\theta(1-\theta)} + \varepsilon$. Where ε is a stochastic demand, consider $E(\varepsilon) = 0$, $Var(\varepsilon) = \sigma^2$, and $\sigma \geq 0$. In particular, when $\sigma = 0$, it indicates that there is no stochastic perturbation in the market demand.

Assumption 3. The market supply of recycled products can be expressed as $G = \alpha + \beta p_r$ [20], α and β are constants greater than 0, s is the disposal price of remanufactured products. To ensure that the remanufacturer is more willing to remanufacture the recovered used products, it is expressed as $c_m > s > c_r > 0$. The residual value of the remanufactured products are not considered for the convenience of the calculation.

Assumption 4. In order to guarantee that companies within the supply chain elect to secure funding through commercial credit, the interest rate applicable to commercial credit financing is set at a lower level than that applicable to bank loans, denoted as $r_f > r_s$.

Assumption 5. For the risk aversion behaviors of the manufacturer , a mean-variance risk measure is used to portray the decision maker's risk perception with a utility function [21, 22] denoted as $U = E(\pi) - \lambda Var(\pi)$. Where $\lambda \geq 0$ denotes the degree of manufacturer's aversion to uncertain risk, $\lambda = 0$ denotes risk-neutral, and $\lambda > 0$ denotes risk-averse, when a larger λ indicates that the decision maker is more risk-averse.

The mathematical symbols used in this paper are summarized as shown in Table I.

TABLE I
EXPLANATION OF RELEVANT VARIABLES AND PARAMETERS

Parameters	Definition
c_m	Manufacturer's production costs for producing a new product
c_r	Production costs for the production of remanufactured goods by remanufacturer
p_1	Retail price of new products
p_2	Retail price of remanufactured goods
w_m	Wholesale prices for new products
w_t	Wholesale prices for remanufactured goods
π	Profit Functions for Nodal Firms and Supply Chains
U	Utility Functions of Nodal Firms and Supply Chains
Q	Potential market demand
α	Recycling base for used and end-of-life products
β	The extent to which changes in recycling prices for used products affect consumers
θ	Consumer acceptance of remanufactured goods
p_r	Recycling prices for used products
τ	Recovery and recycling rate of used and end-of-life products
s	Surplus Recycled Products Disposal Price
φ	Percentage of retailer equity financing
r_f	Interest rates on bank loans
r_s	Interest rates on commercial credit
f	Patent License Fee
λ	Extent of manufacturer's uncertainty risk aversion

C. Model Construction

1) Closed-loop supply chain decision modeling for retailer bank lending (Model 1)

In Model 1, the retailer is constrained by a lack of capital but is still able to obtain sufficient loans from banks to sustain its sales activities. The profit function of the risk-averse manufacturer is:

$$\pi_m = w_m D_1 - c_m D_1 + f\tau G(p_r) \quad (1)$$

The manufacturer with risk aversion will combine the expected return with the magnitude of the variance of the expected return. Using the mean-variance theory to represent the manufacturer's utility function, the expected utility function of a risk-averse manufacturer is:

$$E\left[U_m(\pi_m)\right] = w_m\left[Q - \frac{p_1 - p_2}{1-\theta} - \lambda\sigma^2 w_m\right] - c_m\left[Q - \frac{p_1 - p_2}{1-\theta} - \lambda\sigma^2 c_m\right] + f\tau G(p_r) \quad (2)$$

In this paper, we assume the retailer and remanufacturer to be risk-neutral, and therefore the retailer's profit function and (under the risk-neutral assumption) the expected utility function are:

$$\pi_r = p_1 D_1 - w_m D_1(1+r_f) + p_2 D_2 - w_t D_2(1+r_f) \quad (3)$$

$$E\left[U_r(\pi_r)\right] = p_1\left(Q - \frac{p_1 - p_2}{1-\theta}\right) - w_m\left(Q - \frac{p_1 - p_2}{1-\theta}\right)(1+r_f) + p_2\left[\frac{\theta p_1 - p_2}{\theta(1-\theta)}\right] - w_t\left[\frac{\theta p_1 - p_2}{\theta(1-\theta)}\right](1+r_f) \quad (4)$$

The profit function and expected utility function of the remanufacturer are:

$$\pi_t = w_t D_2 - c_r\tau G(p_r) - f\tau G(p_r) - p_r G(p_r) + s\left[\tau G(p_r) - D_2\right] \quad (5)$$

$$E\left[U_t(\pi_t)\right] = w_t\left[\frac{\theta p_1 - p_2}{\theta(1-\theta)}\right] - c_r\tau G(p_r) - f\tau G(p_r) - p_r G(p_r) + s\left[\tau G(p_r) - \frac{\theta p_1 - p_2}{\theta(1-\theta)}\right] \quad (6)$$

The equilibrium solutions of the closed-loop supply chain decision model for the retailer's bank loans are:

$$w_m^a = -\frac{2Q(1-\theta) + s(1+r_f) + (2-\theta)c_m(1+r_f)}{2\left[(\theta-2)(1+r_f) + 4(\theta-1)\lambda\sigma^2\right]} \quad (7)$$

$$w_t^a = \frac{2s - \theta\left[2Q(1-\theta) + s(1+r_f) + (2-\theta)c_m(1+r_f)\right]}{4\left[(\theta-2)(1+r_f) + 4(\theta-1)\lambda\sigma^2\right]} \quad (8)$$

$$p_1^a = \frac{Q}{2} - \frac{\left[\begin{array}{c}2Q(1-\theta) + s(1+r_f)\\ +(2-\theta)c_m(1+r_f)\end{array}\right](1+r_f)}{4\left[(\theta-2)(1+r_f) + 4(\theta-1)\lambda\sigma^2\right]} \quad (9)$$

$$p_2^a = \frac{1}{2}\left\{Q\theta + \frac{1}{2}\left\{s - \frac{\begin{array}{c}2Q(1-\theta) + s(1+r_f)\\ +(2-\theta)c_m(1+r_f)\end{array}}{2\left[\begin{array}{c}(\theta-2)(1+r_f)\\ +4(\theta-1)\lambda\sigma^2\end{array}\right]}\right\}\right\} \quad (10)$$

$$p_r^a = \frac{\beta\tau(s-c_r) - 3\alpha}{4\beta} \quad (11)$$

$$f^a = \frac{\alpha + \beta\tau(s-c_r)}{2\beta\tau} \quad (12)$$

2) closed-loop supply chain decision modeling for retailer in-chain financing (Model 2)

It is evident that a significant proportion of small and medium-sized enterprises are unable to secure sufficient loans from traditional banking institutions. Consequently, they are compelled to explore alternative avenues for financing. In this study, when the retailer lacks sufficient funds, it obtains business loans from the manufacturer and the remanufacturer. This is done as a means of covering the cost of selling new and remanufactured products, ensuring its own business activities while also maintaining the functionality of the supply chain. And the profit functions for each decision maker are:

$$\pi_m = w_m D_1(1+r_s) - c_m D_1 + f\tau G(p_r) \quad (13)$$

$$\pi_r = p_1 D_1 - w_m D_1(1+r_s) + p_2 D_2 - w_t D_2(1+r_s) \quad (14)$$

$$\pi_t = w_t D_2(1+r_s) - c_r\tau G(p_r) - f\tau G(p_r) - p_r G(p_r) + s\left[\tau G(p_r) - D_2\right] \quad (15)$$

Under the manufacturer's consideration of risk aversion, the expected utility functions of each decision maker are respectively:

$$E\left[U_m(\pi_m)\right] = w_m\left[Q - \frac{p_1 - p_2}{1-\theta} - \lambda\sigma^2 w_m(1+r_s)\right](1+r_s) - c_m\left(Q - \frac{p_1 - p_2}{1-\theta} - \lambda\sigma^2 c_m\right) + f\tau G(p_r) \quad (16)$$

$$E\left[U_r(\pi_r)\right] = p_1\left(Q - \frac{p_1 - p_2}{1-\theta}\right) - w_m\left(Q - \frac{p_1 - p_2}{1-\theta}\right)(1+r_s) + p_2\left[\frac{\theta p_1 - p_2}{\theta(1-\theta)}\right] - w_t\left[\frac{\theta p_1 - p_2}{\theta(1-\theta)}\right](1+r_s) \quad (17)$$

$$E\left[U_t(\pi_t)\right] = w_t\left[\frac{\theta p_1 - p_2}{\theta(1-\theta)}\right](1+r_s) - c_r\tau G(p_r) - f\tau G(p_r) - p_r G(p_r) + s\left\{\tau G(p_r) - \left[\frac{\theta p_1 - p_2}{\theta(1-\theta)}\right]\right\} \quad (18)$$

The equilibrium solutions of the closed-loop supply chain decision-making model considering the case where the remanufacturer provides commercial credit and the remanufacturer does not have sufficient operating capital are:

$$w_m^b = \frac{-s + 2Q(-1+\theta) + (-2+\theta)c_m}{2\left(-2+\theta-4\lambda\sigma^2+4\theta\lambda\sigma^2\right)(1+r_s)} \tag{19}$$

$$w_t^b = \frac{\begin{array}{c}2Q(-1+\theta)\theta + (-2+\theta)\theta c_m \\ +s\left(-4+\theta-8\lambda\sigma^2+8\theta\lambda\sigma^2\right)\end{array}}{4\left(-2+\theta-4\lambda\sigma^2+4\theta\lambda\sigma^2\right)(1+r_s)} \tag{20}$$

$$p_1^b = \frac{Q\left(-6+4\theta-8\lambda\sigma^2+8\theta\lambda\sigma^2\right) + (-2+\theta)c_m - s}{4\left(-2+\theta-4\lambda\sigma^2+4\theta\lambda\sigma^2\right)} \tag{21}$$

$$p_2^b = \frac{Q\theta}{2} + \frac{\begin{array}{c}2Q(-1+\theta)\theta + (-2+\theta)\theta c_m \\ +s\left(-4+\theta-8\lambda\sigma^2+8\theta\lambda\sigma^2\right)\end{array}}{8\left(-2+\theta-4\lambda\sigma^2+4\theta\lambda\sigma^2\right)} \tag{22}$$

$$p_r^b = -\frac{3\alpha - s\beta\tau + \beta\tau c_r}{4\beta} \tag{23}$$

$$f^b = \frac{\alpha + s\beta\tau - \beta\tau c_r}{2\beta\tau} \tag{24}$$

3) Closed-loop supply chain decision model for retailer to undertake portfolio financing (Model 3)

In the real world, the financing methods employed by enterprises at various points along the supply chain are diverse. These methods include not only single financing methods such as bank loans, trade credit, and equity financing, but also a variety of combined financing methods. Commercial credit financing entails the transfer of goods in advance between enterprises within the supply chain, with payment for the goods occurring subsequent to the sale of products. In this study, it is assumed that the retailer raises external financing through a combination of equity transfer and bank loans when it is unable to obtain internal supply chain financing. The equity financing is in the proportion of φ and the bank loan is in the proportion of $1-\varphi$. The investor will give the capital for $\varphi\left(w_m D_1 + w_t D_2\right)$, while the cost of $(1-\varphi)\left(w_m D_1 + w_t D_2\right)$ needs to be borrowed from the bank. At the end of the sales period, the retailer gives $1-\varphi$ times the proceeds as dividends to the investor.

$$\pi_m^c = w_m D_1 - c_m D_1 + f\tau G(p_r) \tag{25}$$

$$\begin{aligned}\pi_r^c &= (1-\varphi)\left(p_1 D_1 + p_2 D_2\right) \\ &\quad -(1-\varphi)^2\left(w_m D_1 + w_t D_2\right)\left(1+r_f\right)\end{aligned} \tag{26}$$

$$\begin{aligned}\pi_t^c &= w_t D_2 - c_r\tau G(p_r) - f\tau G(p_r) \\ &\quad - p_r G(p_r) + s\left[\tau G(p_r) - D_2\right]\end{aligned} \tag{27}$$

The utilisation of a combination of equity transfer and bank financing by the retailer in Model 3 introduces an additional layer of complexity into the modelling process. At this point, the expected utility functions considering the manufacturer's risk aversion are:

$$\begin{aligned}E\left[U_m(\pi_m)\right] &= w_m\left[Q - \frac{p_1-p_2}{1-\theta} - \lambda\sigma^2 w_m\right] \\ &\quad - c_m\left[Q - \frac{p_1-p_2}{1-\theta} - \lambda\sigma^2 c_m\right] + f\tau G(p_r)\end{aligned} \tag{28}$$

$$E\left[U_r(\pi_r)\right] = (1-\varphi)\left\{\begin{array}{l} p_1\left(Q - \dfrac{p_1-p_2}{1-\theta}\right) + p_2\left[\dfrac{\theta p_1 - p_2}{\theta(1-\theta)}\right] \\ -(1-\varphi)\left\{\begin{array}{l} w_t\left[\dfrac{\theta p_1 - p_2}{\theta(1-\theta)}\right] \\ +w_m\left(Q - \dfrac{p_1-p_2}{1-\theta}\right)\end{array}\right\}\left(1+r_f\right)\end{array}\right\} \tag{29}$$

$$\begin{aligned}E\left[U_t(\pi_t)\right] &= w_t\left[\frac{\theta p_1 - p_2}{\theta(1-\theta)}\right] - c_r\tau G(p_r) - f\tau G(p_r) \\ &\quad - p_r G(p_r) + s\left\{\tau G(p_r) - \left[\frac{\theta p_1 - p_2}{\theta(1-\theta)}\right]\right\}\end{aligned} \tag{30}$$

The equilibrium solutions for each decision subject are:

$$w_m^c = \frac{2Q(\theta-1) + \left[s - (\theta-2)c_m\right](\varphi-1)\left(1+r_f\right)}{2\left[4\lambda\sigma^2(\theta-1) + (2-\theta)(\varphi-1)\left(1+r_f\right)\right]} \tag{31}$$

$$w_t^c = \frac{s}{2} + \frac{\theta\left\{\begin{array}{l}2Q(\theta-1) \\ +\left[s-(\theta-2)c_m\right](\varphi-1)\left(1+r_f\right)\end{array}\right\}}{4\left[\begin{array}{l}4\lambda\sigma^2(\theta-1) \\ +(2-\theta)(\varphi-1)\left(1+r_f\right)\end{array}\right]} \tag{32}$$

$$p_1^c = \frac{Q}{2} - \frac{\begin{array}{c}(-1+\varphi)\left(1+r_f\right) \\ \left\{\begin{array}{l}2Q(\theta-1) + \left[s-(\theta-2)c_m\right] \\ (\varphi-1)\left(1+r_f\right)\end{array}\right\}\end{array}}{4\left[\begin{array}{l}4\lambda\sigma^2(\theta-1) \\ +(2-\theta)(\varphi-1)\left(1+r_f\right)\end{array}\right]} \tag{33}$$

$$p_2^c = \frac{Q\theta}{2} - \frac{1}{4}(-1+\varphi)\left(1+r_f\right)\left\{s + \frac{\theta\left\{\begin{array}{l}2Q(\theta-1) \\ +\left[s-(\theta-2)c_m\right](\varphi-1)\left(1+r_f\right)\end{array}\right\}}{2\left[\begin{array}{l}4\lambda\sigma^2(\theta-1) \\ +(2-\theta)(\varphi-1)\left(1+r_f\right)\end{array}\right]}\right\} \tag{34}$$

$$f^c = \frac{\alpha + s\beta\tau - \beta\tau c_r}{2\beta\tau} \tag{35}$$

$$p_r^c = -\frac{3\alpha - s\beta\tau + \beta\tau c_r}{4\beta} \tag{36}$$

Proposition 1 ① $\frac{\partial w_m^c}{\partial \varphi} < 0$, $\frac{\partial w_t^c}{\partial \varphi} < 0$; ② $\frac{\partial p_1^c}{\partial \varphi} < 0$, $\frac{\partial p_2^c}{\partial \varphi} < 0$; ③ $\frac{\partial \left[E\left(D_1^c \right) \right]}{\partial \varphi} < 0$, $\frac{\partial \left[E\left(D_2^c \right) \right]}{\partial \varphi} > 0$.

Proposition 1 demonstrates that an increase in the proportion of equity financing within off-chain financing has a significant impact on the marketing strategies employed for products. In particular, the wholesale and retail prices of new products, along with the market demand for them, are likely to decline. Conversely, wholesale and retail prices for reproduced products will decrease, yet their market demand will increase. This decline in wholesale prices and demand for new products presents a significant challenge for the manufacturer. However, for the remanufacturer, the surge in demand encourages them to increase production in order to reap higher profits. With regard to the retailer, while equity financing entails the sharing of profits with partners, it also facilitates access to funds for daily sales activities, thereby rendering this financing model an acceptable option..

IV. RESULTS

A. Analysis of Model Properties

This section begins with a comparative analysis of the equilibrium solutions for the decision variables in the three scenarios and explores the relationship between the variables, which leads to the following theorem.

Proposition 2 ① $f^a = f^c = f^b$; ② $p_r^a = p_r^b = p_r^c$; ③ $\frac{\partial f}{\partial \tau} < 0$, $\frac{\partial p_r}{\partial \tau} > 0$.

In accordance with Proposition 2, the economic situation of the retailer has no bearing on the recycling activities of the remanufacturer with regard to used products. Rather, these recycling endeavours are exclusively contingent upon factors such as the recycling rate of used products, the cost of manufacturing intermediate goods, and the disposal price of discarded items. It is worthy of note that a higher recycling rate of used products has a favourable impact on the recycling price.

While recycling used products may initially increase the remanufacturer's costs, a higher recycling price ultimately enhances the efficiency of recycling in the market. Furthermore, as the recycling rate increases, the patent license fee decreases, which further incentivises recycling activities. In essence, recycling a larger quantity of used products increases the recycling price but reduces patent licensing expenses. To stimulate remanufacturing activities, a recycling contract between the manufacturer and remanufacturer can be established to alleviate the financial burden on the remanufacturer. Furthermore, the government can implement relevant subsidy policies to provide additional support to the remanufacturer.

Proposition 3 $\frac{\partial w_m^a}{\partial \lambda} < 0$, $\frac{\partial w_m^b}{\partial \lambda} < 0$, $\frac{\partial w_m^c}{\partial \lambda} < 0$; $\frac{\partial w_t^a}{\partial \lambda} < 0$, $\frac{\partial w_t^b}{\partial \lambda} < 0$, $\frac{\partial w_t^c}{\partial \lambda} < 0$; $\frac{\partial p_1^a}{\partial \lambda} < 0$, $\frac{\partial p_1^b}{\partial \lambda} < 0$, $\frac{\partial p_1^c}{\partial \lambda} < 0$; $\frac{\partial p_2^a}{\partial \lambda} < 0$, $\frac{\partial p_2^b}{\partial \lambda} < 0$, $\frac{\partial p_2^c}{\partial \lambda} < 0$; $\frac{\partial \left[\mathrm{E}\left(D_1^a \right) \right]}{\partial \lambda} > 0$, $\frac{\partial \left[\mathrm{E}\left(D_1^b \right) \right]}{\partial \lambda} > 0$, $\frac{\partial \left[\mathrm{E}\left(D_1^c \right) \right]}{\partial \lambda} > 0$; $\frac{\partial \left[\mathrm{E}\left(D_2^a \right) \right]}{\partial \lambda} < 0$.

Proposition 3 indicates that the degree of risk aversion exhibited by the manufacturer is inversely related to the wholesale and retail prices of new and remanufactured products, as well as the demand for remanufactured products. Conversely, it is positively correlated with the demand for new products. This is evidenced by the fact that, following the adoption of risk-averse behaviour, the manufacturer will choose to empty its inventory as much as possible in order to maintain sufficient cash flow in the short term. Consequently, the wholesale price of new products will be reduced in order to promote consumption. At the same time, due to the decrease in the wholesale price of the new product, consumers' demand for the new product will increase. In this process, the manufacturer successfully completes its risk aversion. Once the manufacturer has implemented risk-averse measures, the remanufacturer, as a follower of the manufacturer, will adjust its pricing strategy to align with the declining prices of the new product. This will result in a decrease in the price of remanufactured products. Conversely, as the sales of the new product increase, the demand for remanufactured products will decline, as the market becomes more stable. With respect to the retailer, as the wholesale price of both the new and the remanufactured product declines, the resulting reduction in the retail price of that product will facilitate cost reductions for the retailer, allowing for the promotion of its own sales activities through the manufacturer's risk-averse activities. Price reductions for new and remanufactured products are highly advantageous for consumers, allowing them to procure their desired products at reduced prices.

B. Numerical Simulation Analysis

The previous section derived some properties of the model by analyzing the model, in order to further analyze the implementation effect of risk aversion in the closed-loop supply chain, this section carries out the relevant analysis through the arithmetic example. Through the connection with the actual situation, each parameter in the model is assigned the value of $Q = 1000$, $c_m = 600$, $c_r = 300$, $s = 350$, and the supply function of scrap recycling is taken as the commercial credit interest rate $r_s = 0.03$, and the bank interest rate $r_f = 0.05$.

Firstly, the impact of the recycling rate of used products on the recycling price and patent licensing fee is studied, as depicted in Figure 2. As illustrated in Figure 2, an increase in the recycling rate of used products results in a heightened sensitivity of patent licensing costs, while the recycling price of used products remains relatively stable. Consequently, the remanufacturer will be more inclined to increase the recycling rate in order to obtain lower patent licensing costs and a less burdensome recycling price. We choose the value of τ to be 0.4 for ease of calculation.

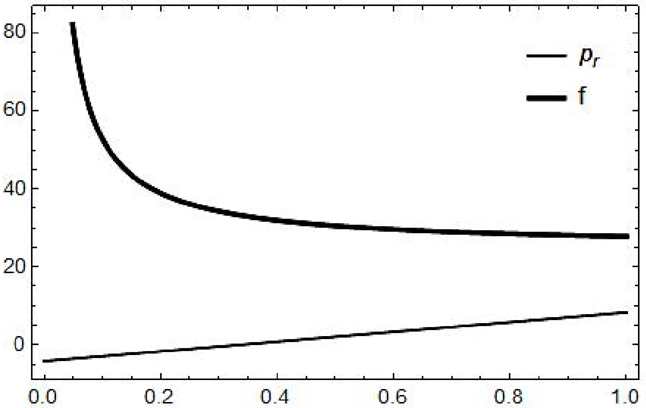

Fig. 2. Schematic diagram of recycling price and patent license fee vs. recycling rate of used products.

In order to ascertain the recycling rate of used products, it is necessary to investigate the impact of different variables on heterogeneous product pricing and risk-averse supply chain returns.

When $\theta = 0.5$, $\tau = 0.4$, $\lambda = 0.5$, and $\sigma = 5$ are taken, the relationship between the retailer's equity financing ratio φ and the variables of the manufacturer, retailer, and remanufacturer in Model 3 can be obtained as shown in Figures 3-6.

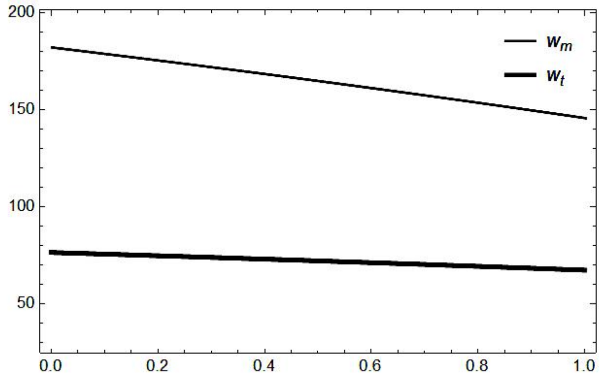

Fig. 3. Schematic of the ratio of wholesale prices to retailer equity financing.

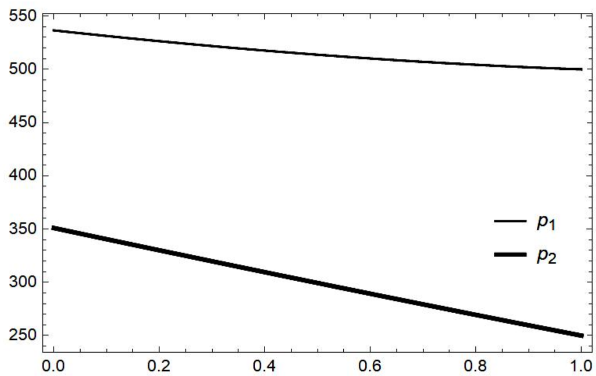

Fig. 4. Schematic of the ratio of retail price to retailer equity financing.

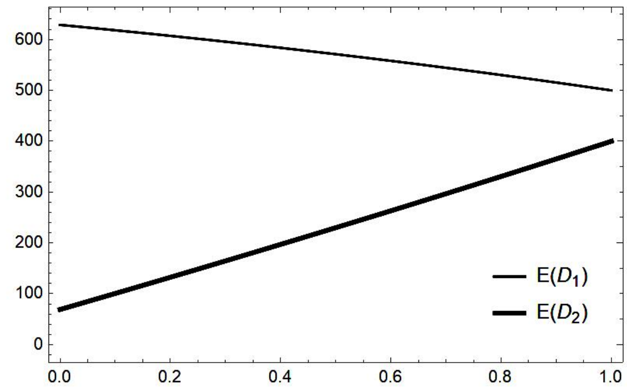

Fig. 5. Schematic of Expected Demand vs. Retailer Equity Financing Ratio.

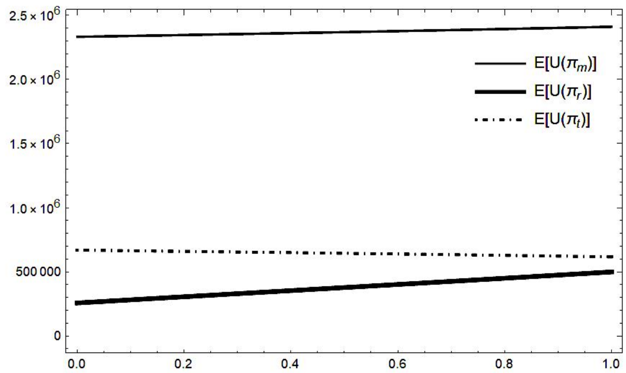

Fig. 6. Schematic of expectancy utility and retailer equity financing ratio.

Figure 3-6 presents a scenario analysis of Model 3, in which the retailer, constrained by financial limitations, finances its operations through equity transfers and bank loans. As the proportion of financing increases, the retail price of the remanufactured product declines more significantly, thereby stimulating an increase in the market demand for remanufactured products. As a consequence of the retailer's financing, the wholesale price and demand for the manufacturer's new products decline, which in turn affects the manufacturer's profits from product sales. Nevertheless, the manufacturer receives some royalties, which contribute to an overall upward trend in profits. For the remanufacturer, despite an increase in sales, the patent licensing fees in this segment also increase, resulting in stable overall profits. It is noteworthy that the off-chain financing employed by the retailer had a comparatively minor impact on the profits of both the manufacturer and the remanufacturer. Nevertheless, this financing activity effectively alleviated the retailer's financial constraints and enabled the retailer to access additional funds more easily, thus overcoming the challenge of financial constraints and ensuring the stable operation of the supply chain.

Figure 3-6 presents the results of a simulation that corroborates the veracity of Proposition 2. It can be observed that as the percentage of retailer equity transfers increases, the sales of remanufactured products also increase. This is indicative of an improvement in the efficiency of the use of used products. As the number of recycled used products increases, the remanufacturer encounters greater challenges in recycling them. Consequently, the remanufacturer is compelled to expend greater financial resources to assume responsibility for the recycling of used products throughout the process. The decline in revenue prompts the remanufacturer to urge the retailer to refrain from equity transfers and to adopt alternative financing models whenever feasible.

The aforementioned figures pertain to Model 3, which assumes a consistent level of risk aversion. A comparison of financing methods can only be considered a valid exercise if all the relevant information is taken into account. This analysis allows us to propose more effective management insights tailored to risk aversion behaviour.

The manufacturer's risk aversion can have a significant impact on the pricing of products and the revenues generated by the supply chain. In order to investigate the effectiveness of risk aversion implementation in the closed-loop supply chain, the relationship between λ and each variable of the manufacturer, the retailer, and the remanufacturer can be obtained when $\theta = 0.5$, $\tau = 0.7$, and $\sigma = 5$ are taken as shown in Figure 7-14.

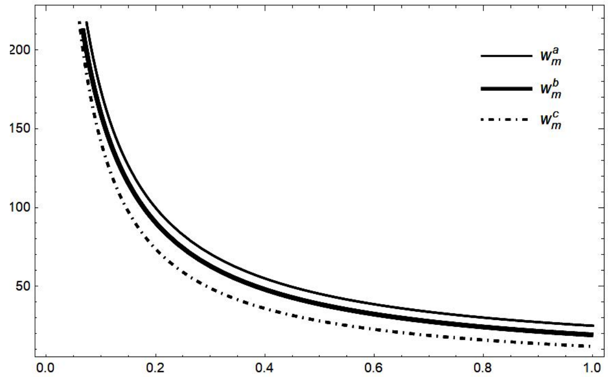

Fig. 7. Schematic diagram of wholesale prices and risk aversion for new products.

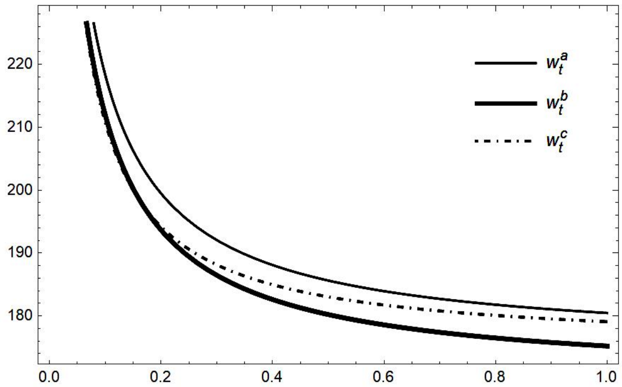

Fig. 8. Schematic of wholesale prices and risk aversion for reproductions.

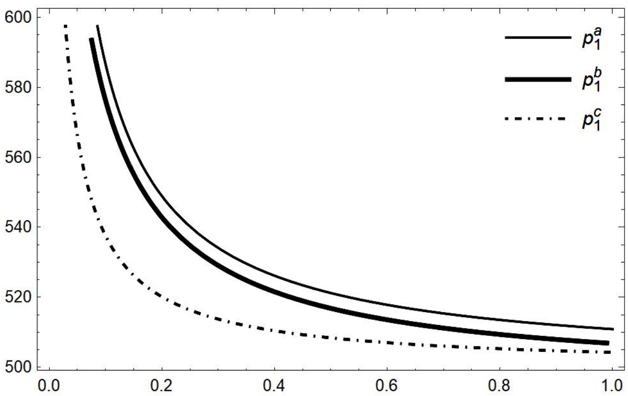

Fig. 9. Schematic of retail prices and risk aversion for new products.

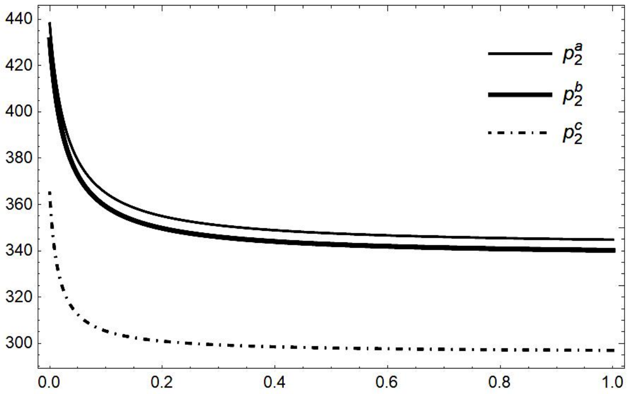

Fig. 10. Schematic of retail prices and risk aversion for recycled products.

As illustrated in Figure 7-10, the wholesale price of new products and remanufactured goods is the highest among the three modes when the retailer borrows through the bank. This is because the retailer is not under pressure to dump products, as the shortage of funds can be solved independently of the manufacturer and remanufacturer. When the retailer finances the chain through commercial credit, the wholesale price of the remanufacturer is the lowest of the three models. This allows the retailer to obtain remanufactured products at a lower cost, which in turn promotes the sale of remanufactured products and is more conducive to the maintenance and operation of the closed-loop supply chain.

When the retailer finances its business through a combination of equity and bank loans, the manufacturer's risk-averse nature will prioritise the clearance of inventory to lower the wholesale price. Conversely, the sale of large quantities of new products will enable the manufacturer to generate more revenue, thus achieving the goal of ensuring that it has cash flow. In response to the manufacturer's strategy of selling at a reduced price, the remanufacturer will also choose to reduce the price in order to ensure the sale of its own remanufactured products. For the retailer, it will take significant price reductions when the manufacturer's risk aversion is low. However, if the manufacturer persists in cutting prices, the retailer will adopt stockpiling and other strategies to maintain a competitive retail price. In general, the pricing of heterogeneous products exhibits an inverse relationship with increasing risk aversion coefficients. In particular, the sensitivity of product pricing to risk aversion coefficients is greater at lower risk aversion coefficients. Concurrently, the retailer that has access to in-chain financing is able to maintain a higher retail price.

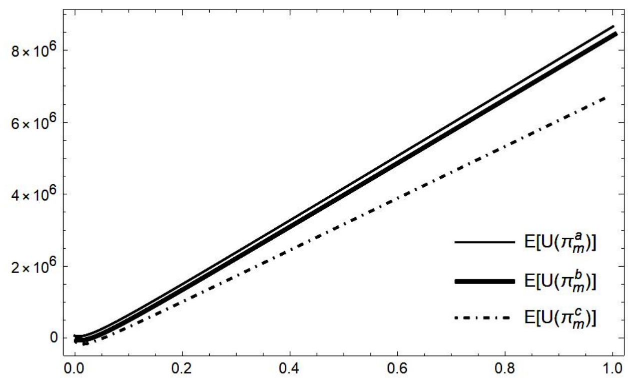

Fig. 11. Schematic diagram of manufacturer's expected utility and risk aversion.

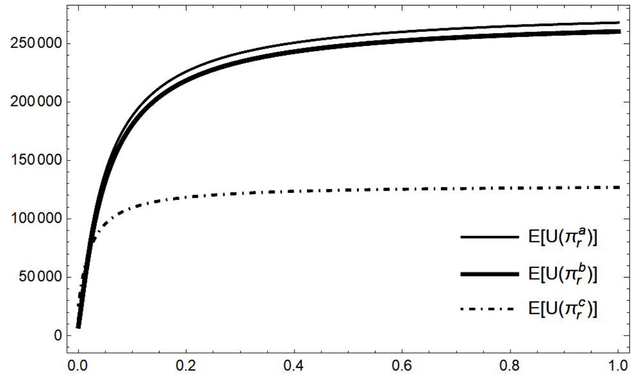

Fig. 12. Schematic of retailer's expected utility and risk aversion.

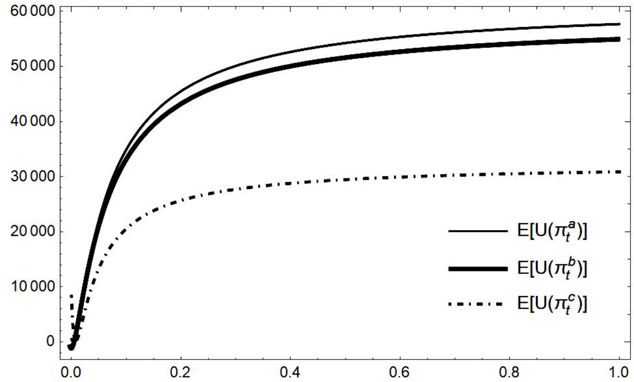

Fig. 13. Schematic of remanufacturer expected utility and risk aversion.

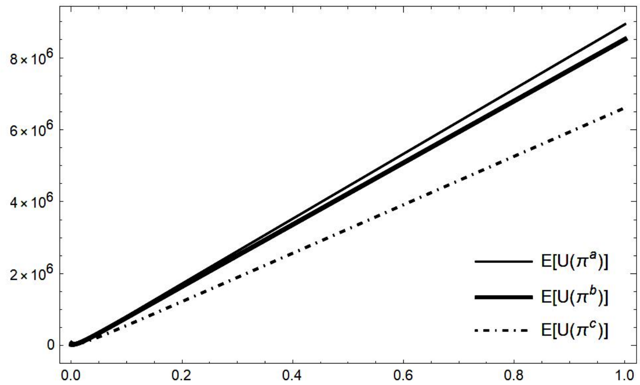

Fig. 14. Schematic diagram of supply chain expected total utility and risk aversion.

As can be seen from Figures 11-14, with the same level of risk aversion, if the retailer finances the sale through a combination of own funds and bank loans, the manufacturer will prioritise emptying its stock and thus reducing the wholesale price, at which point the manufacturer will make higher profits. The retailer's bank loan allows each node in the supply chain to make sufficient profits in this sales segment because the manufacturer and remanufacturer do not need to support the retailer and can obtain sufficient cash in a timely manner. In the case where the retailer adopts the commercial credit financing model, although the manufacturer and the remanufacturer need to get the payment from the retailer after the sales activities, the profit of the node firms in this model does not differ much from the profit in model 1 because the manufacturer and the remanufacturer have sufficient capital reserves. When the retailer faces the problem of capital shortage, it will choose the bank loan as much as possible to solve the problem; however, if the retailer can't get the bank loan, it can choose the commercial credit financing from the enterprises in the supply chain as much as possible, and operate by taking the goods and then selling them, and then repay the outstanding amount of money after getting the profit.

Concurrently, the risk-averse behaviour of the manufacturer results in significant fluctuations in all factors, which can have a more positive effect on the entire supply chain. As a consequence of the decline in the wholesale price, the manufacturer's profit declines. However, once the risk aversion factor exceeds a certain threshold, the manufacturer is able to successfully avoid the risk, resulting in a continued increase in profit. This necessitates that the manufacturer be cognizant of the extent of risk aversion and implement an appropriate risk aversion strategy to enhance its own profitability. The retailer is externally financed due to the necessity to share returns with investors. Consequently, there is a significant discrepancy between the retailer's expected returns and the commercial credit financing model. Therefore, it is of paramount importance for the retailer to endeavour to obtain commercial credit financing as far as possible, in order to ensure the availability of funds. For the remanufacturer, the manufacturer's risk aversion behaviour exerts a greater influence on the remanufacturer's own risk appetite, which is reflected in the decline in profit as the degree of risk aversion increases. Nevertheless, when risk aversion is elevated, the anticipated utility of the remanufacturer also tends to expand.

The profit of each node enterprise will vary considerably with the risk aversion coefficient. Following the manufacturer's adoption of risk aversion behaviour, the price of both new and remanufactured products will decline, stimulating consumer demand and enhancing the expected utility of the entire supply chain. This demonstrates that the manufacturer's risk aversion behaviour can positively influence the production and consumption dynamics of the entire supply chain.

A comprehensive analysis was conducted with the objective of better visualising the impact of risk aversion and financing ratios on the profitability of the supply chain. In order to facilitate a more comprehensive visual exploration of the multifactorial nature of the data, a three-dimensional representation was employed. In consideration of these two variables, profit curves for the manufacturer, retailer, and remanufacturer were calculated and the results are presented in Figures 15-17.

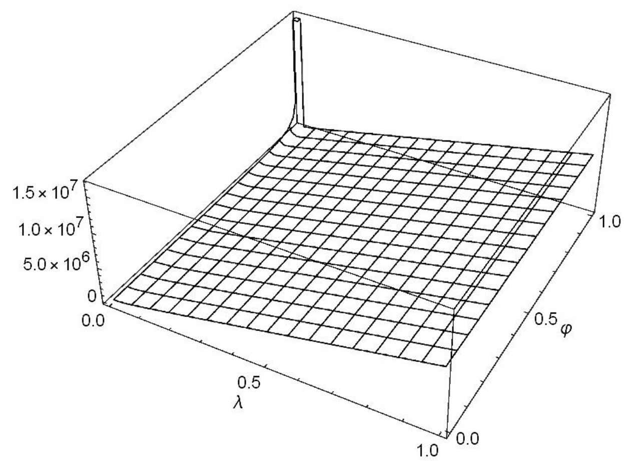

Fig. 15. The manufacturer expects profit in two factors.

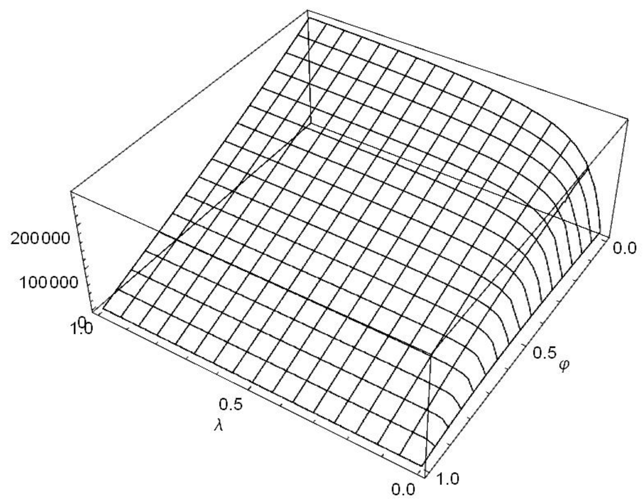

Fig. 16. The retailer expectation of profit in two factors.

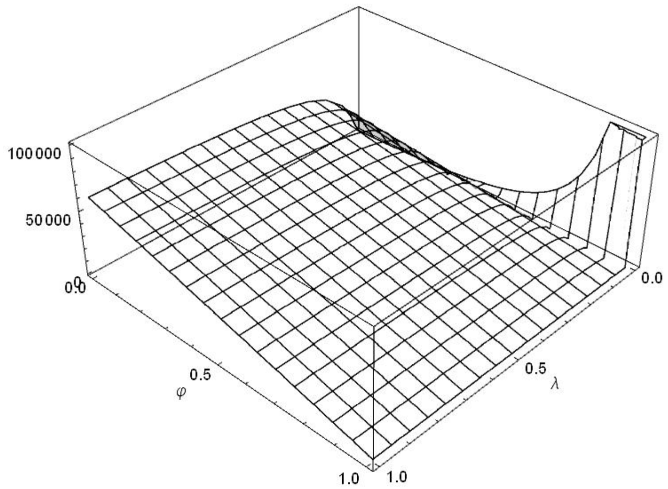

Fig. 17. The remanufacturer expects profits on two factors.

A number of intriguing conclusions can be drawn from Figures 15-17. The manufacturer's expected returns are more susceptible to fluctuations in the risk aversion coefficient. Consequently, the manufacturer is more inclined to adopt a risk-averse strategy with the objective of increasing expected profits. It is noteworthy that the retailer's equity financing activities facilitate sales, particularly when the manufacturer is not compelled to adopt risk-averse measures to guarantee adequate returns. The retailer's expected returns are more sensitive to the risk aversion factor. Nevertheless, this sensitivity diminishes when the value of risk aversion surpasses a specific threshold. Concurrently, the retailer's profit is positively correlated with the proportion of equity transfer, exhibiting a more linear trend.

For the remanufacturer, risk aversion factors exert a greater influence on expected returns in the form of greater fluctuations in expected utility. It is typical for the manufacturer's risk-averse behaviour to have a significant effect on the remanufacturer's relevant price and demand, which in turn affects the remanufacturer's expected returns. Similarly, the retailer's equity financing activities can have a greater impact on the profitability of the remanufacturer. In practice, therefore, the remanufacturer tends to provide support to the retailer.When considered collectively, the risk aversion coefficient exerts a more pronounced influence on the anticipated benefits of the supply chain. Consequently, the manufacturer, as the primary figure within the supply chain, is advised to adopt a cautious approach when implementing risk aversion strategies.

V. CONCLUSION

Supply chains are composed of multiple node firms [23-24], and it is of particular importance to ensure the exchange of funds, goods and information within the firms that comprise the supply chain. When engaging in sales activities, the retailer often encounters financial shortages and technological barriers, which may lead to the risk of supply chain disruption. Currently, the provision of commercial credit and equity financing within the supply chain can be an effective solution to the problem. However, market demand and profit fluctuations among node firms represent a significant challenge. This paper presents a Stackelberg game model that considers demand uncertainty and manufacturer patent licensing factors. The study examines various financing models and assesses the impact of the retailer's financing ratio on the supply chain.

In accordance with the findings of Zhuo [25], we observe that the manufacturer exhibiting risk-averse behaviour is more inclined to reduce the wholesale price, which consequently leads to a larger order book for the retailer. In light of the aforementioned findings, we propose the introduction of the remanufacturer, which would engage in the recycling of used products with subsequent remanufacturing. Our findings align with those of Sun [26]. As the proportion of equity financing increases, the retailer will increase its revenue through promotions, thereby mitigating the effect of the manufacturer's risk aversion factor. It is noteworthy that when the proportion of the retailer's financing is high, the manufacturer in the supply chain reduces the wholesale price in order to promote sales activities.

The construction of the model and subsequent analyses have led to the following conclusions: firstly, in the third-party remanufacturing closed-loop supply chain, faced with the remanufacturer's demand for recycling of used products, the manufacturer chooses to support the remanufacturer by lowering the patent licence fee. This strategy not only preserves the manufacturer's profits but also enables the remanufacturer to invest more capital in recycling activities, thereby increasing the efficiency of resource utilisation within the supply chain.

Secondly, while the retailer's choice of a combined financing model of equity transfer and bank financing may increase its expected utility, there are significant disadvantages to this choice, which may result in lower retail prices for both new and remanufactured products. In the long term, the combination financing model of equity transfer and bank financing is highly disadvantageous to both the retailer and the remanufacturer. In instances where the retailer encounters a dearth of capital, the bank loan model can sustain a higher product price and guarantee the highest returns as the optimal financing option. Nevertheless, it is more often than not the case that the retailer is unable to access bank loans, which consequently places certain limitations on the applicability of bank loan financing. The commercial credit financing model is more applicable as it can guarantee higher revenue for each node and the expected utility is less different from the bank loan financing model. It is important to note that the remanufacturer in the supply chain is more willing to assist the retailer in overcoming financial constraints, which makes the commercial credit financing model a more viable option.

Thirdly, the manufacturer's risk aversion results in a reduction in the wholesale price of new and remanufactured products. Consequently, the retailer also reduces the retail price of the new product, which allows consumers to purchase their preferred product at a lower price, thereby promoting product upgrading. Consequently, an increase in consumer product consumption leads to an enhancement in the expected utility of the entire supply chain, which in turn stimulates production and recycling along the supply chain.

By employing formula calculation, sensitivity analysis and simulation analysis, it is possible to derive insights into effective management strategies. In terms of recycling and remanufacturing, the availability of capital and the financing methods employed by enterprises with insufficient capital have a significant impact on the profits of each enterprise within the supply chain. The implementation of closed-loop supply chains can facilitate the optimal utilisation of resources and the minimisation of waste generated by used products. Nevertheless, in contrast to the conventional supply chain model, the closed-loop supply chain necessitates the involvement of a greater number of enterprises. Consequently, the effective operation of closed-loop supply chains is contingent upon the sufficiency of capital. It is imperative that enterprises are fully cognizant of the pivotal role of capital in maintaining recovery and remanufacturing activities and promoting resource recycling. This awareness should inform the strengthening of capital management and planning, thereby ensuring the stability and sustainability of the capital chain.

In terms of financing strategies, when enterprises within the supply chain experience a shortage of funds, it is imperative that they take proactive measures to ensure the uninterrupted flow of the supply chain. Commercial credit financing represents a more favourable approach for enterprises within the supply chain to address the challenge of limited financial resources. It is recommended that enterprises actively publicise and promote the advantages of the commercial credit financing model, with the aim of encouraging upstream and downstream enterprises in the supply chain to adopt this model for financing. The advance delivery of goods and subsequent promise of repayment after sales can effectively alleviate the pressure of funds while maintaining the continuity and stability of the supply chain. However, in practice, there is a lack of sufficient trust between the upstream and downstream parties in the supply chain. Consequently, in the subsequent research and practical operation, in order to further reduce the financing risk, enterprises in the supply chain may wish to consider introducing a contractual coordination mechanism to clarify the rights and obligations of all parties and reduce disputes caused by information asymmetry or understanding bias. Furthermore, the establishment of a third-party guarantee institution to provide credit enhancement support for financing can alleviate the concerns of funders regarding risk and facilitate the conclusion of financing transactions.

In the context of a complex and evolving market, characterised by uncertainty in demand, enterprises within the supply chain will adopt a range of strategies to mitigate risk and safeguard their own interests. The results of the model calculations indicate that the interests of enterprises in the closed-loop supply chain are not significantly divergent. It is of paramount importance that enterprises within the supply chain recognise the significance of collaboration. The timely and accurate dissemination of information is facilitated by the establishment of regular or irregular communication channels, such as supply chain coordination meetings and information-sharing platforms. This enables enterprises to respond promptly to market fluctuations, collaborate in the formulation of contingency plans, and minimise the occurrence of erroneous decisions and the wastage of resources resulting from information asymmetry. Concurrently, enterprises should proactively investigate and implement the closed-loop supply chain model to enhance resource utilisation efficiency and reduce costs through recycling, reuse and remanufacturing, while fortifying the resilience and sustainability of the supply chain. The closed-loop supply chain can mitigate the impact of external market fluctuations on enterprises, while simultaneously enhancing brand image and consumer trust.

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