Received 22 October 2022
Revised 7 January 2023
24 March 2023
Accepted 30 April 2023

The production and pricing strategy of the two-echelon remanufacturing supply chain with government subsidy under patent protection

Xiaogang Cao
School of Management, Wuhan Textile University, Wuhan, China
Hui Wen
School of Science, Hubei University of Technology, Wuhan, China, and
Bowei Cao
School of Management, Wuhan Textile University, Wuhan, China

Abstract

Purpose – In this paper, the authors study the production and pricing decisions of a remanufacturing supply chain composed of a supplier, an assembler and a remanufacturer, in which the remanufacturing of components requires patent licensing from the supplier.

Design/methodology/approach – The authors consider three different models with government subsidy for remanufacturing: (1) no government subsidies; (2) the government subsidizes the remanufacturing behavior of the supplier and (3) the government subsidizes the remanufacturing behavior of the remanufacturer and use the Stackelberg game model to solve and analyze the equilibrium wholesale prices of components and the equilibrium outputs of new and remanufactured products under three subsidy modes.

Findings – The results show that the equilibrium wholesale prices of two kinds of components decrease with the unit patent licensing fee and the unit government subsidy, and the equilibrium quantity of the remanufactured products under the three modes is obviously higher than that of the new products.

Originality/value – Finally through numerical simulation, it is found that the equilibrium profits of the supplier, the manufacturer and the supply chain increase monotonously in relation to the unit government subsidy, while the optimal profit of the assembler in relation to the unit government subsidy tends to decrease first and then increase.

Keywords Two-echelon remanufacturing, Cournot competition, Patent licensing, Government subsidy, Stackelberg game

Paper type Research paper

1. Introduction

Recycling and remanufacturing of used products has become an important problem affecting economic development, resource conservation and environmental protection. Taking the

This research was supported by Key Research Base of Humanities and Social Sciences in Hubei Province- -Key Project of Enterprise Decision Support Research Center (DSS20220602) and Key Project of Philosophy and Social Science Research of Hubei Provincial Education Department (20D056).

Declaration of conflict of interest: The authors declare that there is no conflict of interest with this manuscript.

electronics manufacturing industry as an example, international renowned companies such as Apple, HP and Fuji Xerox have induced product remanufacturing to the company, with a view to achieving coordinated economic and environmental development (Ginsburg, 2001). Xerox reduced $200mn in raw material costs over five years through recycling. Volkswagen's engines have also been remanufactured, and the FAW-Volkswagen engine (Dalian) remanufacturing project, a joint venture between FAW and Volkswagen, was first launched in September 2010 and officially launched in August 2011. It was also Volkswagen's first remanufacturing project outside Germany. Therefore, remanufacturing attracted the extensive attention of academic and enterprise circles. For example, the components supplied by Junsheng Electronics for the German Volkswagen brand have reached five categories, including a washing system, turbocharged tube, air conditioning system, mailbox cover and rear-view mirror.

Furthermore, due to recovery cost and brand reasons, many manufacturers do not recycle and remanufacture used products, but authorize third-party remanufacturing companies such as Apple and IBM, which dominate the remanufacturing market, to remanufacture and pay patent licensing fees to the original manufacturers. Patent licensing is a source of profit for the inventor when his/her invention is granted a patent (Kamien, 1992). The increase in the effectiveness of patent protection increases licensing propensity when a company faces challenges trying to commercialize new technologies (Arora and Ceccagnoli, 2006). In remanufacturing, patent licensing from manufacturers is required when companies desire to remanufacture their products under patent protection; otherwise, there would be legal risks (Hong *et al.*, 2017). In order to obtain the licensing, the main method is to pay patent licensing fees to the manufacturer as it required. For example, an investigation of 150 US corporations finds that 39% of companies adopt variable patent licensing fees and 13% adopt fixed patent licensing fees (Rostoker, 1983). When the licensing is obtained, third-party companies are able to legally remanufacture the products with patent protection.

In fact in real life, there are many examples of suppliers and manufacturers involved in the remanufacturing of parts at the same time, such as the core parts of used air conditioning compressors, condensers and so on which have to be remanufactured by the supplier, while other parts such as capillaries, one-way valves and so on can be remanufactured directly by the remanufacturer. On the other hand, in order to drive the development of the remanufacturing industry, the government often introduces some remanufacturing subsidy policies, such as additional subsidies to consumers who pay back used products, which can attract price-sensitive consumers and increase the scale of recycling of used products, or subsidies to recyclers and remanufacturers to inject vitality into the enterprises in the industry and increase their enthusiasm for recycling and remanufacturing, thus increasing consumers' surplus and improving the social welfare. In December 2014, the Chinese government implemented the "replacing old products with remanufactured ones" project throughout the country, subsidizing 10% of the replacement price for eligible automobile engines, gearboxes and so on, with a maximum subsidy of 2000 yuan for remanufactured engines and 1,000 yuan for remanufactured gearboxes. This is not the government's first introduced corresponding subsidy policy. Industry insiders believe that similar subsidies are attractive to logistics companies and private owners who emphasize operational economy. For example, the government of Liuyang in Hunan province subsidizes remanufacturers entering industrial parks at 20% of their total construction and equipment investment, which effectively motivates enterprises to participate in remanufacturing activities. Moreover, after applying to become a remanufacturing pilot enterprise, Sevalo Construction Machinery Remanufacturing Co. Ltd. obtained subsidies of seven million yuan from the National Development and one million yuan from Wuhan. Stimulated by government subsidies, it has expanded rapidly and expanded its remanufacturing business, setting up remanufacturing bases in Henan and Hebei province (IRDRI, 2013).

Therefore, this paper studies the two-level remanufacturing decision in which the supplier and the remanufacturer participate in the remanufacturing of parts at the same time under patent protection, in which the remanufacturer needs to obtain the patent licensing of the supplier for the remanufacturing of the parts, solves and analyzes the equilibrium decision of the supply chain under consideration of the government's three different subsidy policies for the remanufacturing behavior and tries to solve the questions below:

(1) How will patent licensing influence the supply chain equilibrium decision under different government subsidy models?

(2) What are the effects of government unit subsidies on equilibrium decisions and profit in different subsidy models?

(3) What are the results of production competition and equilibrium profit distribution of products under different government subsidy modes?

The rest of this paper is organized as follows. We take a literature review in Section 2 and describe the model and assumptions in Section 3. In Section 4, we conduct an analysis of three types of government subsidies. We comparatively analyze the equilibrium decisions of the three models in Section 5, and numerical analysis is studied in Section 6. Finally, we conclude the paper in Section 7.

2. Literature review

At present, there are lots of achievements in the study of remanufacturing and closed-loop supply chain focusing on product recovery, reverse channel design, product quality and remanufacturing decision, pricing and coordination decisions (Savaskan *et al.*, 2004; Debo *et al.*, 2005; Savaskan and Van Wassenhove, 2006; Ferrer and Swaminathan, 2006; Ferguson and Toktay, 2006; Atasu *et al.*, 2008; Ferrer and Swaminathan, 2010; Abbey *et al.*, 2015). One focus is the recycling channels decision of closed-loop supply chain. For example, Savaskan *et al.* (2004), Savaskan and Van Wassenhove (2006) and Huang *et al.* (2013) investigate the pricing decisions and profits with two or three recycling channels. Debo *et al.* (2005) propose pricing and technology selection of manufacturers in a heterogeneous consumer market. Remanufacturing in the closed-loop supply chain also attracts much attention. The following literature focuses on remanufacturing decision problems under different situations. Ferrer and Swaminathan (2006) discuss remanufacturing decision-making in two cycles, multiple cycles and unlimited planning periods. Ferguson and Toktay (2006) explore the pricing and remanufacturing decisions of manufacturers in the face of competitive threats in the remanufacturing market. Ferrer and Swaminathan (2010) study the manufacturing and pricing strategies of a monopoly manufacturer in three cases. There are three aspects closely related to this paper: government subsidy and intervention in remanufacturing, patent product remanufacturing and two-level remanufacturing decision-making as follows:

(1) Remanufacturing with government subsidy and intervention

Many scholars focus on the impact of government subsidies on remanufacturing, including the impact on decisions, profits, etc. Webster and Mitra (2007) analyze the influence of government recycling laws on the profits of manufacturers and remanufacturers in a competitive environment. Mitra and Webster (2008) propose the competitive decision of manufacturers and manufacturers from the perspective of government subsidies. Li *et al.* (2014) study the influence of carbon subsidies on the remanufacturing system. Hong *et al.* (2014) analyze the impact of prepaid and subsidy interventions on reverse supply chain decision-making. Hong *et al.* (2016a, b) study the effect of external government subsidies on the flow of recycled materials in decentralized reverse supply chains. Jena *et al.* (2018) focus on how government incentives influence business decision-making. Li *et al.* (2019) consider a two-period competition model of a remanufacturing supply chain with government subsidy and tax. Chen *et al.* (2019) analyze the impact of government subsidies on the sustainability innovation of the supply chain. Liu *et al.* (2019) study the impacts of corporate social responsibility (CSR) and government subsidies on the supply chain. Xue *et al.* (2019) study the impact of subsidies on sales prices of green supply chain. In addition to the impact of government subsidies, more and more literature concentrates on optimal decisions like pricing, quantity, remanufacturing modes, etc. under government subsidy. Yu *et al.* (2019) coordinate a supply chain with subsidies of option premiums. Feng *et al.* (2022) establish three models with and without government involvement to study the pricing and coordination of remanufacturing supply chains. He *et al.* (2019) study the decision problem of a closed-loop supply chain in the presence of possible government subsidies. Sun *et al.* (2019) explore the green investment strategy for manufacturers and material suppliers under a government subsidy policy. Cao *et al.* (2020) focus on trade-in strategies for new and remanufactured products under government tax policy. Zhang *et al.* (2021) investigate the optimal remanufacturing mode of waste electrical and electronic equipment (WEEE) products with or without government fund policy. But these studies do not take into account the involvement of third-party manufacturers in recycling.

(2) Remanufacturing of patented products

Patent licensing is common in remanufacturing. Some scholars discuss supply chain coordination under patent licensing. Xiong *et al.* (2011) establish the coordination mechanism of a supply chain under patent protection. Zhang and Ren (2016) coordinate a remanufacturing supply chain under patent protection. Decision problems are also one focus in remanufacturing. Hong *et al.* (2017) study the quantity and collection decisions in a closed-loop supply chain with technology licensing. Zou *et al.* (2016) compare and analyze the advantages and disadvantages of outsourcing remanufacturing and authorizing remanufacturing of brand or patented products. Liu *et al.* (2022) investigate different patent licensing strategies for remanufacturing products. Ke *et al.* (2023) discuss the pricing problem of new and remanufacturing products in a three-period closed-loop supply chain. None of these studies takes into account the remanufacturing of components or the influence of government subsidies.

(3) Decisions of two-level remanufacturing

Zhao *et al.* (2012) use game theory to study the supplier-manufacturer (S-M) two-level closed-loop supply chain. Ding and Ma (2015) use the Stackelberg game to study the two S-M closed-loop supply chains in which suppliers choose to take part and choose not to take part in the recycling and remanufacturing of parts. However, it does not consider the differential remanufacturing of components.

The above literature studies the remanufacturing competition and closed-loop supply chain equilibrium decision-making and benefits coordination from different perspectives but does not analyze the two-level remanufacturing supply chain considering the difference of components and government subsidies. This paper analyzes the production and pricing decision-making of two-level remanufacturing supply chain under three kinds of subsidy in patent protection environment. The comparison between related literature and this paper is shown in Table 1.

Table 1. Comparisons between this paper and related literature

Literature	Remanufacturing	Government subsidy	Different subsidy modes	Production strategy	Patent licensing	Two echelon remanufacturing
Savaskan *et al.* (2004)	√					
Ferrer and Swaminathan (2010)	√			√		
Zhao *et al.* (2012)	√					√
Li *et al.* (2014)	√	√				
Ding and Ma (2015)	√					√
Zhang and Ren (2016)	√				√	
Liu *et al.* (2019)	√	√				
Zhang *et al.* (2021)	√	√	√	√		
Liu *et al.* (2022)	√				√	
Feng *et al.* (2022)	√	√	√			
Liu *et al.* (2022)	√				√	
This article	√	√	√	√	√	√

Note(s): There are the following contributions: (1) we focus on the production strategy of a closed-loop supply chain with two-echelon remanufacturing under patent protection, analyzing the equilibrium decisions and profits of supply chain members from the perspective of different government subsidy models; (2) we analyze the impacts of patent licensing and government subsidy on the pricing and production quantities decisions from the perspective of two echelon remanufacturing, focusing on the interaction mechanism between the two components

Source(s): Authors own work

3. Model description and assumptions

3.1 Symbol description

Description of the symbols used in this article is shown in Table 2 of Appendix.

3.2 Model description

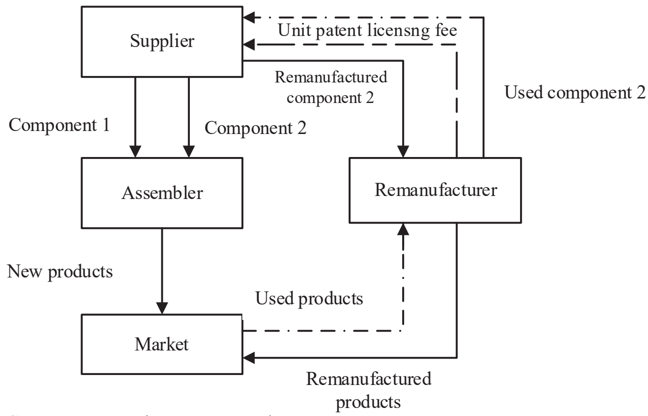
Based on game theory, we establish a supply chain model composed of a supplier (she), an assembler (he) (with sales function) and a remanufacturer (he) (with assembly and sales function) to investigate the impact of patent protection and different government subsidies on decisions and profits of supply chain members. In this model, the supplier produces two new components, respectively, by purchasing two kinds of raw materials, and then wholesales the two new components to the assembler. The assembler uses the two new parts to assemble into a new product 1 in a 1:1 ratio and then sells to the market. At the same time, the remanufacturer recovers a certain amount of used products from the consumer at a certain recycling price, and the used products are disassembled to obtain two kinds of components, of which the component 1 are ordinary components, which are directly remanufactured by the remanufacturer, and the same quantity of component 2 are regarded as the core components, so they cannot be remanufactured directly, which are then delivered by the remanufacturer to the supplier free of charge for remanufacturing, and then the supplier wholesales the remanufactured component 2 at wholesale price $\gamma W_{2j},\ j \in \{N, VS, VR\}$ to the remanufacturer, in which the wholesale price discount γ is given to the remanufacturer, and the remanufacturer assembles two kinds of remanufactured components into a remanufactured product and then sells them to the market.

For the demand function, we assume that the demand for products Q_j is the linear decreasing function of the retail price P_j. According to Xiong *et al.* (2011), we assume $Q_j = q_{mj} + q_{rj} = a - bP_j > 0$, so $P_j(Q_j) = (a - Q_j)/b = (a - q_{mj} - q_{rj})/b$. Moreover, the collecting quantity function is assumed to be $G_j(P_{rj}) = \phi + sP_{rj} > 0$ (Liu *et al.*, 2016; Wu *et al.*, 2020; Wang *et al.*, 2022), and we assume that all recycled used products can be used for remanufacturing (this assumption simplifies the computation but does not affect the basic conclusions of this article), so $q_{rj} = G_j(P_{rj}) = \phi + sP_{rj}, j \in \{N, VS, VR\}$.

In addition, the supplier has a patent right for the production of the two components and provides technical support for the remanufacturing activities of the remanufacturer on the remanufacturing of component 1, and the remanufacturer must pay a certain patent licensing fee to the supplier for each remanufactured component 1 (Hong *et al.*, 2017; Ke *et al.*, 2023). We assume there is no quality difference between the newly manufactured components and products and the remanufactured components and products, and the two products have the same selling price (Hong *et al.*, 2016a, b). For example, the remanufactured photocopiers of Fuji Xerox are of the same quality and performance as the new photocopiers of the same type and are priced at the same price, and the assembler and remanufacturer form a Cournot competition in the sales market. Among them, the remanufacturing of component 2 can reduce the raw material cost input of unit component 2, and the remanufacturing of component 1 can reduce the cost input of component 1. The basic structure is shown in Figure 1.

Based on Model N, the government adopts different policies for remanufacturing activities. Therefore, this article discusses three situations: (1) government does not provide subsidies (Model N); (2) government provides subsidies to the supplier (model VS) and (3) government provides subsidies to the manufacturer (model VR). $SW_j = \Pi_{sj} + \Pi_{mj} + \Pi_{rj} + CS - GS$ denotes the social welfare when the government selects strategy j, where

$CS = \int_{P_j}^{P_{j\max}} Q_j dP = (q_{mj} + q_{rj})^2/2b$ denotes the consumer surplus, and $GS = vq_{rj}$ denotes government expenditures, $j \in \{N, VS, VR\}$.



Source(s): Authors own work

Figure 1.
The decision structure without government subsidy (Model N)

The specific decision structure is as follows: the Stackelberg game is formed between the supplier, assembler and remanufacturer, where the supplier acts as the leader, the assembler and the remanufacturer act as the followers. The decision order is as follows:

Step 1: the supplier decides the wholesale price of the two new components to maximize her own profit;

Step 2: the assembler and remanufacturer determine the production quantity of the respective products to maximize their own profit based on the wholesale prices of the two new components, where the assembler and remanufacturer form Cournot game about the production quantity competition.

4. Model analysis

This section will address and analyze the equilibrium production quantities of products, the equilibrium selling price of products, the optimal recycling price of used products, the equilibrium profits of the supplier, assembler remanufacturer and supply chain systems under the three models of government subsidies for remanufacturing behavior of the supplier and the equilibrium production quantity of new and remanufactured products under the three models of government subsidies for remanufacturing behavior, with a focus on the impact of unit patent licensing fee and government subsidy on equilibrium decision-making.

4.1 No government subsidy (Model N)

According to the above description and assumptions, it can be seen that when there are no subsidies the optimization problems of the supplier, the assembler and the remanufacturer are denoted as follows, respectively.

$$\max\Pi_{sN}(W_{1N}, W_{2N}) = (W_{1N} - C_{s1} - m_1 + W_{2N} - C_{s2} - m_2)q_{mN} + (\gamma W_{2N} + f - C_{s2})q_{rN} \tag{1}$$

$$\max\Pi_{mN}(q_{mN}) = \left(\frac{a - q_{mN} - q_{rN}}{b} - A_m - W_{1N} - W_{2N}\right)q_{mN} \tag{2}$$

$$\max\Pi_{rN}(q_{rN}) = \left(\frac{a - q_{mN} - q_{rN}}{b} - P_{rN} - A_r - C_{r1} - \gamma W_{2N} - f\right)q_{rN} \quad (3)$$

We use backward induction to solve the functions and obtain equilibrium decisions (the solving process and equilibrium decisions is shown in Appendix).

Proposition 1. On the relationships of the equilibrium wholesale prices of components with the unit patent licensing fee when there are no subsidies, we have

$$\text{(I)}\ \partial W_{1N}^{*} \Big/ \partial f > 0;$$

$$\text{(II)}\ \partial W_{2N}^{*} \Big/ \partial f < 0.$$

Proposition 1 indicates that the rise of unit patent licensing fee increases the supplier's own profit patent licensing income and the cost of the remanufacturer. But what the higher patent licensing fee brings is also related with the quantity of remanufactured products. To guarantee profitability, the supplier reduces the wholesale price of component 2 at the same time in order to encourage the remanufacturing process, while increasing the wholesale price of component 1 to make up for her own loss.

Proposition 2. On the relationships between the equilibrium outputs of new and remanufactured products with the assembly costs of the assembler and remanufacturer when there are no subsidies, we have

$$\text{(I)}\ \partial q_{mN}^{*} \Big/ \partial A_m < 0, \partial q_{mN}^{*} \Big/ \partial A_r > 0;$$

$$\text{(II)}\ \partial q_{rN}^{*} \Big/ \partial A_m > 0, \partial q_{rN}^{*} \Big/ \partial A_r < 0.$$

Proposition 2 indicates that when there are no subsidies, the increase in assembly costs of the assembler reduces his profit per unit product, thus increasing the selling price of the product by reducing the output of the new product, resulting in an increase in the production of the remanufactured product. Similarly, the growth in assembly costs of the remanufacturer increases the output of new products and that of the assembler leads to a rise in the production of remanufactured goods.

4.2 Government subsidizes to the supplier (model VS)

In model VS, the government offers unit subsidy to the supplier for the remanufacturing process. The optimization problems of the supplier, the assembler and the remanufacturer are denoted as follows, respectively.

$$\max\Pi_{sVS}(W_{1VS}, W_{2VS}) = (W_{1VS} - C_{s1} - m_1 + W_{2VS} - C_{s2} - m_2)q_{mVS} + (\gamma W_{2VS} + f - C_{s2} + v)q_{rVS} \quad (4)$$

$$\max\Pi_{mVS}(q_{mVS}) = \left(\frac{a - q_{mVS} - q_{rVS}}{b} - A_m - W_{1VS} - W_{2VS}\right)q_{mVS} \quad (5)$$

$$\max\Pi_{rVS}(q_{rVS}) = \left(\frac{a - q_{mVS} - q_{rVS}}{b} - P_{rVS} - A_r - C_{r1} - \gamma W_{2VS}\right)q_{rVS} \quad (6)$$

We use backward induction to solve the functions and obtain equilibrium decisions (the solving process and equilibrium decisions is shown in Appendix).

Proposition 3. On the relationships of the equilibrium wholesale prices of components with the unit patent licensing fee and unit government subsidy when the government subsidizes to the supplier, we have

$$\text{(I) } \partial W^*_{1VS} \Big/ \partial f > 0, \partial W^*_{2VS} \Big/ \partial f < 0;$$

$$\text{(II) } \partial W^*_{1VS} \Big/ \partial v > 0, \partial W^*_{2VS} \Big/ \partial v < 0.$$

From Part (I) of Proposition 4, we find that when the government subsidizes the supplier's remanufacturing activities, the increasing unit patent licensing fee increases the cost of the remanufacturer. On the one hand, the supplier increases its own patent licensing fee revenue by encouraging the remanufacturing of component 1; on the other hand, she reduces the wholesale price of component 2 to acquire more government subsidies and raises the wholesale price of parts 1 to compensate for its own losses.

From Part (II) of Proposition 4, it is the supplier's remanufacturing activity that the government subsidies to encourage, so when the unit government increases, the supplier tends to obtain more subsidies through more remanufacturing, which requires the remanufacturing ordering a larger number of component 2. Thus, she chooses to reduce to wholesale price of component 2 to achieve that. Moreover, the supplier raises the wholesale price of component 1 at the same time to compensate for her concession on the wholesale price of component 2, which accurately depicts the game leader's dominance.

Proposition 4. On the relationships of the equilibrium production quantities of new and remanufactured products, the recycling price of used products, the selling price of products and the consumer surplus with the unit government subsidy when the government subsidizes to the supplier, we have

$$\text{(I) } \begin{cases} \partial q^*_{mVS} \Big/ \partial v > 0, if\ 0 < \gamma \leq \gamma_1 \\ \partial q^*_{mVS} \Big/ \partial v < 0, if\ \gamma_1 < \gamma < 1 \end{cases};$$

$$\text{(II) } \partial q^*_{rVS} \Big/ \partial v > 0, \partial P^*_{rVS} \Big/ \partial v > 0;$$

$$\text{(III) } \begin{cases} \partial P^*_{VS} \Big/ \partial v < 0, if\ 0 < \gamma \leq \gamma_1 \\ \partial P^*_{VS} \Big/ \partial v > 0, if\ \gamma_1 < \gamma < 1 \end{cases};$$

$$\text{(IV) } \begin{cases} \partial CS^*_{VS} \Big/ \partial v > 0, & if\ v > v_{VS} \\ \partial CS^*_{VS} \Big/ \partial v < 0, & if\ v < v_{VS} \end{cases}.$$

where $v_{VS} = -\dfrac{3\gamma\left\{-a(b+4s)+b\left[b(A_m+F)+2\begin{pmatrix}A_m+A_r\\+C_{r1}+C_{s2}+F\end{pmatrix}s-2\phi\right]\right\}}{b[6s(\gamma-1)+b(2\gamma-1)]}$, $\gamma_1 = \frac{b+6s}{2b+6s}$.

From Part (I) of Proposition 5, we find that in the case of government subsidies for the supplier's remanufacturing actions, there is a critical value of wholesale price discount rate for a supplier's supply to a remanufacturer's component 2. When the wholesale price discount rate is less than or equal to this critical value, the supplier's wholesale profit is not large enough, so the increase of wholesale price of component 1 caused by the increase of unit government subsidy is larger than the decrease of wholesale price of component 2, which increases the assembler's wholesale cost of components, and the profit of unit product decreases, so the assembler increases the production quantity of new products to increase the profit. When the wholesale price discount rate exceeds this threshold, the supplier's profit from selling remanufactured component 2 becomes large enough, which means she no longer have to obtain more extra profit from selling component 1. So the increase of the wholesale price of component 1 caused by the increase of the unit government subsidy is less than the decrease of the wholesale price of component 2, which reduces the wholesale cost of the components of the assembler and increases the profit of the unit product, so the assembler increases the selling price of the product by reducing the output of the new product.

From Part (II) of Proposition 5, we find that in the case of government subsidies for the remanufacturing actions of the supplier, the increase in government unit subsidies has prompted the supplier to reduce the wholesale price of components 2, resulting in lower wholesale cost for the remanufacturer and higher profit per unit product, so that remanufacturer increases his own profit by increasing the output of remanufactured products, resulting in a higher recycling price for used products more subsidies revenue for the supplier.

From Part (III) of Proposition 5, we find that in the case of government subsidies for supplier remanufacturing, when the wholesale price discount rate is less than or equal to this critical value, the wholesale price of component 1 increased more than that of component 2 decreased. For the assembler, this means the whole cost he should pay to sell new products increases. Therefore, he adopted a bulk-cheap strategy to recover losses, which can explain the decrease in the selling price; when the wholesale price discount rate exceeds this critical value, the wholesale profit of parts of supplier is large enough. Therefore, the wholesale price of component 1 increased less than that of component 2 decreased, which makes the wholesale cost of components of the assembler decrease and the profit of unit product increase, so the assembler increases the selling price of products by reducing the output of new products.

From Part (IV) of Proposition 5, we find that when government subsidies for the supplier's remanufacturing actions, the relationship between government subsidies and the consumer surplus does not always remain invariable. When the amount of government subsidies is higher than a certain value (v_{VS}), consumer surplus increases with the increase of government subsidies; when the amount of government subsidies is lower than this value (v_{VS}), the increase in government subsidies cannot stimulate the growth of consumer surplus. This indicates that the government should make careful decisions on subsidies; otherwise, it will not benefit consumers.

Proposition 5. On the relationships of the equilibrium production quantities of new and remanufactured products, the recycling price of used products and the selling price of products with the unit government subsidy when the government subsidizes to the supplier, we have

$$\text{(I) } \partial q^*_{mVS} \Big/ \partial \gamma < 0, \partial q^*_{rVS} \Big/ \partial \gamma < 0;$$

$$\text{(II) } \partial P^*_{rVS} \Big/ \partial \gamma < 0, \partial P^*_{VS} \Big/ \partial \gamma > 0.$$

Proposition 6 indicates that the increase in wholesale price discount rate of component 2 provided by the supplier to the remanufacturer results in higher wholesale cost for the remanufacturer so that the remanufacturer increases the selling price of their products by reducing the output of remanufactured products, thus reducing aggregate demand and resulting in a decrease in the production of new products. At the same time, the reduction of the output of remanufactured products reduces the recycling price of used products.

4.3 Government subsidizes to the remanufacturer (model VR)

In model VR, the government offers unit subsidy to the retailer for the remanufacturing process. The optimization problems of the supplier, the assembler and the remanufacturer are denoted as follows, respectively.

$$\max\Pi_{sVR}(W_{1VR}, W_{2VR}) = (W_{1VR} - C_{s1} - m_1 + W_{2VR} - C_{s2} - m_2)q_{mVR} + (\gamma W_{2VR} + f - C_{s2})q_{rVR} \tag{7}$$

$$\max\Pi_{mVR}(q_{mVR}) = \left(\frac{a - q_{mVR} - q_{rVR}}{b} - A_m - W_{1VR} - W_{2VR}\right)q_{mVR} \tag{8}$$

$$\max\Pi_{rVR}(q_{rVR}) = \left(\frac{a - q_{mVR} - q_{rVR}}{b} - P_{rVR} - A_r - C_{r1} - \gamma W_{2VR} - f + v\right)q_{rVR} \tag{9}$$

We use backward induction to solve the functions and obtain equilibrium decisions (the solving process and equilibrium decisions is shown in Appendix).

Proposition 6. On the relationships of the equilibrium wholesale prices of components with the unit patent licensing fee and unit government subsidy when the government subsidizes to the remanufacturer, we have

$$\text{(I) } \partial W^*_{1VR}\big/\partial f > 0, \partial W^*_{2VR}\big/\partial f < 0;$$

$$\text{(II) } \partial W^*_{1VR}\big/\partial v > 0, \partial W^*_{2VR}\big/\partial v < 0.$$

Part (I) of Proposition 7 indicates that in the case where the government subsidizes for the remanufacturing behavior of the remanufacturer, the increase in unit patent licensing fee increases the cost of the remanufacturer, and the supplier reduces the wholesale price of component 2 to encourage the remanufacturer to remanufacture component 1 and thereby increase the patent licensing fee of the supplier and at the same time, the supplier increases the wholesale price of component 1 to make up her own loss.

Part (II) of Proposition 7 indicates that in the case where the government subsidizes for the remanufacturing behavior of the remanufacturer, the increase in unit government subsidy has led the supplier to increase the wholesale price of component 2 to share the government subsidy received by the remanufacturer, while reducing the wholesale price of component 1 to encourage the assembler to order component 1.

Proposition 7. On the relationships of the equilibrium production quantities of new and remanufactured products, the selling price of products, the recycling price of used products and the consumer surplus with the unit government subsidy when the government subsidizes to the remanufacturer, we have

$$\text{(I) } \partial q^*_{mVR}\big/\partial v < 0, \partial q^*_{rVR}\big/\partial v > 0;$$

$$\text{(II) } \partial P^*_{VR}\big/\partial v < 0, \partial P^*_{rVR}\big/\partial v > 0;$$

$$(\text{III})\begin{cases}\partial CS_{VR}^{*}\big/\partial v>0 & if\ v>v_{VR}\\ \partial CS_{VR}^{*}\big/\partial v<0 & if\ v<v_{VR}\end{cases}.$$

where $v_{VR}=\frac{-a(b+4s)+b[b(A_m+F)+2(A_m+A_r+C_{r1}+C_{s2}+F)s-2\varphi]}{2bs}$.

Part (I) of Proposition 8 indicates that in the case where the government subsidizes for the remanufacturing behavior of the remanufacturer, the increase in unit government subsidy leads to an increase in the unit profit of remanufactured products and causes the remanufacturer to increase his profit by increasing the production of remanufactured products, thus enabling the assembler to increase the selling price of products by reducing the production of new products.

Part (II) of Proposition 8 indicates that in the case where the government subsidizes for the remanufacturing behavior of the remanufacturer, the increase in unit government subsidy has led to an increase in the production of remanufactured products, which has led to higher recycling price for the remanufacturer and lower sales price for the products.

Part (III) of Proposition 8 shows that in the case where the government subsidizes for the remanufacturing behavior of the remanufacturer, whether government subsidies have a positive effect on consumer surplus depends on the amount of government subsidies, which is similar to Model VS. When the amount of government subsidies is higher than v_{VR}, consumer surplus rises with the increase of government subsidies; when the amount of government subsidies remains lower than v_{VR}, consumer surplus decreases with the increase of government subsidies.

5. comparative analysis of equilibrium results

This section focuses on the results of the equilibrium analysis in Section 3 and explores the comparison of the equilibrium sales price of the product, and the equilibrium output of new and remanufactured products under different subsidy modes. The following results can be obtained by comparative calculation (all the proofs of the observations are shown in Appendix).

Corollary 1.

$$\begin{cases}P_{VS}^{*}<P_{VR}^{*}<P_{N}^{*}, & if 0<\gamma<0.5\\ P_{VS}^{*}=P_{VR}^{*}<P_{N}^{*}, & if \gamma=0.5\\ P_{VR}^{*}<P_{VS}^{*}<P_{N}^{*}, & if 0.5<\gamma<\gamma_1\\ P_{VR}^{*}<P_{VS}^{*}=P_{N}^{*}, & if \gamma=\gamma_1\\ P_{VR}^{*}<P_{N}^{*}<P_{VS}^{*} & if \gamma_1<\gamma<1\end{cases},\ where\ \gamma_1=\frac{b+6s}{2b+6s}.$$

Corollary 1 shows that there are two critical values for the discount rate of component 2, which is provided to the remanufacturer by the supplier, and when the discount rate is small, the profit of the supplier from supplying component 2 to the remanufacturer is lower, so when the government subsidizes the supplier, the supplier reduces the wholesale price of component 2 to get more subsidy and then cause the unit product profit of the assembler and remanufacturer to increase, which push both to boost production of new and remanufactured products, resulting in the lowest selling price and the biggest profit for consumers while the government subsidizing to the remanufacturer enables the remanufacturer to increase government subsidies by increasing the output of remanufactured products, thus making the selling price of products sub-lower; when there is no government subsidy, the production of new and remanufactured products is the lowest, which makes the highest selling price of products and the most disadvantageous to consumers.

When the discount rate is high, the profit of component 2 which is provided by the supplier to the remanufacturer is higher, the profit of the unit product of the remanufacturer is lower, and the government subsidizes to the remanufacturer causes the remanufacturer to increase the output of remanufactured products and thus increase the government subsidy, thus making the sales price the lowest and the most beneficial to the consumer. When there is no government subsidy, the supplier encourages the remanufacturer to increase the wholesale quantity of component 2 by reducing the wholesale price of component 2, and the unit product profits of the assembler and remanufacturer are increased, allowing the assembler and remanufacturer to increase the output of new and remanufactured products and sell them at lower prices; when the government subsidizes the supplier, the supplier's unit profit is already high, so it is not necessary to reduce the wholesale price of component 2 to make the production of new and remanufactured products lowest, thus making the product sell the highest price, which is the most disadvantageous to the consumer.

Corollary 2.

$$\begin{cases} q_{mVS}^* > q_{mN}^* > q_{mVR}^*, & if 0 < \gamma < \gamma_1 \\ q_{mVS}^* = q_{mN}^* > q_{mVR}^*, & if \gamma = \gamma_1 \\ q_{mN}^* > q_{mVS}^* > q_{mVR}^*, & if \gamma_1 < \gamma < 0.5, \, where \; \gamma_1 = \frac{b+6s}{2b+6s}. \\ q_{mN}^* > q_{mVR}^* = q_{mVS}^*, & if \gamma = 0.5 \\ q_{mN}^* > q_{mVR}^* > q_{mVS}^*, & if 0.5 < \gamma < 1 \end{cases}$$

Corollary 2 shows that there are two critical values of the discount rate for the supplier supplying remanufactured component 2, and when the discount rate is small, the profit of the supplier supplying remanufactured component 2 is lower, so in order to obtain more subsidies, the supplier will reduce the wholesale price of component 2, which will increase the unit product profit of the assembler and increase the output of the new product, so the production of the new product is the highest. When there is no government subsidy, in order to encourage the remanufacturer to increase the wholesale quantity of component 2, the supplier reduces the wholesale price of component 2 so that the profit of the unit product of the assembler is increased, the output of the new product is increased and the output of the new product is secondary high. When the government subsidizes the remanufacturer, the remanufacturer increases the production of remanufactured products, which reduces the selling price of the products and reduces the production of new products to increase the selling price, so the production of new products is the lowest.

When the discount rate is high, the profit of component 2 which is provided to the remanufacturer by the supplier is higher, and the profit of the unit product of the remanufacturer is lower, and when there is no government subsidy, the supplier will encourage the assembler and remanufacturer to increase the wholesale quantity of the components by reducing the wholesale price of component 1 and component 2, thus leading to the highest production of the new products. When the government subsidizes the remanufacturer, the remanufacturer increases the production of remanufactured products in order to increase the government subsidy, resulting in a lower selling price of the products and the lower production of the new products in order to increase the selling price and reduce the production of the new products. When the government subsidizes the supplier, the supplier increases the government subsidy by encouraging the remanufacturer to increase the production of remanufactured products by lowering the wholesale price of component 2, so the production of the new products is the lowest.

Corollary 3.

$$\begin{cases} q^*_{rVS} > q^*_{rVR} > q^*_{rN}, & if 0 < \gamma < 0.5 \\ q^*_{rVS} = q^*_{rVR} > q^*_{rN}, & if \gamma = 0.5 \\ q^*_{rVR} > q^*_{rVS} > q^*_{rN}, & if 0.5 < \gamma < 1 \end{cases}$$

Corollary 3 shows the existence of a critical value of the discount rate at which the supplier supplies component 2 to the remanufacturer; when the discount rate is small, the profit of the supplier supplying to the remanufacturer component 2 is lower, and the profit of remanufacturer is higher, so the supplier will increase the government subsidy by reducing the wholesale price of component 2; therefore, the output of remanufactured products is the highest; when the government subsidy is given to the remanufacturer, the remanufacturer will increase the profit by increasing the output of remanufactured products, so the production of remanufactured products is high; when there is no government subsidy, the production of remanufactured products will be the lowest.

When the discount rate is high, the profit of the supplier supplying component 2 to the remanufacturer is higher, the profit of the remanufacturer is lower and the government subsidizes the remanufacturer causes the remanufacturer to increase the output of the remanufactured product to increase the government subsidy, so the production of the remanufactured product is the highest. The government subsidizes to the supplier has prompted the supplier to lower the wholesale price for component 2, which has led the remanufacturer to increase the production of remanufactured products; therefore, the production of remanufactured products is second highest; when there is no government subsidy, the production of remanufactured products is lowest.

6. Numerical analysis

This section uses numerical examples to further verify and analyze the impact of key parameters in the model on equilibrium decision-making and profit. From the topic of this paper, analyzing the impact of unit patent licensing fee and the level of unit government subsidy on the model will help the supplier and remanufacturer to formulate wholesale, recycling and two-level remanufacturing decisions and then affect the production decisions of the assembler, thus further clarifying the role of patent licensing and government subsidies on the performance of the two-level remanufacturing supply chain. Benchmark parameters are selected as follows (the base parameter is fixed in order to make the equilibrium decisions are positive, and the change of parameters will not influence the basic results of the paper). $a = 150,\ b = 5,\ A_m = 10,\ A_r = 6,\ C_{s1} = 4,\ C_{s2} = 5,\ \nu = 5,\ \gamma = 0.5,\ C_{r1} = 2,\ \varphi = 5,\ s = 2,$ $m_1 = 1, m_2 = 2, f = 4.$

6.1 Impacts of $0 < \gamma < 0.5$ *on equilibrium decisions and profits when the government subsidizes the supplier*

It can be seen from Figure 2(a) that when government subsidies are given to the supplier, the equilibrium wholesale price of component 1 increases with the unit government subsidy, and the equilibrium wholesale price of component 2 decreases with the unit government subsidy, which is consistent with the conclusion of Part (II) of Proposition 3. When government subsidies are given to the supplier, the equilibrium sales price of the product decreases with the unit government subsidy($0 < \gamma \le \gamma_1$), and the equilibrium recycling price of used products increases in government

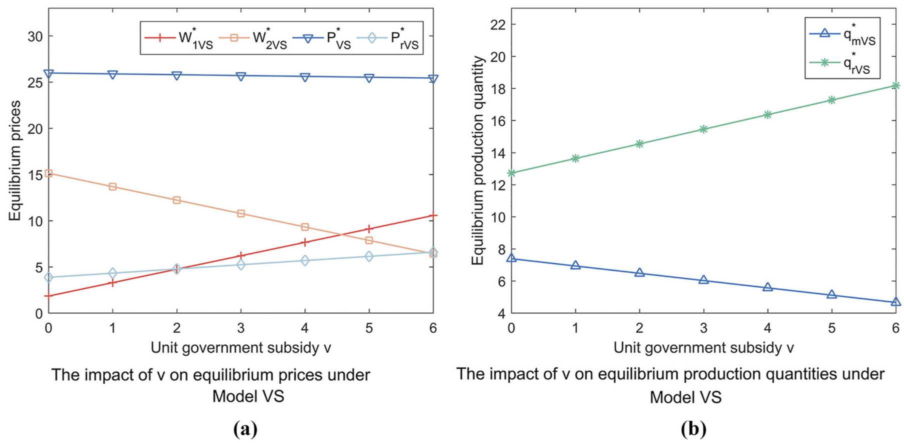


Figure 2.
Impacts of unit subsidy on equilibrium decisions when the government subsidizes the supplier

Source(s): Authors own work

unit subsidies, which is consistent with the conclusions of Part (II) and Part (III) of Proposition 4. In addition, it is obvious that when the unit government subsidy is higher than 2, the recycling price of used products even remains lower than the wholesale price of component 1. This illustrates that the subsidy not only benefits its direct receiver but also the other member of the supply chain. In Figure 2(b), when government subsidies are given to the supplier, the equilibrium output of new products decreases with the unit government subsidy($\gamma_1 < \gamma = 0.5 < 1$), and the equilibrium output of remanufactured products increases with the unit government subsidy, which are consistent with the conclusions of Part (I) and Part (II) of Proposition 4.

From Figure 3, it can be seen that the equilibrium profit of the supplier, the equilibrium profit of the remanufacturer and the equilibrium total profit of the supply chain system when the government subsidizes the supplier all increase with the unit government subsidy, while the equilibrium profit of the assembler decreases first and then increases with the unit government subsidy, and the equilibrium profit of the supplier is always higher than the equilibrium profit of

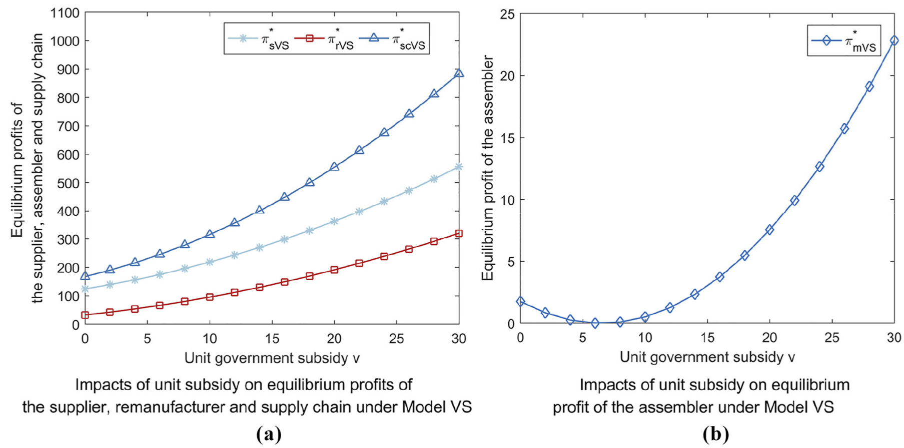


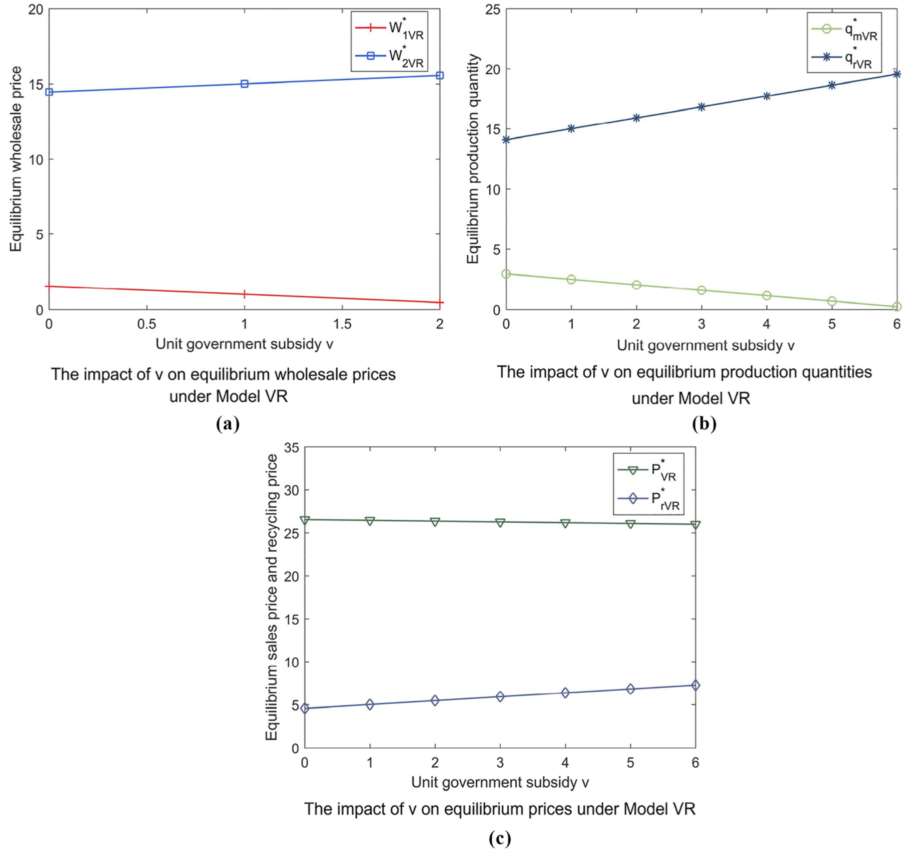
Figure 3.
Impacts of unit subsidy on equilibrium profits of the supply chain and its members when the government subsidizes the supplier

Source(s): Authors own work

the remanufacturer. This is because when the government subsidizes the supplier, the increase of government subsidy decreases the production of new productions and increases the production of remanufactured products, causing the profit of the assembler to decline while that of the supplier and remanufacturer increases. But the assembler's profits is rather small comparing to the other members of the supply chain, thus the overall profit of the supply chain system still increases. The supplier is the leader of the Stackelberg game, so she shares the most profits of the entire supply chain system. When the unit government subsidy reaches a certain degree, the profit of the unit product of the supplier shared by the remanufacturer also increases to a certain extent, which urges the remanufacturer to increase the selling price of the product by reducing the output of remanufactured products, so the output of the new product increases and the profit of the assembler recovers.

6.2 Impacts of $0.5 < \gamma < 1$ *on equilibrium decisions and profits when the government subsidizes the remanufacturer*

From Figure 4(a) it can be seen that when the government subsidizes the remanufacturer, the equilibrium wholesale price of component 1 decreases with the unit government subsidy,



Source(s): Authors own work

Figure 4. Impacts of unit subsidy on equilibrium decisions when the government subsidizes the remanufacturer

while the equilibrium wholesale price of component 2 increases with the unit government subsidy, which is different form model VS shown in Figure 3. The cause for this phenomenon is that the supplier as the leader intends to share the subsidies which are given to the remanufacturer, thus she increases the wholesale price of component 2 to make a profit from the remanufacturer. As can be seen from Figure 4(b), when the government subsidizes the remanufacturer, the equilibrium output of new products decreases with the unit government subsidy, and the equilibrium output of remanufactured products increases with the unit government subsidy, which is consistent with the conclusion of Part (I) of Proposition 7. It can be seen from Figure 4(c) that when the government subsidizes the remanufacturer, the equilibrium sales price of products decreases with the unit government subsidy, and the equilibrium recycling price of used products increases with the unit government subsidy, which is consistent with the conclusion of Part (II) of Proposition 7.

As can be seen from Figure 5, when the government subsidizes the remanufacturer, the equilibrium profit of the supplier, the remanufacturer and the supply chain system all increase with the unit government subsidy, while the assembler's equilibrium profit first reduces and then increases with the unit government subsidy, and the supplier's equilibrium profit is always higher than the remanufacturer's equilibrium profit. This is because the increase of government subsidy to the remanufacturer results in the decrease of equilibrium output of new products and the increase of equilibrium output of remanufactured products, which makes the profits of the supplier and remanufacturers increase, the profit of the assembler decreases, while the profit of supply chain system is increased in general, and the supplier is the leader of Stackelberg game, so the supplier shares the most profit of the whole supply chain system. When the unit government subsidy reaches a certain degree, the profit per unit product of the remanufacturer also increases to a certain extent, which urges the remanufacturer to increase the selling price of products by reducing the output of the remanufactured product, so the output of new products increases and the profit of the assembler picks up. In addition, it is obvious that the profit gap between the supplier and the remanufacturer becomes smaller comparing to model VS shown in Figure 3. This indicates the direct incentive effect of government subsidies on the remanufacturer and the dominant power of the game leader. According to Proposition 6, the supplier shares the subsidies by increasing the wholesale price of component 2, so the profit of the remanufacturer always remains lower than hers.

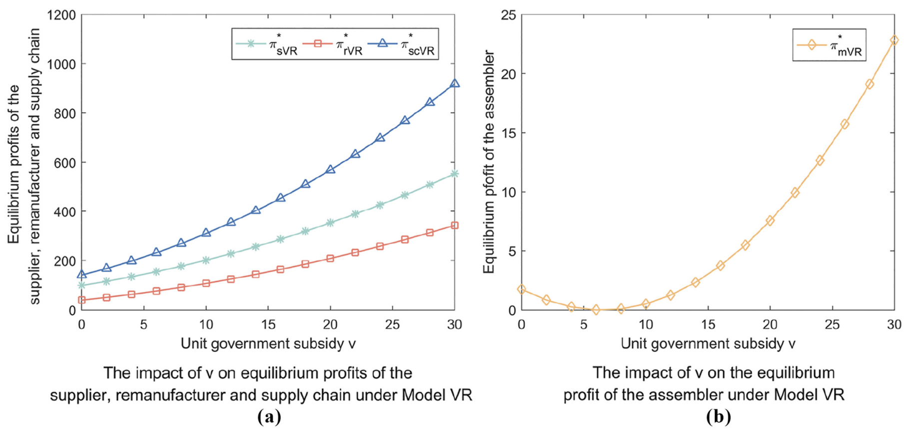


Figure 5.
Impacts of unit subsidy on equilibrium profits of the supply chain and its members when the government subsidizes the remanufacturer

Source(s): Authors own work

6.3 Impacts of $0.5 < \gamma < 1$ *on social welfare under three models*

Figure 6 presents the trend of social welfare with government subsidy under three models. When government subsidy remains zero, the social welfare is the highest under model VS, followed by model VR and the lowest under model N. And no matter how high the subsidy reaches, the social welfare is always the highest under model VS, in which the government subsidizes the supplier. As for the relationship between government subsidy and social welfare, it is obvious that social welfare increases in a linear way with the growth of government subsidy under model VS and model VR. When government subsidy is higher than a certain value, the social welfare under VR mode will exceed that under N mode. Thus, the case that the government subsidizes the supplier is most beneficial to the society.

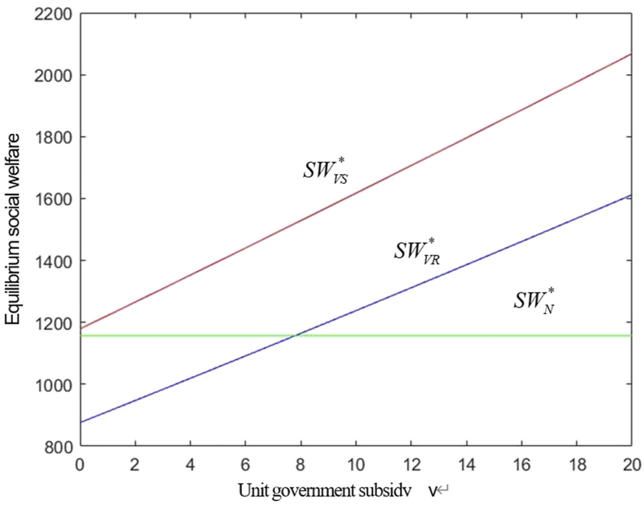
7. Concluding remarks

This paper mainly studies the two-level remanufacturing supply chain including one supplier, one assembler and one remanufacturer. The supplier and the remanufacturer carry out the remanufacturing of the core component 2 and the ordinary component 1, respectively. The remanufacturer pays the patent licensing fee to the supplier for the remanufacturing of component 1. On the other hand, considering the factors of the government subsidy on the remanufacturing behavior, we analyze the Stackelberg game in which the supplier is the leader, the assembler and the remanufacturer are the followers and the assembler and remanufacturer form Cournot competition with respect to production quantity. Referring back to the three research questions posed at the introduction:

RQ1. How will patent licensing influence the supply chain equilibrium decision under different government subsidy models?

RQ2. What are the effects of government unit subsidies on equilibrium decisions and profit in different subsidy models?

RQ3. What are the results of production competition and equilibrium profit distribution of products under different government subsidy modes?



Source(s): Authors own work

Figure 6.
Impacts of unit subsidy on equilibrium social welfare

We provide a summary of our models' key findings and respond to each of the questions.

(1) Patent licensing mainly affects the supply chain decisions through the supplier's equilibrium wholesale prices. Specifically, it enforces the supplier to raise the wholesale price of ordinary component 1 and decrease that of core component 2 under all three models. This indicates that raising the unit patent license fee will reduce the willingness of remanufacturers to cooperate, which needs the supplier to reduce the wholesale price of component 2 to encourage the remanufacturer and increase the wholesale price of component 1 to make up.

(2) The impact of government unit subsidies on equilibrium decisions and profit varies.

- First, when the government subsidizes the supplier, the growth of subsidies fosters the increase of the equilibrium wholesale price of ordinary component 1 and the decrease of that of core component 2. In that case, government subsidies enable the supplier to reduce wholesale prices to encourage remanufacturers to produce more remanufactured products, which can not only increase the quantity of remanufacturing products but also the government subsidy revenue.
- Second, regardless of the subsidy model, the equilibrium output of the new product and its equilibrium sales price is negatively correlated with the unit subsidy, while the equilibrium output of the remanufactured product and the equilibrium recycling price is positively correlated with it. This indicates that government subsidizing the remanufacturing process can improve competitiveness of remanufactured products, but the price of new products must be lower to stimulate consumers to buy them.
- Third, regardless of the subsidy model, the equilibrium profit of the supplier, remanufacturer and supply chain system is positively related to the unit subsidy, while the assembler's equilibrium profit is first negatively but then positively related. And the social welfare is always the highest under VS model, which means subsiding the supplier can achieve a maximum growth in social welfare and is most beneficial to the society.

(3) Regardless of the subsidy model, the supplier (the game leader) always owes the highest profit, then the remanufacturer who has the advantage of remanufacturing and assembling cost relative to the assembler, which makes the production of the remanufactured product very high, resulting in the low production of the new product, thus making the lowest profit of the assembler.

The findings of this study are of great practical significance for the upstream supplier who implements remanufacturing and downstream remanufacturer and government. The two-echelon remanufacturing of components and the wholesale price discount of the supplier to component 2 can improve the recycling and remanufacturing efficiency of the remanufacturer and enable the supplier to share the profit from remanufacturing through patent licensing. At the same time, the mode of government subsidy for remanufacturing behavior can improve the performance of supply chain system and motivate the supplier and remanufacturer to invest more resources for remanufacturing, which is of great economic and social significance for saving resources and improving the environment.

In this paper, we consider the situation of a supplier participating in the remanufacturing of components, but there is more than one product core component in reality, which leads to more than one supplier of remanufacturing core components. How to analyze the decision problem of multiple suppliers participating in the remanufacturing of core components will be a more practical research. In addition, this paper discusses the two-echelon remanufacturing decision in the case of demand determination, and the two-echelon remanufacturing supply chain decision in the case of demand uncertainty is also the next direction to be considered.

References

Abbey, J.D., Blackburn, J.D. and Guide, V.D.R. (2015), "Optimal pricing for new and remanufactured products", *Journal of Operations Management*, Vol. 36, pp. 130-146.

Atasu, A., Sarvary, M. and Van Wassenhove, L.N. (2008), "Remanufacturing as a marketing strategy", *Management Science*, Vol. 54 No. 10, pp. 1731-1746.

Arora, A. and Ceccagnoli, M. (2006), "Patent protection, complementary assets, and firms' incentives for technology licensing", *Management Science*, Vol. 52 No. 2, pp. 293-308.

Cao, K., Xu, B. and Wang, J. (2020), "Optimal trade-in and warranty period strategies for new and remanufactured products under carbon tax policy", *International Journal of Production Research*, Vol. 58 No. 1, pp. 180-199.

Chen, J.Y., Dimitrov, S. and Pun, H. (2019), "The impact of government subsidy on supply chains' sustainability innovation", *Omega*, Vol. 86, pp. 42-58.

Debo, L.G., Toktay, B. and Van Wassenhove, L.N. (2005), "Market segmentation and product technology selection for remanufacturable products", *Management Science*, Vol. 51 No. 8, pp. 1193-1205.

Ding, B. and Ma, H.Q. (2015), "Decision-making and performance analysis of S-M closed-loop supply chain with two-echelon remanufacturing", *Chinese Journal of Management Science*, Vol. 23 No. 6, pp. 118-125, (in Chinese).

Feng, Y., Xia, X., Yin, X., Wang, L. and Zhang, Z. (2022), "Pricing and coordination of remanufacturing supply chain with government participation considering consumers' preferences and quality of recycled products", *Complexity*, Vol. 2022, pp. 1-25.

Ferguson, M. and Toktay, L. (2006), "The effect of competition on recovery strategies: the effect of competition on recovery strategies", *Production and Operations Management*, Vol. 15 No. 3, pp. 351-368.

Ferrer, G. and Swaminathan, J.M. (2006), "Managing new and remanufactured products", *Management Science*, Vol. 52 No. 1, pp. 15-26.

Ferrer, G. and Swaminathan, J.M. (2010), "Managing new and differentiated remanufactured products", *European Journal of Operational Research*, Vol. 203 No. 2, pp. 370-379.

Ginsburg, J. (2001), "Manufacturing: once is not enough", *Business Week*, No. 16, pp. 128-129.

He, P., He, Y. and Xu, H. (2019), "Channel structure and pricing in a dual-channel closed-loop supply chain with government subsidy", *International Journal of Production Economics*, Vol. 213, pp. 108-123.

Hong, I.H., Chen, P.C. and Yu, H.T. (2016a), "The effects of government subsidies on decentralised reverse supply chains", *International Journal of Production Research*, Vol. 54 No. 13, pp. 3962-3977.

Hong, X.P., Zhang, H., Zhong, Q., Liu, L.W. (2016b), "Optimal decisions of a hybrid manufacturing-remanufacturing system within a closed-loop supply chain", *European Journal of Industrial Engineering*, Vol, *10* No. 1, pp. 21-50.

Hong, I.H., Lee, Y.T. and Chang, P.Y. (2014), "Socially optimal and fund-balanced advanced recycling fees and subsidies in a competitive forward and reverse supply chain", *Resource, Conservation and Recycling*, Vol. 82 No. 82, pp. 75-85.

Hong, X.P., Govindan, K., Xu, L. and Du, P. (2017), "Quantity and collection decisions in a closed-loop supply chain with technology licensing", *European Journal of Operational Research*, Vol. 256 No. 3, pp. 820-829.

Huang, M., Song, M., Lee, L.H. and Ching, W.K. (2013), "Analysis for strategy of closed-loop supply chain with dual recycling channel", *International Journal of Production Economics*, Vol. 144 No. 2, pp. 510-520.

Investigation Report on the Development of Remanufacturing Industry (IRDRI) (2013), (in Chinese), available at: http://www.docin.com/p-672746406.html

Jena, S.K., Sarmah, S.P. and Padhi, S.S. (2018), "Impact of government incentive on price competition of closed-loop supply chain systems", *Information Systems and Operational Research*, Vol. 56 No. 2, pp. 192-224.

Kamien, M.I. (1992), *Chapter 11 Patent Licensing. Handbook of Game Theory with Economic Applications*, Elsevier, Amsterdam, pp. 331-354.

Ke, C., Yan, B. and Ji, J. (2023), "Pricing new and remanufactured products under patent protection and government intervention", *Annals of Operations Research*, Vol. 324 Nos 1-2, pp. 131-161, doi: 10.1007/s10479-022-05149-6.

Li, J., Du, W.H., Yang, F.M. and Hua, G.W. (2014), "The carbon subsidy analysis in remanufacturing closed-loop supply chain", *Sustainability*, Vol. 6 No. 6, pp. 3861-3877.

Li, Z., Zheng, W., Meng, Q.F. and Jin, S. (2019), "The impact of government subsidy and tax policy on the competitive decision-making of remanufacturing supply chains", *International Journal of Sustainable Engineering*, Vol. 12 No. 1, pp. 18-29.

Liu, H., Lei, M., Deng, H., Keong Leong, G. and Huang, T. (2016), "A dual channel, quality-based price competition model for the WEEE recycling market with government subsidy", *Omega*, Vol. 59, pp. 290-302.

Liu, L., Pang, C. and Hong, X. (2022), "Patented product remanufacturing and technology licensing in a closed-loop supply chain", *Computers and Industrial Engineering*, Vol. 172, 108634.

Liu, Y., Quan, B.T., Xu, Q. and Forrest, J.Y.-L. (2019), "Corporate social responsibility and decision analysis in a supply chain through government subsidy", *Journal of Cleaner Production*, Vol. 208, pp. 436-447.

Mitra, S. and Webster, S. (2008), "Competition in remanufacturing and the effects of government subsidies", *International Journal of Production Economics*, Vol. 111 No. 2, pp. 287-298.

Rostoker, M.D. (1983), "A survey of corporate licensing", *Idea*, Vol. 24, p. 59.

Savaskan, R.C., Bhattacharya, S. and Van Wassenhove, L.N. (2004), "Closed-loop supply chain models with product remanufacturing", *Management Science*, Vol. 50 No. 2, pp. 239-252.

Savaskan, R.C. and Van Wassenhove, L.N. (2006), "Reverse channel design: the case of competing retailers", *Management Science*, Vol. 52 No. 1, pp. 1-14.

Sun, H.X., Wan, Y., Zhang, L.L. and Zhou, Z. (2019), "Evolutionary Game of the green investment in a two-echelon supply chain under a government subsidy mechanism", *Journal of Cleaner Production*, Vol. 235, pp. 1315-1326.

Wang, Y., Yu, Z., Shen, L. and Jin, M. (2022), "Operational modes of E-closed loop supply chain considering platforms' services", *International Journal of Production Economics*, Vol. 251, 108551.

Webster, S. and Mitra, S. (2007), "Competitive strategy in remanufacturing and the impact of take-back laws", *Journal of Operations Management*, Vol. 25 No. 6, pp. 1123-1140.

Wu, D., Chen, J., Li, P. and Zhang, R. (2020), "Contract coordination of dual channel reverse supply chain considering service level", *Journal of Cleaner Production*, Vol. 260, 121071.

Xiong, Z.K., Shen, C.R. and Peng, Z.Q. (2011), "Closed-loop supply chain coordination research with remanufacturing under patent protection", *Journal of Management Sciences in China*, Vol. 14 No. 6, pp. 76-85, (in Chinese).

Xue, J., Gong, R.F., Zhao, L.J., Ji, X.Q. and Xu, Y. (2019), “A Green supply-chain decision model for energy-saving products that accounts for government subsidies”, *Sustainability*, No. 11, pp. 1-17.

Yu, X., Zhang, W.G. and Liu, Y.J. (2019), “Coordination mechanism for contract farming supply chain with government option premium subsidies”, *Asia Pacific Journal of Operational Research*, Vol. 36 No. 5, pp. 1-27.

Zhang, C.T. and Ren, M.L. (2016), “Closed-loop supply chain coordination strategy for the remanufacture of patented products under competitive demand”, *Applied Mathematical Modelling*, Vol. 40 Nos 13-14, pp. 6243-6255.

Zhang, X., Li, Q., Liu, Z. and Chang, C. (2021), “Optimal pricing and remanufacturing mode in a closed-loop supply chain of WEEE under government fund policy”, *Computers and Industrial Engineering*, Vol. 151, 106951.

Zhao, X.M., Lin, Y.H. and Su, C.M. (2012), “Performance analysis of S-M closed-loop supply chain under different channel power structures”, *Chinese Journal of Management Science*, Vol. 20 No. 2, pp. 78-86, (in Chinese).

Zou, Z.B., Wang, J.J., Deng, G.S. and Chen, H. (2016), “Third-party remanufacturing mode selection: outsourcing or authorization?”, *Transportation Research Part E: Logistics and Transportation Review*, Vol. 87, pp. 1-19.

Further reading

Arda, Y. (2016), “Managing new and remanufactured products to mitigate environmental damage under emissions regulation”, *European Journal of Operational Research*, Vol. 249 No. 1, pp. 117-130.

Sheu, J.B. and Chen, Y.J. (2012), “Impact of government financial intervention on competition among green supply chains”, *International Journal of Production Economics*, Vol. 138 No. 1, pp. 201-213.

Appendix

The supplementary material for this article can be found online.

Corresponding author

Xiaogang Cao can be contacted at: caoxiaogang1982@hotmail.com