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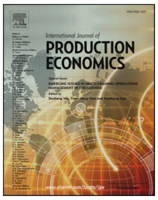

How to balance economic profits and environmental protection: The impacts of cash hedging on remanufacturing firms

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ABSTRACT

The popularity of the circular economy attracts more attention to balance environmental and economic impacts. Many supply chain remanufacturing firms have started to use the cash flow to invest in cost-reduction technologies to increase profits. However, the uncertainty of cash flow significantly affects the technology investment effectiveness, and therefore, some firms attempt to adopt cash hedging strategies to mitigate the uncertainty. This study investigates the impacts of cash hedging on remanufacturing firms' profits and the environment through the lenses of cost-reduction technologies investments. The proposed nonlinear programming models were drawn on cash hedging and risk management theory. Empirical regression analysis was conducted using longitudinal datasets of listed Chinese remanufacturing firms for ten years ranging from 2010 to 2019. Different from the traditional wisdom which argues that cash hedging has a single effect (i.e., positive, negative, or no impact) on corporate economic performance, this paper's results indicate that the impact of cash hedging on corporate profits varies in different conditions; Further, this study is one of the first to identify some interesting conditions, in which cash hedging can bring along remanufacturing firms with profits while protect environment. This study provides insightful suggestions for the manufacturer's and government's policy design.

1. Introduction

The manufacturing industry has witnessed extensive waste generation and associated negative environmental impacts of wasted resources owing to the linear life cycle of new products. The shift to a circular economy directly responds to growing concerns about resource scarcity and negative environmental impacts in the manufacturing industry (Milios et al., 2019; Jin et al., 2022). Remanufacturing refers to the process of repairing and transforming old-use products to like-new products (i.e., remanufactured products), which provides a feasible way to convert a linear product life-cycle to a circular one (Atasu et al., 2008). As a significant and commonly used circular economy practice within the manufacturing industry, remanufacturing is extremely helpful in reducing waste products disposal, natural resources consumption, and materials to landfills (Alizadeh-Basban and Taleizadeh, 2019; Zhou et al., 2021). Nowadays, many manufacturers begin to embrace this environmentally friendly practice (remanufacturing), and transform themselves into remanufacturing firms that produce both new and remanufactured products.

However, remanufacturing firms may be reluctant to conduct remanufacturing when they cannot reap profits from remanufacturing. One critical factor that can significantly affect remanufacturing firms' profits is the risk of high production cost, which may originate from the price changes of primary commodities (e.g., steel, plastic, and aluminium) and fluctuations of exchange rates and interest. To offset the potential cost increase and gain profits, a growing number of

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remanufacturing firms have been investing in cost-reduction technology with available cash flow. For example, the leading equipment-remanufacturing firm Caterpillar has been investing in automation technology and production processes technology to boost productivity and reduce the production cost, with an ultimate intention to counter higher material expenses and increase profits (Kouvelis et al., 2019). It has been widely acknowledged that cost-reduction technology innovation or investment is a value-enhancing investment, which is effective in reaping huge profits (Adam et al., 2007; Kouvelis et al., 2019).

In practice, however, the effectiveness of cost-reduction technology innovation can be tremendously affected by the available cash flow used for technology innovation investment. Actually, cash flow is often uncertain, since remanufacturing firms are often affected by the volatility of unpredictable factors, such as the cost of material purchase, price of sales price, the interest rate, and the exchange rate. To obtain enough and stable cash flows, corporations have widely adopted cash hedging as a useful financial risk management operation, which protects firms from the risk of cash flow volatility (Ha et al., 2017; Kouvelis et al., 2019). Cash hedging is a financial investment strategy that aims to protect individuals from the variable cash flow risk and to obtain stable cash flow (Kouvelis and Turcic, 2021). The essential operation for cash hedging is as follows: to buy (sell) commodity in the practical or spot market, and at the same time to sell (buy) the same commodity in the financial market. Owing to the opposite transactions in the spot and financial market, the cash flow loss in the spot market could be compensated by the revenue in the financial market, and vice versa. Consequently, stable cash flow is obtained via cash hedging (Sun et al., 2017). Generally, the transaction in the financial market is based on derivatives (e.g., options and futures), thus firms oftentimes use derivatives to avoid cash flow risk and obtain stable cash flow. For example, according to the annual report of Caterpillar in 2020, to protect the firm from the cash flow risk from the increase in the interest rate, foreign currency exchange rates, and commodity price, Caterpillar has used various types of derivatives including foreign currency forward contracts, interest rate forward contracts, and commodity forward contracts and option contracts.

Although remanufacturing firms oftentimes use cash hedging to provide stable financial support for cost-reduction technology investment, the impact of cash hedging still remains unclear. On the one hand, when there is unfavorable cash flow volatility, remanufacturing firms adopt cash hedging to obtain stable cash flow for cost-reduction technology investment, which could decrease the production cost and consequently increase the profit (Chod et al., 2010; Sun et al., 2017). On the other hand, cash hedging also avoids favorable cash flow volatility (Adam et al., 2007; Kouvelis et al., 2019). For example, when a remanufacturing firm uses cash hedging to avoid the risk of the rising price of the commodities for production, the firm would obtain less cash flow with cash hedging if the price of commodities decreases rather than increases as expected. Therefore, when there is favorable cash flow volatility, cash hedging would reduce the available cash flow, which would adversely affect the effectiveness of cost-reduction technology investment (e.g., increase the product cost), and ultimately reduce the profit of the remanufacturing firm. Thus, it is unclear how cash hedging would influence the profit of a remanufacturing firm. Moreover, existing study indicates that the remanufacturing firm's cash hedging has a significant impact on the environment (Sun et al., 2017). However, the specific influence of cash hedging on the environment is far from clear, which requires further investigation. Motivated by the practice and discussions above, our research intends to investigate the following two questions.

RQ1. How does cash hedging affect the profit of a remanufacturing firm with investments in cost-reduction technologies?

RQ2. What is the influence of cash hedging on the environment?

Currently, the above two questions cannot be answered by the previous literature on cash hedging, because most literature investigated cash hedging from the perspective of non-remanufacturing firms. However, compared with non-remanufacturing firms, remanufacturing firms have different products and supply chain structures, and these differences significantly influence firms' decisions and strategies (Randall and Ulrich, 2001; Zhang et al., 2019). Specifically, non-remanufacturing firms mainly engage in the forward supply chain as they sell new products only. But remanufacturing firms are involved in both forward and reverse supply chains, as they not only sell new products to consumers (i.e., a forward supply chain), but also collect old-use products from consumers (i.e., a reverse supply chain) (Sun et al., 2017). Therefore, the previous research on non-remanufacturing firms' strategies (e.g., cash hedging strategy) may not be applicable in the remanufacturing context. Remanufacturing firms' cash hedging strategy and its impacts on profits and the environment deserve further investigation.

To address the aforementioned two questions, this study adopts a multi-methodological approach, i.e., a mix of nonlinear programming models and regression analysis. The nonlinear programming models can answer our research questions from a theoretical perspective. The regression analysis is used for two reasons. First, the regression analysis could strengthen the robustness of the main theoretical results in the nonlinear programming models (Agrawal, 1996; Amato et al., 2015). Specifically, nonlinear programming models could offer the theoretical results that whether cash hedging would have impacts on the remanufacturing firm's profit. Further, the regression analysis could verify the relationship between cash hedging and remanufacturing firms' profits from an empirical perspective. Second, the regression analysis could supplement the qualitative results of nonlinear programming models from a quantitative perspective (Ba et al., 2012; Przepiorka et al., 2020). Specifically, the nonlinear programming models would investigate the impacts of cash hedging from the qualitative perspective by answering "whether cash hedging would influence a remanufacturing firm's profit", which cannot depict the extent of influence. However, the regression analysis could empirically quantify the magnitude of influence. Therefore, the combination of both nonlinear programming models and regression analysis could contribute to a deeper understanding of the impacts of cash hedging on remanufacturing firms' profits, from both qualitative and quantitative perspectives.

To investigate the impacts of cash hedging on remanufacturing firms' profits and environmental performance, we first develop a benchmark model, in which a manufacturer invests in cost-reduction technologies and only participates in manufacturing new products. This model considers two scenarios in which the manufacturer either gets involved in cash hedging or does not do so, and consequently the profits and environmental impacts in these two scenarios are obtained and compared. Then, we consider the case that the manufacturer conducts remanufacturing and becomes a remanufacturing firm that produces both new and remanufactured products. We develop two nonlinear programming models in which the remanufacturing firm either engages in cash hedging or does not do it. Similarly, the profits and environmental impacts in these two models are compared to reveal the impacts of cash hedging. Finally, taking some representative remanufacturing firms in China as samples, a regression analysis is conducted to have a better understanding of the impacts of cash hedging on remanufacturing firms' profits.

Our research is expected to make several significant contributions. First, we extend the existing research on cash hedging to the area of remanufacturing, which is important but neglected in previous studies. Moreover, our research compensates the existing literature on remanufacturing by considering cash hedging as a way to reduce cash flow volatility risk. In addition, the study is one of the first to present the influence mechanism by which firms' cash hedging strategy influences the environment. Finally, this study provides insightful suggestions for the manufacturer's cash hedging strategies, as well as the government's policy design on environmental protection.

The rest of this paper is organized as follows. Section 2 reviews related literature. Section 3 describes the model setting and related assumptions. Section 4 develops the benchmark models without remanufacturing. Section 5 formulates the model with remanufacturing, and analyzes the impact of cash hedging on profits and environmental impacts. Section 6 conducts an empirical regression analysis to test the impact of cash hedging on remanufacturing firms' profits. Section 7 closes this paper by summarizing the main results, offering theoretical and practical contributions, and pointing out limitations for future research. All the proofs are included in Appendix.

2. Literature review

Our study is closely related to the literature on corporate risk management, with a particular focus on firms' cash hedging. Cash hedging is beneficial to reducing the volatility of cash flows risk and the adverse cash flow shocks related to the unfavorable change in the price, such as the price of input material, the selling price of products, the interest rate, or the exchange rate (Bartram, 2019). Previous studies have investigated many aspects relevant to cash hedging, such as the hedging tools, the value of hedging, and factors that affect firms' hedging strategy. Firms often use financial instruments such as futures and options derivatives to hedge cash flow risks (Yu et al., 2020). Turcic et al. (2015) find the benefits of hedging of stochastic input cost in ensuring continuity of a supply chain. Some studies such as Mackay and Moeller (2007), and Disatnik et al. (2014) reveal the significant positive impacts of cash hedging on improving the value of firms, which provide a reason for the choices of firms' hedging strategies. However, some studies such as Ben (2010), and Bartram et al. (2011) find that whether firms use derivatives would not affect the firm's value. Thus, many studies try to analyse the impact of different factors on firms' hedging strategies. Some researchers have investigated internal factors such as financial constraints (Rampini et al., 2014), net worth (Rampini et al., 2020), and firm size (Géczy et al., 1997). For example, Rampini et al. (2014) find that firms' financial constraints would hamper the use of derivatives. Rampini et al. (2020) investigate financial institutions' hedging for the interest rate and foreign exchange risk and find that the firm with the higher net worth will hedge more. Other researchers investigate the effects of external factors on firms' hedging strategies, such as externally provided liquidity (Disatnik et al., 2014), competition (Adam et al., 2007; Loss, 2012; Adam and Nain, 2013; Hoang and Ruckes, 2017), firm's market sizes (Fok, 1997), and correlation of a supply chain members (Kouvelis et al., 2019).

Although previous literature has investigated cash hedging strategies from many perspectives, there are a few significant research gaps. First of all, the above studies try to examine the impact of cash hedging and the factors affecting cash hedging strategy from non-remanufacturing firms' perspectives, while ignoring the remanufacturing firms. In practice, many remanufacturing enterprises have adopted cash hedging strategy. Compared with non-remanufacturing firms, the remanufacturing firms have different product manufacturing strategies and supply chain structures. Different from non-remanufacturing firms that only manufacture new products, remanufacturing firms produce both new and remanufactured products (Sun et al., 2017). Moreover, non-remanufacturing firms are usually involved in a forward supply chain structure only, while remanufacturing firms are generally involved in both forward and reverse supply chains (Reimann et al., 2019). According to Randall and Ulrich (2001), product types and supply chain structures can have significant impacts on firms' decisions and performance. Thus, it is worth asking whether the theoretical research on non-remanufacturing enterprises can be applied to remanufacturing enterprises.

Our research is also related to the economic and environmental impacts of remanufacturing firms' strategies and decisions in the literature on the closed supply chain with remanufacturing. Remanufacturing is the process of repairing and transforming old-use products to remanufactured products, which have the same quality as new products (Zhou et al., 2021). Due to its role in reducing environmental impacts and promoting the development of circular economy, remanufacturing has been sufficiently investigated. The earliest literature emphasizes remanufacturing firms' economic profits, and thus analyses the factors, the strategy, and operational decisions affecting remanufacturing firms' profits. For instance, Atasu et al. (2008) identify the different factors affecting the profitability of remanufacturing strategy, and find that cost savings, green consumers, market growth rate, and consumers' value for remanufactured products are the influential factors. Some researchers try to analyse how the remanufacturing firms can use production decisions to maximize its profit by examining how many used products can be remanufactured or how many remanufactured products should be produced (Galbreth et al., 2010; Ferguson et al., 2011; Raz and Souza, 2018). Besides the economic profit, more and more scholars began to focus on the remanufacturing firms' environmental performance (e.g., Yenipazarli, 2016; Sarkar et al., 2017; Wang et al., 2017; Dou and Cao, 2020). For example, Wang et al. (2017) investigate the profitability and environmental impact of different remanufacturing strategies (i.e., in-house and outsourcing). Dou and Cao (2020) try to find a win-win collection channel strategy among three collection channels (i.e., manufacturer collection channel, retailer collection channel, and third party collection channel) for economic profit and the environment. Unfortunately, most studies believe that the remanufacturing firm's strategy is difficult to achieve both economic and environmental performance. Thus, our paper is going to explore whether the belief is still holding when a new strategy (i.e., cash hedging strategy) is considered, which can be explored by comparing both the economic and environmental impacts of this new strategy.

For remanufacturing firms, uncertainties and risks are inherent characteristics in a closed-loop supply chain, as suggested in a systematic review by Master et al. (2020). Many studies have investigated the risk types and risk management measures. Previous studies have investigated different risks or various uncertainty factors, such as uncertainty of the production cost (Han et al., 2016; Huang et al., 2019), uncertainties of the recycled products (He, 2017), stochastic remanufacturing capacity or yield (Heydari et al., 2018; Li et al., 2015), and demand uncertainties in the market (Liao, 2018; Huang and Wang, 2018; Zhao and Zhu, 2018). Based on the above risk factors, different supply chain contracts have been designed to reduce specific risk in remanufacturing activities (He and Zhang, 2008; He, 2015; He, 2017; Zhong et al., 2022). However, only limited studies have considered using financial risk management tools to reduce the risk of remanufacturing firms. Wei and Tang (2014) use a real option approach to evaluate the economic value of collected old-use products to minimize the risk of the price of remanufactured products. Sun et al. (2017) use cash hedging to reduce the demand uncertainties in the market. Different from Wei and Tang (2014), and Sun et al. (2017), we use cash hedging to reduce the cash flow risks, with a final aim to reduce the risk of production cost uncertainty risk.

Two gaps are existing in the risk management literature associated with remanufacturing. Firstly, the financial risk management strategy is rarely considered, although commonly used in practice. Quite limited studies have incorporated the financial risk management tool in remanufacturing models (Wei and Tang, 2014; Sun et al., 2017). The research considering using cash hedging to reduce cost uncertainty risk is even scarcer. According to Han et al. (2016) and Huang et al. (2019), the production cost risk is critical to remanufacturing firms, as it can affect remanufacturing firms' strategy (such as reverse channel selection) and economic performance. Some researchers (e.g., Adam et al., 2007; Kouvelis et al., 2019) have pointed out the potential of cash hedging in reducing cash flow risks and cost uncertainty risk for a non-remanufacturing firm. Based on their research, we consider using cash hedging to minimize the cash flow risks and the cost uncertainty risk for a remanufacturing firm. Secondly, the existing studies lack an understanding of the environmental impacts of cash hedging. Although Sun et al. (2017) have shown that cash hedging can have an impact on the environment, the specific influence and the influence mechanism are unclear in their studies, which require more research effort.

3. Model development

In this section, we first present the model setting and assumptions from the perspective of firms, consumers, and environment, respectively. Then the timeline of events will be described.

3.1. Firms

We consider a firm (i.e., a manufacturer) who produces new products with potential high unit production cost (UPC). To reduce the cost of new products and increase production efficiency, the manufacturer can invest in cost-reduction technology with cash flow. However, the cash flow is uncertain, which can be affected by the volatility of unpredictable factors, such as cost of material purchase, price of sales price, the interest rate, and the exchange rate. The manufacturer can choose to hedge its cash flow to mitigate uncertain factors and volatility. Following previous literature on hedging, such as Adam et al. (2007) and Kouvelis et al. (2019), we assume that the manufacturer can choose to hedge all the cash flow or not to hedge cash flow, and cash hedging is a costless choice. If the manufacturer decides not to hedge, the amount of available cash flow is a random variable k. If the manufacturer chooses to hedge, the cash flow would be a constant $k_0 = E(k)$, where $E(k)$ is the expected value of k. As stated by Kouvelis et al. (2019), the cash flow could be high or low, and thus we assume that the cash flow k follows a two-point distribution. That is, the cash flow k is a random variable which can be either be low (i.e., $k = k_l$) with probability ρ or high (i.e., $k = k_h$) with probability $1-\rho$, where $\rho \in (0,1)$. Correspondingly, we can obtain the expected value of the cash flow, i.e., $k_0 = E(k) = \rho k_l + (1-\rho)k_h$.

After the cash flow is realized, the manufacturer will invest in cost-reduction technology with the available cash flow. Consistent with Adam et al. (2007) and Kouvelis et al. (2019), we assume that the marginal benefit of investing in cost-reduction technology is higher than the opportunity cost, which implies that the manufacturer will invest all the cash flow in cost-reduction technology. According to Adam et al. (2007), the pursuit of market growth and empire-building tendencies of shareholders and managers could be the motivation for this kind of investment behavior.

We assume the UPC of new products is C, which satisfies

$$C = \begin{cases} c_0 \equiv c(k_0), if \;\; the \;\; manufacturer \;\; hedge, \\ c \equiv c(k), if \;\; the \;\; manufacturer \;\; does \;\; not \;\; hedge, \end{cases}$$

where $c(.)$ is the UPC function of new products. Following Kouvelis et al. (2019), we assume that $c(.)$ is a decreasing function of cash flow investment (i.e., $c^{'}(.) < 0$). If the manufacturer chooses to hedge, the UPC of the new product will be a constant c_0. If the manufacturer does not hedge, the UPC of the new product will be a random variable c. In addition, the UPC of new products (i.e., c) can be either high (i.e., $c = c(k = k_l) = c_h$) when the cash flow k is low (i.e., $k = k_l$), or be low (i.e., $c = c(k = k_h) = c_l$) when the cash flow k is high ($k = k_h$), where $c_h > c_l \geq 0$. After that, c_h is named high-state UPC for convenience. Recall that the cash flow k satisfies $k = k_l$ with probability ρ, and $k = k_h$ with probability $1-\rho$. Correspondingly, we can obtain that the unit cost of a new product satisfies $c = c_h$ with probability ρ, and $c = c_l$ with probability $1-\rho$. Without loss of generality, similar to Huang et al. (2019), we normalize c_l to zero, and a positive c_l would not affect the nature of results in this paper. Assume that the expected value and variance of c are $E(c)$ and θ, it is easy to obtain that $E(c) = \rho c_h + (1-\rho)c_l = \rho c_h$ and $\theta = \rho(1-\rho){c_h}^2$, respectively. In our model, the manufacturer's hedging strategies will affect the cash flow available and then affect the UPC of new products (i.e., c_0 and c), which could finally affect the manufacturer's profit.

In reality, many manufacturers (e.g., Caterpillar, Xerox, Apple, Volkswagen, and Boeing) will engage in remanufacturing at a component level. Specifically, the end-of-use products would be collected from the consumers. Then they are disassembled into components, and the components are remanufactured to achieve the same quality and performance as the component of new products. The remanufactured components would be tested and sold as remanufactured products. It is widely acknowledged that the remanufactured product is a cost-saving alternative to the new product (see. e.g., Savaskan et al., 2004; Geyer et al., 2007; Wu and Zhou, 2017; Reimann et al., 2019). In line with prior studies, we assume that the UPC of new products is C, and normalize the UPC of remanufactured products to 0. Hence, C also implies how cost-saving the remanufacturing is (Zhou et al., 2021). We assume $C \leq 1$ in our model to avoid the trivial case in which the quantity of new products is negative.

3.2. Consumers

In this study, the market size is normalized to 1. Consumers are heterogeneous, and their willingness to pay (WTP) for a new product is v, which is uniformly distributed over the interval $[0,1]$. According to practices and literature on remanufacturing (Xiong et al., 2013; Yenipazarli, 2016; Zhou et al., 2021), a consumer's WTP for a remanufactured product is lower than that for a new product, since consumers often perceive that the remanufactured products have lower quality than new products. Thus, we assume that each consumer's WTP for a remanufactured product is a fraction $\delta \in (0,1)$ of that for a new product, i.e., δv. Define $p_i (i \in \{n, r\})$ as the price of product i, where n stands for new products and r stands for remanufactured products. The net utility of a consumer who purchases a new product and remanufactured product (i.e., U_n, U_r) would be $U_n = v - p_n$, and $U_r = \delta v - p_r$, respectively. In the scenario without remanufacturing, the manufacturer will only sell new products. Each consumer would purchase a new product if $U_n > 0$. Correspondingly, we can obtain that consumers' demand for new products is $q_n = 1 - p_n$, and the inverse demand function would be $p_n = 1 - q_n$. In the scenario with remanufacturing, the manufacturer will sell both new and remanufactured products. Each consumer will purchase a new product if $U_n > 0$ and $U_n > U_r$, and purchase a remanufactured product if $U_r > 0$ and $U_r > U_n$. Thus we can obtain that consumers' demand for new products and remanufactured products are $q_n = 1 - \frac{p_n - p_r}{1-\delta}$, and $q_r = \frac{p_n - p_r}{1-\delta}$. Through simple mathematical algebra, we can obtain the inverse demand functions of new products and remanufactured products, which are

$$p_n = 1 - q_n - \delta q_r, p_r = \delta(1 - q_n - q_r) \tag{1}$$

Remanufacturing is a multi-period problem in that products can be collected and remanufactured only if the new products are end-of-use. We assume that the new products can be used for one period and can be remanufactured in the next period. Thus, the quantity of remanufactured products is naturally restricted by the quantity of new products in the previous period. Following previous studies on remanufacturing (e.g., Wu and Zhou, 2017; Zhou et al., 2021), we consider a steady-state period model in which the manufacturer uses the same production strategy in every period after the first period, which implies that the quantity of new products in the current period is same to that in the previous period. Thus, in a representative period, we have $q_r \leq q_n$.

3.3. Environment

The manufacturing of new products will lead to significant amount of undesirable pollutants, such as carbon dioxide. Remanufacturing, as a substitute for all-new-manufacturing, is recognized as effective way to reduce raw materials use, energy consumption, and finally reduce environmental impacts and move towards a circular economy (Yenipazarli, 2016; Zhou et al., 2021; Xia et al., 2022). In our paper, environmental impacts reflect raw materials and energy consumption of products, and tell the capability of remanufacturing firms in boosting the development of a circular economy. In our models, when there is a lower environmental impact (which means less raw materials and energy consumption of products), remanufacturing is perceived as a more effective circular economy practice. We assume that environmental impacts generated by a new product and a remanufactured product are γ and $\gamma\alpha$, where $\alpha \in (0,1)$ reflects that the remanufactured products consume less raw materials and energy consumption than new products. Here unit environmental impact cut by a remanufactured product is $1-\alpha$, and α depends on the properties (such as types and quality) of collected products. Without loss of generality, consistent with Zhou et al. (2021), we set $\gamma = 1$ in our model for ease of exposition. In fact, the qualitative results of this paper would not be changed if $\gamma \neq 1$. Following Raz et al. (2013) and Mazahir et al. (2019), we assume that the environmental impact is related to both the quantity of products and unit environmental impact of each product. We can now calculate the environmental impact of products of the firm with remanufacturing and without remanufacturing. When the manufacturer does not engage in remanufacturing, the environmental impact (denoted by G) would be $G = q_n$. When the manufacturer engages in remanufacturing, the manufacturer's environmental impact would be $G = q_n + \alpha q_r$. Then, the expected value of the environmental impact would be $E(G)$.

3.4. Timeline of events

The decision sequence is as follows. In the first stage, the manufacturer decides whether to produce remanufactured products. In the second stage, the manufacturer can choose between hedging cash flow or not hedging. In the third stage, when the cash flow is realized, the manufacturer invests cash flow in reducing the UPC of new products and decides the production quantity of new products and remanufactured products.

4. Non-remanufacturing model (benchmark model)

In this part, we assume that the manufacturer does not engage in remanufacturing. We use backward induction to derive the manufacturer's hedging decisions. That is, taking the manufacturer's hedging strategy as given, we first analyse the manufacturer's production quantity decisions (i.e., the quantity of new products). Then, we analyse the manufacturer's hedging strategy by comparing the expected profits in the model without cash hedging (i.e., model *ON*) and that in the model with cash hedging (i.e., model *OH*). Finally, we examine the impacts of cash hedging on the environment by comparing the expected environmental impacts of products in models *OH* and *ON*.

When the manufacturer's hedging strategy is given and the cash flow is realized, the manufacturer decides the optimal new product quantity to maximize the profit. Thus, the manufacturer's optimization problem is

$$\max_{q_n} \pi(C) = p_n q_n - C q_n \tag{2}$$

where $p_n = 1 - q_n$. It is easy to obtain the optimal new product quantity and profit of the manufacturer, which are

$$q_n^* = \frac{1-C}{2}, \pi^* = \frac{(1-C)^2}{4} \tag{3}$$

Recall that $C = c$ in model *ON*, and $C = c_0$ in model *OH*. It is easy to obtain that the expected new product quantity under the model *ON* and model *OH* are $E(q_n^{ON^*}) = (1-\rho c_h)/2$, and $E(q_n^{OH^*}) = (1-c_0)/2$, respectively. The manufacturer will make its hedging decision by comparing the expected profit under the model *OH* and model *ON*, which is

$$E(\pi^{OH^*}) - E(\pi^{ON^*}) = E\left(\frac{(1-c_0)^2}{4}\right) - E\left(\frac{(1-c)^2}{4}\right)$$
$$= \frac{(1-c_0)^2}{4} - \left[\frac{(1-E(c))^2}{4} + \frac{\theta}{4}\right] = \frac{(1-c_0)^2}{4} - \left[\frac{(1-\rho c_h)^2}{4} + \frac{{c_h}^2\rho(1-\rho)}{4}\right] \tag{4}$$

It is optimal for the manufacturer to hedge if hedging could increase its expected profit (i.e., $E(\pi^{OH^*}) - E(\pi^{ON^*}) > 0$), and not to hedge if hedging would decrease its expected profit (i.e., $E(\pi^{OH^*}) - E(\pi^{ON^*}) < 0$). When the manufacturer does not remanufacture, Proposition 1 gives the firm's cash hedging strategy.

PROPOSITION 1. *Provided that the manufacturer is not engaged in remanufacturing, there exists a threshold* $\rho_1 \in (0,1)$ *such that it is optimal for the manufacturer to hedge its cash flow if* $c_h > c_0$ *and* $\rho > \rho_1$*, and not to hedge if 1)* $c_h \le c_0$*, or 2)* $c_h > c_0$ *and* $\rho < \rho_1$*, where* $\rho_1 = \frac{c_0(2-c_0)}{c_h(2-c_h)}$.

Proposition 1 tells that the firm's optimal cash hedging strategy varies in different conditions. Intuitively, when the high-state UPC is low (i.e., $c_h \le c_0$), the manufacturer's cash hedging is not effective in reducing the UPC, and thus cash hedging cannot increase manufacturer's expected profit. Hence, under this circumstance, the manufacturer always abandons the cash hedging strategy.

However, when the high-state UPC is high (i.e., $c_h > c_0$), the manufacturer may embrace cash hedging strategy. Specifically, when there is a high probability of high-state UPC (i.e., $\rho > \rho_1$), the manufacturer chooses cash hedging to effectively reduce the expected UPC, which encourages the manufacturer to produce more new products and finally increases its expected profit. However, when the probability of high-state UPC is low (i.e., $\rho < \rho_1$), the manufacturer's choice of cash hedging cannot effectively reduce the expected UPC and increase its expected profits. Furthermore, when the probability of high-state UPC is moderate (i.e., $\rho = \rho_1$), the manufacturer's choice of cash hedging will not affect the manufacturer's expected profits, which implies that the manufacturer could choose no cash hedging or cash hedging.

When the manufacturer does not engage in remanufacturing, Proposition 2 characterizes the influences of cash hedging on the environment.

PROPOSITION 2. *Provided that the manufacturer does not remanufacture, compared with no cash hedging, there exists a threshold* $\rho_2 \in (0,1)$ *such that cash hedging has the following impacts on the environment:*

(1) *a negative impact (i.e.,* $E(G^{OH^*}) - E(G^{ON^*}) > 0$*) on the environment if* $c_h > c_0$ *and* $\rho > \rho_2$*,*
(2) *a positive impact (i.e.,* $E(G^{OH^*}) - E(G^{ON^*}) < 0$*) on the environment if i)* $c_h \le c_0$*; or ii)* $c_h > c_0$ *and* $\rho < \rho_2$*,*
(3) *no impact (i.e.,* $E(G^{OH^*}) - E(G^{ON^*}) = 0$*) if* $c_h > c_0$ *and* $\rho = \rho_2$*, where* $\rho_2 = c_0/c_h$*.*

It can be seen from Proposition 2 that cash hedging can have differentiated impacts (i.e., negative, positive, and no impacts) on the environment. Specifically, when the high-state UPC is low (i.e., $c_h \le c_0$), the manufacturer's cash hedging is not effective in reducing the UPC of new products, and thus the manufacturer would reduce the expected production quantity of new products. Consequently, the reduction in the expected production quantity of new products would consume less energy and consequently lead to less environmental impacts.

However, when the high-state UPC is high (i.e., $c_h > c_0$), cash hedging can have negative impacts on the environment under a certain condition. Specifically, when there is a high probability of high-state UPC (i.e., $\rho > \rho_2$), the manufacturer can use cash hedging to effectively reduce the expected UPC of new products, which encourages the manufacturer to produce more new products. Ultimately, the increase in new products consumes more energy and causes more environmental impacts. However, when the probability of high-state UPC is low (i.e., $\rho < \rho_2$), the manufacturer's choice of cash hedging cannot effectively reduce the expected UPC of new products, and thus the manufacturer would produce less new products. As a result, the reduction in the production quantity of new products would consume less energy and consequently lead to less environmental impacts. In addition, when the probability of high-state UPC is moderate (i.e., $\rho = \rho_2$), the manufacturer will not change its production decisions, which results in no impacts on the environment.

PROPOSITION 3. Provided that the manufacturer does not remanufacture, compared with no cash hedging, cash hedging can never create a win-win outcome (i.e., increasing manufacturer's expected profit and decreasing environmental impacts of products simultaneously).

When the manufacturer does not remanufacture, Proposition 3 shows the economic goal (i.e., maximizing expected profit) and the environmental goal (i.e., minimizing environmental impacts) cannot be aligned in terms of cash hedging. This result is consistent with traditional wisdom that oftentimes firms' decisions cannot achieve both economic and environmental benefits (Niu et al., 2017; Wang et al., 2017; Dou and Cao, 2020). The reason for Proposition 3 is as follows. When cash hedging can effectively reduce the expected UPC of new products, on the one hand, the manufacturer can produce more products, which would finally increase the manufacturer's expected profit. However, on the other hand, more products will require more raw materials and consume more energy, which will cause more negative environmental impacts.

5. Remanufacturing model

In this section, we assume that the manufacturer engages in remanufacturing. Similar to section 4, we use backward induction to derive the manufacturer's cash hedging decision. That is, given the manufacturer's hedging strategy, we first analyse the manufacturer's production quantity decisions (i.e., the quantity of new products and remanufactured products). Then, we analyse the manufacturer's hedging strategy by comparing the expected profits in the model without cash hedging (i.e., model *TN*) and that in the model with cash hedging (i.e., model *TH*). Finally, we examine the impacts of cash hedging on the environment by comparing the expected environmental impacts of products in the model *TH* and model *TN*.

5.1. Non-cash-hedging model (TN)

Under the model *TN*, the manufacturer chooses not to hedge and the unit cost of new products is c. The manufacturer decides the quantity of new products and remanufactured products to maximize the profit. The manufacturer's optimization problem is

$$\begin{cases} \max\limits_{q_n, q_r} \pi^{TN}(c) = (p_n - c)q_n - p_r q_n, \\ \text{s.t.} \;\; q_r \geq 0, q_r \leq q_n, \end{cases} \tag{5}$$

where $p_n = 1 - q_n - \delta q_r$, and $p_r = \delta(1 - q_n - q_r)$. Solving equation (5), we can obtain the optimal quantity of new products and remanufactured products, and the profit of the manufacturer, which are (1) when $0 \leq c \leq \frac{1-\delta}{2}$, $q_n^{TN*} = \frac{1-\delta-c}{2(1-\delta)}$, $q_r^{TN*} = \frac{c}{2(1-\delta)}$, and $\pi^{TN*} = \frac{(1-\delta)-2(1-\delta)c+c^2}{4(1-\delta)}$; (2) when $\frac{1-\delta}{2} < c \leq 1$, $q_r^{TN*} = q_n^{TN*} = \frac{1+\delta-c}{2(1+3\delta)}$, and $\pi^{TN*} = \frac{(1+\delta-c)^2}{4(1+3\delta)}$.

LEMMA 1. *Under the model TN, the expected quantity of new products and remanufactured products, and the expected profit of the manufacturer are*

(1) *when* $0 \leq c_h \leq \frac{1-\delta}{2}, E(q_n^{TN*}) = \frac{\rho(1-\delta-c_h)}{2(1-\delta)} + \frac{(1-\rho)}{2}$, *and* $E(q_r^{TN*}) = \frac{\rho c_h}{2(1-\delta)}$, $E(\pi^{TN*}) = \frac{\rho(\delta(1-2c_h)-(1-c_h)^2)}{4(1-\delta)} + \frac{(1-\rho)}{4}$;

(2) *when* $\frac{1-\delta}{2} < c_h \leq 1$, $E(q_n^{TN*}) = \frac{\rho(1+\delta-c_h)}{2(1+3\delta)} + \frac{1-\rho}{2}$, $E(q_r^{TN*}) = \frac{\rho(1+\delta-c_h)}{2(1+3\delta)}$, *and* $E(\pi^{TN*}) = \frac{\rho(1+\delta-c_h)^2}{4(1+3\delta)} + \frac{(1-\rho)}{4}$.

Lemma 1 characterizes the manufacturer's optimal expected quantity of new and remanufactured products and expected profit in model *TN*. Lemma 1 indicates that the manufacturer has two optimal production strategies, which depend on the value of the high-state UPC (i.e., c_h). It can be easily inferred from Lemma 1 that when the high-state UPC is low (i.e., $0 \leq c_h \leq \frac{1-\delta}{2}$), the expected quantity of new products would decrease in c_h, but the expected quantity of remanufactured products would increase in c_h. The reason is that as c_h increases, the expected cost of new products would increase, which motivates the remanufacturing firm to produce less new products and more remanufactured products. However, when the high-state UPC is large (i.e., $\frac{1-\delta}{2} < c_h \leq 1$), an increase in c_h would decrease both the expected quantity of new products and remanufactured products. The reason is that although the remanufacturing firm is motivated to increase the quantity of remanufactured products, the remanufactured products would be bound to the quantity of new products. Consequently, both the expected quantity of new products and remanufactured products would decrease in c_h. Moreover, Lemma 1 also tells that the expected profit of manufacturer would always decrease in c_h in two cases (i.e., when the high-state UPC is low or high). The reason is that the decrease in c_h would increase the expected UPC for the manufacturer, which ultimately leads to the loss of expected profit.

The main conclusion of Lemma 1 is shown in Fig. 1 by setting $\delta = 0.5$, $\rho = 0.5$. It can be seen from Fig. 1 that when c_h is small, as the UPC increases, intuitively, the manufacturer reduces the quantity of the new product, but increases the quantity of the remanufactured product. Interestingly, when c_h is large, the manufacturer reduces the quantity of both new and remanufactured products. In addition, Fig. 1 also indicates that the manufacturer's expected profit is decreasing in c_h, which demonstrates the necessity of reducing c_h.

5.2. Cash-hedging model (TH)

Under the model *TH*, the manufacturer chooses to hedge and the unit cost of new products is c_0. The manufacturer decides the quantity of new products and remanufactured products to maximize the profit. The manufacturer's optimization problem is

$$\begin{cases} \max\limits_{q_n, q_r} \pi^{TH}(c_0) = (p_n - c_0)q_n - p_r q_n, \\ \text{s.t.} \;\; q_r \geq 0, q_r \leq q_n, \end{cases} \tag{6}$$

where $p_n = 1 - q_n - \delta q_r$, and $p_r = \delta(1 - q_n - q_r)$. The optimal quantity and profit of the manufacturer are as follows:

(1) when $0 \leq c_0 \leq \frac{1-\delta}{2}$, $q_n^{TH*} = \frac{1-\delta-c_0}{2(1-\delta)}$, $q_r^{TH*} = \frac{c_0}{2(1-\delta)}$, and $\pi^{TH*} = \frac{(1-\delta)-2(1-\delta)c_0+{c_0}^2}{4(1-\delta)}$;

(2) when $\frac{1-\delta}{2} < c_0 \leq 1$, $q_r^{TH*} = q_n^{TH*} = \frac{1+\delta-c_0}{2(1+3\delta)}$, and $\pi^{TH*} = \frac{(1+\delta-c_0)^2}{4(1+3\delta)}$.

Since cash hedging eliminates the uncertainty about the UPC, the optimal quantities of the new and remanufactured products and the optimal profit of the manufacturer are independent of the random variable.

It is optimal for the remanufacturing firm to hedge if hedging could increase its expected profit (i.e., $E(\pi^{TH*}) - E(\pi^{TN*}) > 0$), and not to hedge if hedging would decrease its expected profit (i.e., $E(\pi^{TH*}) - E(\pi^{TN*}) < 0$). Proposition 4 gives the cash hedging strategy when the manufacturer engages in remanufacturing.

PROPOSITION 4. *Provided that the manufacturer engages in remanufacturing, there exists a threshold* $\rho_3 \in (0, 1)$, *such that it is optimal for the manufacturer to hedge its cash flow only if* $c_h > c_0$ *and* $\rho > \rho_3$, *where*

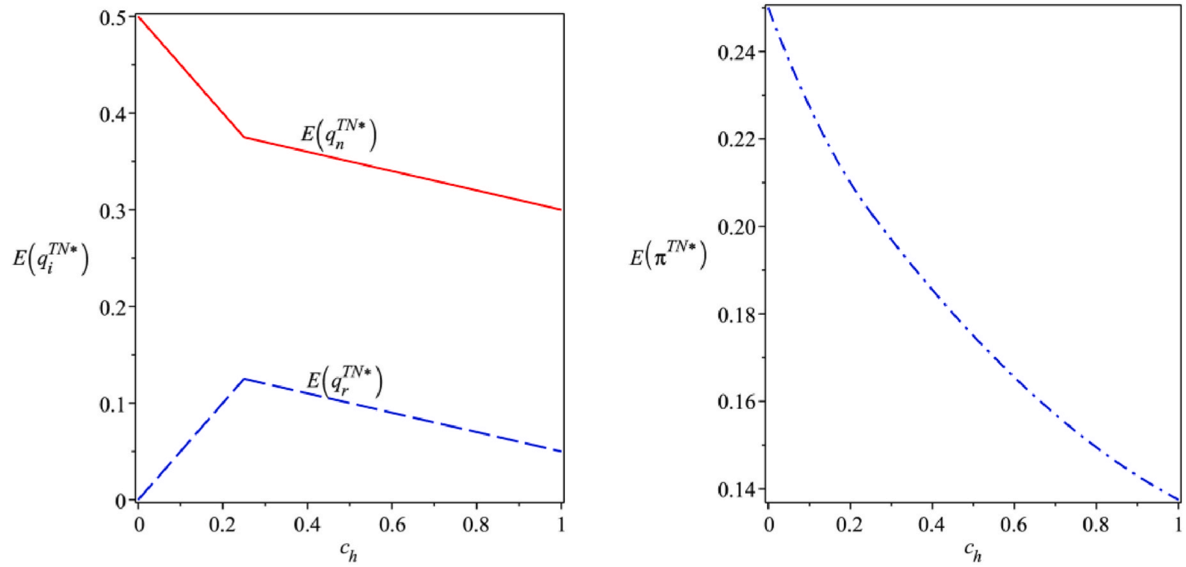

Fig. 1. The effects of c_h on the optimal expected quantities and profit.

$$\rho_3 = \begin{cases} \dfrac{c_0(2+2\delta-c_0)}{c_h(2+2\delta-c_h)}, \mathit{if}\ \ 0 \le c_0 < c_h \le \dfrac{1-\delta}{2}, \\ \dfrac{c_0(1+3\delta)(2+2\delta-c_0)}{(1-\delta)(\delta-\delta^2+c_h(2+2\delta)-{c_h}^2)}, \mathit{if}\ \ 0 \le c_0 \le \dfrac{1-\delta}{2} < c_h \le 1, \\ \dfrac{(\delta-\delta^2+c_0(2+2\delta)-{c_0}^2)}{(\delta-\delta^2+c_h(2+2\delta)-{c_h}^2)}, \mathit{if}\ \ \dfrac{1-\delta}{2} < c_0 < c_h \le 1. \end{cases}$$

Proposition 4 still states that the manufacturer takes cash hedging only and only if the high-state UPC is high (i.e., $c_h > c_0$) and the probability of occurrence is high (i.e., $\rho > \rho_3$). In these two conditions ($c_h > c_0, \rho > \rho_3$), cash hedging can significantly reduce the expected UPC and finally increase the manufacturer's profit.

However, in other cases, the manufacturer should not adopt cash hedging since it cannot increase the remanufacturing firm's profit. Specifically, when the high-state UPC is small (i.e., $c_h \le c_0$), intuitively, the cash hedging adopted by the manufacturer cannot effectively reduce the UPC, which will lead to profit loss for the manufacturer if cash hedging is adopted. When the high-state UPC is large (i.e., $c_h > c_0$), although the manufacturer adopts cash hedging strategy to reduce the high-state UPC, it cannot effectively reduce the expected UPC (i.e., ρc_h) when the probability of high-state UPC is low (i.e., $\rho < \rho_3$). Thus, the manufacturer will not choose cash hedging strategy in this case.

Proposition 5 characterizes the influences of cash hedging on the environment when the manufacturer engages in remanufacturing, which provides insights into how cash hedging can promote the remanufacturing firms to conduct a more effective circular economy practice.

PROPOSITION 5. *Provided that the manufacturer remanufactures, compared with no cash hedging, there exists a threshold* $\rho_4 \in (0,1)$ *such that cash hedging has the following impacts on the environment:*

(1) *a negative impact (i.e.,* $E(G^{TH^*}) - E(G^{TN^*}) > 0$*) on the environment if* $c_h > c_0$ *and* $\rho > \rho_4$*,*
(2) *a positive impact (i.e.,* $E(G^{TH^*}) - E(G^{TN^*}) < 0$*) on the environment if i)* $c_h \le c_0$*; or ii)* $c_h > c_0$ *and* $\rho < \rho_4$*,*
(3) *no impact (i.e.,* $E(G^{TH^*}) - E(G^{TN^*}) = 0$*) on the environment if* $c_h > c_0$ *and* $\rho = \rho_4$*, where*

$$\rho_4 = \begin{cases} c_0/c_h, \mathit{if}\ \ 0 \le c_0 < c_h \le \dfrac{1-\delta}{2}, \\ \dfrac{c_0(1+3\delta)(1-\alpha)}{(1-\delta)(2\delta+c_h-\alpha(1+\delta-c_h))}, \mathit{if}\ \ 0 \le c_0 \le \dfrac{1-\delta}{2} < c_h \le 1, \\ \dfrac{(2\delta+c_0-\alpha(1+\delta-c_0))}{(2\delta+c_h-\alpha(1+\delta-c_h))}, \mathit{if}\ \ \dfrac{1-\delta}{2} < c_0 < c_h \le 1. \end{cases}$$

Similar to Proposition 2, cash hedging can have differentiated impacts (i.e., negative, positive, and no impacts) on the environment. Specifically, when the high-state UPC is low (i.e., $c_h \le c_0$), the manufacturer's cash hedging is not effective in reducing the UPC of new products. Thus, the manufacturer would reduce the expected production quantity of new products, and increase the expected production quantity of remanufactured products. Although the increase of remanufactured products would consume more energy and result in more environmental impacts, the reduction in the expected production quantity of new products would consume less energy and lead to less environmental impacts. Consequently, the total environmental impacts are reduced owing to the reduction of the environmental impacts of new products.

However, when the high-state UPC is high (i.e., $c_h > c_0$), cash hedging would have negative impacts on the environment under a certain condition. Specifically, when there is a high probability of high-state UPC (i.e., $\rho > \rho_4$), cash hedging can effectively reduce the expected UPC of new products, which encourages the manufacturer to produce more new products and less remanufactured products. Although the reduction of remanufactured products would consume less energy and result in less environmental impacts, the increase in the expected production quantity of new products would consume more energy and result in more environmental impacts. Consequently, the environmental impacts will increase due to the increase in the environmental impacts of new products. Nevertheless, when the probability of high-state UPC is low (i.e., $\rho < \rho_4$), cash hedging cannot effectively reduce the expected UPC of new products, and thus the manufacturer would produce less new products and more remanufactured products. The reduction in the production quantity of new products would consume less energy and consequently lead to less environmental impacts. In addition, when the probability of high-state UPC is moderate (i.e., $\rho = \rho_4$), the manufacturer's choice of cash hedging will not affect the expected UPC, and thus the manufacturer will not change its production decisions, which leads to no impacts on the environment.

PROPOSITION 6. *Provided that the manufacturer remanufactures,* *compared with no cash hedging, cash hedging can create a win-win outcome (i.e., increasing the manufacturer's profit and decreasing environmental impacts of products simultaneously) if* $c_h > c_0$ *and* $\rho_3 < \rho < \rho_4$.

Although Proposition 3 tells that without remanufacturing, cash hedging cannot be advantageous for both the expected profit and the environment simultaneously, Proposition 6 argues that a win-win outcome can be achieved under certain conditions. Specifically, when high-state UPC is low (i.e., $c_h \le c_0$), cash hedging is detrimental to the expected profit but beneficial to the environment, and thus a win-win outcome cannot be achieved under this condition. The reason is that in this case, cash hedging cannot effectively reduce the UPC of new products (see Proposition 4), and ultimately leads to profit loss. Moreover, fewer new products would be produced under this condition (see Proposition 5), which would be beneficial to the environment.

When high-state UPC is high (i.e., $c_h > c_0$), there are three cases. Specifically, in the case with a low probability of high-state UPC (i.e., $\rho < \rho_3$), cash hedging is detrimental to the expected profit but beneficial to the environment. On the one hand, cash hedging cannot effectively reduce the expected UPC of new products (i.e., ρc_h) and would be detrimental to the expected profit. On the other hand, in this case, the manufacturer would produce more new products, which would be detrimental to the environment. In the case with a high probability (i.e., $\rho > \rho_4$), cash hedging is beneficial to the expected profit but detrimental to the environment, and the reason is as follows. Firstly, cash hedging can significantly reduce the expected UPC of new products and finally increase the manufacturer's profit (see Proposition 4). Secondly, the increase in the expected production quantity of new products would lead to more environmental impacts (see Proposition 5). Summarizing the above two cases, we can obtain that a win-win outcome cannot be achieved when $\rho < \rho_3$ or $\rho > \rho_4$.

However, in the case with a moderate probability (i.e., $\rho_3 < \rho < \rho_4$), a win-win outcome can be achieved, that is, cash hedging is beneficial to both the expected profit and the environment. The reason for this outcome is as follows. On the one hand, cash hedging can significantly reduce the expected UPC of new products and finally increase the manufacturer's expected profit. On the other hand, compared with the quantity without cash hedging, the production quantity of new products with cash hedging would be lower, and the quantity of the remanufactured products would be higher. Although the increased quantity of remanufactured products will lead to more environmental impacts, the decreased quantity of new products will result in less environmental impacts. Since the total environmental impact is more sensitive to the change in the quantity of new products than remanufactured products, the overall environmental impact would be reduced owing to the decreased quantity of new products.

6. Empirical evidence from Chinese remanufacturing firms

In the previous section, we have developed theoretical models to discuss the impacts of cash hedging on a remanufacturing firm's profit, which is characterized in Proposition 4. In this section, taking some representative Chinese remanufacturing firms as samples, we conduct an empirical analysis to have a better understanding of the theoretical results in the previous section. Specifically, a regression analysis is conducted to investigate the impacts of cash hedging on remanufacturing firms' profits.

Our study tests the impact of cash hedging on remanufacturing firms' performance based on the pilot remanufacturing firm catalogue conducted by the Ministry of Industry and Information Technology (MIIT) of China (MIIT, 2009; MIIT, 2016; MIIT, 2020). To guarantee the data quality, we screen the 89 firms to select those that are publicly listed on stock markets. This is to ensure that all the firms in our sample follow the same and consistent information reporting and disclosure standards. Also, many prior studies on manufacturing enterprises' cash hedging adopt data from publicly listed manufacturing firms (Gamba and Triantis, 2014; Treanor et al., 2014; Sun et al., 2017). Finally, we drop 79 firms and keep 10 firms that are publicly listed on the stock market while belonging to the pilot remanufacturing catalogue issued by MIIT. By obtaining these 10 firms' annual reports, we record three major accounting statements – the balance sheet, cash flow statement and income statement, covering useful variables such as cash hedging and revenue for the period of 2010–2019. This study has in total 100 observations, which is similar to some previous research adopting GMM based on a relatively small sample size, such as Elhorst (2010). Within the 100 observations, 14 are missed and created by using the linear interpolation method. Those missing observations are mainly because some firms in the sample did not record hedging investments in the early years.

6.1. *The measure*

The dependent variable is the profitability ratio of the remanufacturing firm, as calculated by the natural log of net income (total revenue - total operating expenses) divided by total revenue. Profitability ratios are a class of financial metrics that are used to assess a business's ability to generate earnings relative to its revenue, operating costs, balance sheet assets, or shareholders' equity over time, using data from a specific point in time (Ningsih and Sari, 2019; Xu et al., 2022). In short, a profitability ratio indicates how efficiently a company generates profit and value for shareholders. The data on the dependent variable is obtained from the annual audited financial statements.

The explanatory variable is cash hedging, measured by the natural log of the investment amount of financial derivatives by remanufacturing firms (He and Wong, 2004). For a cash hedging of a forecast transaction, the forecast transaction shall be likely to occur and shall make the enterprise face the risk of changes in cash flow, which will ultimately affect the profits and losses (Adam et al., 2007). With the help of cash hedging, remanufacturing firms can obtain stable cash flow to invest in cost-reduction technologies (Kouvelis et al., 2019). This study follows the procedure employed by He and Wong (2004) to derive cash hedging data from the annual report of listed remanufacturing firms.

This study adopts four control variables. The first two control variables are firm size and age, as they might influence regression results. Some literature suggests that smaller and younger firms tend to conduct more cash hedging than larger firms (Stock et al., 2002). Firm size is measured by the logarithmic transformation of each firm's total employees (Cui and Jiang, 2012). Firm age is measured by the number of years since the establishment of the parent company (Eisenberg et al., 1998). The third control variable is the capital stock of remanufacturing firm as it is associated with revenue and cash hedging (Wang et al., 2012). Finally, our research measures remanufacturing firm input as the work-in-process production inventory (value), the higher the degree of work-in-process production inventory, the more likely the firm will conduct cash hedging to reduce cost, because of its increased dependence on recycled parts (Helpman et al., 2004). The data of four control variables is obtained from the annual report of listed remanufacturing firms. The key variables including dependent variable, explanatory variable, and control variables, are summarized in Table 1.

6.2. *Model specification*

This study considers the system-GMM dynamic panel data econometric model to investigate the relationship between cash hedging and remanufacturing firm performance. Arellano and Bond (1991) and Blundell and Bond (2000) argued that the dynamic panel data econometric model can handle unobservable individual effects and time effects of different cross-sections, facilitating the description and analysis of dynamic adjustment processes, and deal with error components. The general dynamic panel model is:

Table 1
Description of key variables.

Variable name	Acronym	Operationalization
Profitability ratio	$Pro_{i,t}$	Natural log of net income (total revenue - total operating expenses) divided by total revenue of remanufacturing firm i in year t.
Cash hedging	$Inv_{i,t}$	Natural log of the investment amount of financial derivatives by remanufacturing firms i in year t.
Employee	$Emp_{i,t}$	Natural log of the employee of remanufacturing firm i in year t.
Capital stock	$Cap_{i,t}$	Natural log of the capital stock of remanufacturing firm i in year t
Work-in-process production inventory	$Wip_{i,t}$	Natural log of work-in-process production inventory value of remanufacturing firm i in year t.
Firm age	$Age_{i,t}$	Natural log of firm age of remanufacturing firm i in year t.

$$y_{i,t} = \gamma_o + \sum_{j=1}^{n} \varphi_{t,j} y_{i,t-j} + \sum_{k=1}^{n} \delta_{t,k} x_{i,t-k} + \gamma_{i,t} + u_{i,t} \quad (i = 1, 2, \cdots, N, t = 1, 2, \cdots, T), \tag{7}$$

where i refers to remanufacturing firm, j, k refers to the lag, γ_0 refers to constant, γ_i refers to individual effects, and $u_{i,t}$ refers to residuals. This basic model gives a way of avoiding endogenous problems. Here, this study augments the basic model as follows to include our variables.

$$\begin{aligned} logPro_{i,t} = \alpha_0 + \alpha_1 logPro_{i,t-1} + \alpha_2 logInv_{i,t-1} + \beta_1 logEmp_{i,t} + \beta_2 logCap_{i,t} \\ + \beta_3 \log Wip_{i,t} + \beta_4 logAge_{i,t} + \varepsilon_{i,t}. \end{aligned} \tag{8}$$

By construction, all variables are in logarithm. In our model, t denotes year. We set $Pr\, o_{i,t}$ and $Inv_{i,t}$ to be in $t - 1$ year. This is based on the rationale that benefits from cash hedging may take time to be reflected in remanufacturing firms and that performance accumulation also requires a lengthy process. Our dynamic equation uses up to thrice lagged instruments in the model.

6.3. Estimation method

In this study, reverse causation may well generate estimation problems (Arellano and Bond, 1991; Blundell and Bond, 2000) when studying remanufacturing firms' profitability ratios. For instance, cash hedging may lead to better remanufacturing firm profitability ratios, but remanufacturing firms with higher profitability ratios are also likely to be more involved in cash hedging. It means that the explanatory variables may have an impact on remanufacturing firm profitability ratios, but in the meantime, remanufacturing firm profitability ratios may also have an impact on some of the explanatory variables. These endogeneity issues may arise through investment effects, or the self-selection of better-performing firms. Ordinary Least Square (OLS) and within estimators will tend to overestimate the effects of the explanatory variables and are also unable to address the simultaneity and endogeneity issues (Li et al., 2016; Wang et al., 2020). Thus, our study employs the generalized method of moments (GMM).

In general, there are two typical ways of GMM estimation: difference-GMM and system-GMM (Roodman, 2009). Blundell and Bond (2000) suggest that the difference-GMM estimation method is easily affected by weak instrumental variables. They also describe if the original equation in levels is added to the system, how additional instruments can be brought to bear to increase efficiency (Blundell and Bond, 2000). In other words, the system-GMM estimator is a system that contains both the levels and the first difference equations. It provides an alternative to the standard first difference GMM estimator. Therefore, the system GMM is regarded as an appropriate method for dealing with unobserved heterogeneity, endogeneity, and also situations where the explanatory variables are not strictly exogenous (Liu et al., 2014; Wang et al., 2020). To solve the potential endogeneity problem in the model, we estimate the equation using the system GMM approach developed by Blundell and Bond (2000).

In this study, we use the system-GMM estimator. Previous literature suggests that the *Sargan* test is more appropriate for the difference-GMM estimator and under the assumption of homoskedasticity and no serial correlation (in levels) of the idiosyncratic error term, while the system-GMM estimator should consult the Hansen test (Roodman, 2020). Therefore, the Hansen statistic of overidentifying restrictions was used to test the validity of the instruments. The Arellano–Bond (AR) test is also employed to detect the existence of the first or second-order serial correlation.

6.4. Estimation results

The regression results are reported in Table 2. Models 1 and 2 pass the specification tests, as they both reject the null hypothesis of AR (1), showing that the dynamic model is correct. Furthermore, the result of our specification tests does not reject the null hypothesis of the AR (2) and *Hansen* tests. In summary, the specification tests show that no further autocorrelation is present in the model and the *Hansen* test confirms the validity of the instruments used in each model.

In model (2), the lagged value of the dependent variable $Pro_{i,t}$ is significant as expected, and so is the variable of cash hedging. This result suggests that the profit of remanufacturing firm is a gradual and accumulated process. In this sense, during the formulation of business principles and strategies, the remanufacturing firm should consider the dynamic development process of the performance, as well as the long-term sustainable development of remanufacturing business.

Furthermore, cash hedging is highly significant in model (2). In particular, cash hedging ($Inv_{i,t}$) has the strongest effect, where the estimated coefficient is 0.224. Therefore, it is reasonable to argue that cash hedging provides a major force for remanufacturing firms' profits and promotes productivity development in remanufacturing firms. Meanwhile, as a new tool of financial management, cash hedging can improve the overall efficiency of the financial system, hedge risk, and guard against even overcoming the financial crisis. This has subsequently promoted the transformation of productive forces and the enhancement of remanufacturing firm performance. In this case, the result of our empirical test supports Proposition 4, which argues that cash hedging increases the remanufacturing firm's profit.

7. Discussion and conclusions

In this study, we adopt a mixed research method (i.e., developing

Table 2
GMM regression results.

	(1)	(2)
Pro	0.460**	0.507***
	(1.12)	(1.33)
Emp	0.091	0.683
	(0.98)	(1.29)
Cap	0.163	1.175***
	(0.89)	(0.80)
Wip	1.023	1.104
	(0.78)	(0.92)
Age	0.102	0.075
	(0.61)	(0.23)
Inv		0.224**
		(2.35)
AR(1)	0.041	0.026
AR(2)	0.107	0.280
Hansen test	0.022	0.039
Observations	100	100

p-values in parentheses: *$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

nonlinear programming models, conducting empirical regression analysis) to analyse the impacts of cash hedging on remanufacturing firms with cost-reduction technology innovation investment from the perspective of profits and environment, which can be helpful in realizing both economic and environmental benefits in a circular economy.

The results show that the impact of cash hedging on firms' profits varies in different conditions, depending on two factors, i.e., the high-state UPC of new products and the probability of high-state UPC. Although the existing literature generally believes that cash hedging has a single effect (i.e., positive, negative, or no impact) on corporate economic performance (e.g., Mackay and Moeller, 2007; Ben 2010; Bartram et al., 2011; Disatnik et al., 2014), our study suggests that cash hedging has varied impacts. Specifically, when the high-state UPC of new products is high, and the probability of high-state UPC is high, cash hedging can lead to higher profit. When the high-state UPC of new products is high, and the probability of high-state UPC is moderate, the cash hedging has no impact on a firm's profit. Otherwise, the cash hedging strategy can decrease a firm's profit.

The results also reveal that cash hedging can have positive impacts on the environment and thus boost the development of a circular economy. Intuitively, cash hedging may lead to cost reduction of new products and encourage firms to produce more products, which leads to more negative environmental impacts. This intuition is true under some conditions (such as when the high-state UPC of new products is high, and the probability of high-state UPC is high). However, in other cases (such as when the high-state UPC of new products is high, and the probability of high-state UPC is low), cash hedging can decrease environmental impacts, which means that cash hedging can make remanufacturing become a more effective circular economy practice in these cases.

Our results also tell that cash hedging can increase the profit of a firm and reduce the negative environmental impact under certain conditions. Traditionally, it is believed that a firm's strategy may not promote economic performance (such as maximizing profits) and environmental performance (such as minimizing environmental impacts) simultaneously. It is true for the firm that has not engaged in remanufacturing, but not the case for the firm involved in remanufacturing. Specifically, for a non-remanufacturing firm, our results show that cash hedging cannot increase the manufacturer's expected profit and decrease the negative environmental impact of products simultaneously. For a remanufacturing firm, the cash flow can create a win-win outcome (the profit attainment and environment protection) when certain conditions are satisfied (i.e., when the high-state UPC of new products is high, and the probability of high-state UPC is moderate). Under these conditions, cash hedging can decrease the quantity of new products and increase the quantity of environmentally friendly remanufactured products, which eventually contribute to a win-win outcome for the profit and the environment.

7.1. Theoretical contributions

This study contributes to the theoretical literature mainly in the following four ways. Firstly, this paper identifies the economic impact of cash hedging through the lenses of remanufacturing firms, compensating the previous literature on corporate risk management primarily from the perspective of non-remanufacturing firms. Considering the considerable differences in products and supply chain structures between non-remanufacturing firms and remanufacturing firms, the theoretical research results of non-remanufacturing companies may not apply to remanufacturing companies. For the above consideration, our research enriches the existing literature on cash hedging's economic impact by considering the remanufacturing firms in a circular economy, which provides a theoretical basis for remanufacturing companies to choose cash hedging strategies. Moreover, through investigating remanufacturing firms, our research echoes with the study of Treanor et al. (2014), Berghöfer and Lucey (2014), and Krause and Tse (2016), who pointed out that more industry and product differences, need to be considered when examining the impacts of cash hedging.

Secondly, this study is one of the first to investigate how remanufacturing companies with cost-reduction technology investment use cash hedging strategies to reduce cash flow volatility risk and ultimately reduce cost volatility risk. Existing studies have shown the urgency of cost volatility management in assuring remanufacturing firms' economic performance and the potential role of financial risk management tools (such as cash hedging) in reducing cost volatility (see Adam et al., 2007; Kouvelis et al., 2019; Huang et al., 2019). Studies (Wei and Tang, 2014; Sun et al., 2017) have begun to model the financial risk management tool in the remanufacturing literature, but there is limited literature on investigating using cash hedging strategies to manage cost volatility risk. To the best knowledge of us, Sun et al. (2017) is the only study that considers using financial cash hedging to mitigate the demand volatility risk, while our paper discusses reducing cost fluctuation through managing cash flow risk volatility. Thus, our paper adds to the remanufacturing literature by considering the use of cash hedging to reduce cost volatility risk in remanufacturing activities.

Thirdly, this paper contributes to the existing literature by revealing the influence mechanism of cash hedging on the environment, which opens up the black box of current theories about the impact of cash hedging on the environment. Owing to the government's tighter environmental protection laws and policies (such as carbon tax policy, and carbon limit policy)(Ling et al., 2021; Nie et al., 2020), and consumers' increased environmental awareness, the environmental impacts of enterprise strategy including cash hedging strategy are critical to business running and profitability. Existing literature (such as Sun et al., 2017) has revealed the potential relationship between cash hedging and environmental impacts. Nevertheless, specific impact (i.e., positive, negative and no impact) and the influence mechanism are still unclear now. Our paper contributes to the literature by identifying the specific influence of cash hedging and uncovering the influence mechanism of cash hedging. Specifically, we identify the interaction patterns among the main transmission factors (i.e., the UPC and the quantity of new and remanufactured products).

Fourthly, our study complements the existing studies that argue that firms' decisions are difficult to achieve both economic and environmental benefits (Niu et al., 2017; Wang et al., 2017; Dou and Cao, 2020). Existing research shows that it is vital for remanufacturing companies to achieve both economic performance and environmental performance (Yenipazarli et al., 2016; Sarkar et al., 2017; Dou and Cao, 2020). Unfortunately, most studies argue that remanufacturing companies' strategic choices cannot achieve a win-win outcome between economic performance and environmental performance. However, this paper points out that remanufacturing enterprises' cash hedging strategy can make a win-win outcome for financial performance and environmental performance under certain conditions, which provides a new insight into existing literature from the perspective of the cash hedging strategy.

7.2. Practical implications

This study helps the remanufacturing firm, and the stakeholders who are concerned with environmental benefits (such as the government) to understand how to make decisions on cash hedging to maximize their profits and minimize the negative environmental impacts. For the remanufacturing firm, our results provide informative implications for hedging decisions. For instance, remanufacturing firms can make the optimal cash hedging decisions, depending on the high-state UPC of new products and the probability of high-state UPC. Moreover, our results also present the condition that remanufacturing firms can use cash hedging to increase their profits and decrease the environmental impacts of products simultaneously. For governments who care about the environmental benefits and promoting the development of circular economy, our results are also informative in answering when and how governments should intervene. Specifically, based on our findings, for the profit-maximizing oriented firm without remanufacturing, its optimal cash hedging strategy will cause more environmental impacts. Thus, for the non-remanufacturing firm who uses cash hedging, an environmental tax can be levied by the government. However, for a profit-maximizing oriented remanufacturing firm, its optimal cash hedging strategy can have a positive impact on the environment when some conditions are met. Thus, governments should not intervene when cash hedging can achieve a win-win outcome for the profit and the environment. Furthermore, in the case that cash hedging can increase the profit while bring about environmental issues, governments can impose an environmental tax on the remanufacturing firm who chooses cash hedging.

7.3. Limitations for future research

As with all studies, our work has two main limitations, which provide opportunities for future research. First, this study's sample size is relatively limited because of two reasons: 1) the data comes only from China's remanufacturing firms in the catalogue issued by MIIT; 2) to ensure the reliability and availability of data, we drop unlisted remanufacturing firms. Although some previous research has used GMM depending on a relatively small sample (e.g., Elhorst 2010), quantitative studies with limited sample size may not fully uncover the impacts of cash hedging on remanufacturing firm, to some extent. Therefore, future research with large sample size is strongly encouraged. Also, future studies might wish to examine remanufacturing firms in other emerging economies. Second, we do not identify the risk preference of China's remanufacturing firms. For future research, it would be interesting to find out how risk preference affects China's remanufacturing firms' cash hedging activities.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix

Proof of Lemma 1. Under the model ***TN***, the Lagrangean function and the KKT optimality conditions of the manufacturer are

$$L^{TN}=(p_n-c)q_n-p_rq_n-\lambda_1(-q_{r1})-\lambda_2(q_r-q_n), \tag{A1}$$

$$\partial L^{TN}/\partial q_r=0, \tag{A2}$$

$$\partial L^{TN}/\partial q_n=0, \tag{A3}$$

$$\lambda_1 q_r=0, \tag{A4}$$

$$\lambda_2(q_r-q_n)=0 \tag{A5}$$

Scenario (a). $\lambda_1=0$, and $\lambda_2=0$. Substituting $\lambda_1=0$, and $\lambda_2=0$ into (A2) and (A3), and solving q_r, q_n simultaneously, we have $q_r=\frac{c}{2(1-\delta)}$, $q_n=\frac{1-\delta-c}{2(1-\delta)}$.

In this scenario, $q_r \geq 0$ and $q_r \leq q_n$ require $0 \leq c \leq \frac{1-\delta}{2}$.

Scenario (b). $\lambda_1>0$, and $\lambda_2=0$. From (A4), we obtain $q_r=0$. Substituting $\lambda_2=0$ and $q_r=0$ into (A2) and (A3), and solving λ_1, q_n simultaneously, we have $\lambda_1=-\delta c$, $q_n=\frac{1-c}{2}$.

Obviously, $\lambda_1<0$. Thus we discard scenario (b).

Scenario (c). $\lambda_1=0$, and $\lambda_2>0$. From (A5), we obtain $q_r=q_n$. Substituting $\lambda_1=0$, and $q_r=q_n$ into (A2) and (A3), and solving λ_2, q_n simultaneously, we have $\lambda_2=\frac{\delta(2c+\delta-1)}{1+3\delta}$, $q_n=\frac{1+\delta-c}{2(1+3\delta)}$.

Correspondingly, we can obtain $q_r=q_n=\frac{1+\delta-c}{2(1+3\delta)}$. Here, $\lambda_2>0$ and $q_r \geq 0$, require $\frac{1-\delta}{2}<c \leq 1+\delta$. Since $c \leq 1$ in our model, we have $\frac{1-\delta}{2}<c \leq 1$ in scenario (c).

Scenario (d). $\lambda_1>0$, and $\lambda_2>0$. From (A4) and From (A5), we have $q_r=q_n=0$. Substituting $q_r=0$, and $q_n=0$ into (A2) and (A3), and solving λ_1, λ_2 simultaneously, we have $\lambda_1=c-1-\delta$, $\lambda_2=c-1$.

Obviously, $\lambda_1<0$, and $\lambda_2<0$, thus we discard scenario (d).

Summarizing above four scenarios, we can obtain the optimal quantity of the manufacturer under the model *TN*, which are

(1) decision 1: $q_n^{TN*}=\frac{1-\delta-c}{2(1-\delta)}$, $q_r^{TN*}=\frac{c}{2(1-\delta)}$, if $0 \leq c \leq \frac{1-\delta}{2}$;
(2) decision 2: $q_r^{TN*}=q_n^{TN*}=\frac{1+\delta-c}{2(1+3\delta)}$, if $\frac{1-\delta}{2}<c \leq 1$.

Correspondingly, we can obtain the optimal profit of the manufacturer under the model *TN*, which is

$$\pi^{TN*} = \begin{cases} \dfrac{(1-\delta) - 2(1-\delta)c + c^2}{4(1-\delta)}, if \;\; 0 \le c \le \dfrac{1-\delta}{2}, \\ \dfrac{(1+\delta-c)^2}{4(1+3\delta)}, if \;\; \dfrac{1-\delta}{2} < c \le 1. \end{cases}$$

Now we calculate the optimal expected number and expected profit of the manufacturer. Recall that the unit cost of new product satisfies $c = c_h$ with probability ρ, and $c = 0$ with probability $1-\rho$. Here we need to dicuss two cases.

Case 1. when $0 \le c_h \le \frac{1-\delta}{2}$, the manufacturer would choose decision 1 if $c = 0$ or $c = c_h$. Thus, the optimal expected quantities and expected profit of the manufacturer under in Case 1 are

$$\begin{cases} E\left(q_n^{TN*}\right) = \dfrac{\rho(1-\delta-c_h)}{2(1-\delta)} + \dfrac{(1-\rho)}{2}, E\left(q_r^{TN*}\right) = \dfrac{\rho c_h}{2(1-\delta)}, \\ E\left(\pi^{TN*}\right) = \dfrac{\rho\left(\delta(1-2c_h) - (1-c_h)^2\right)}{4(1-\delta)} + \dfrac{(1-\rho)}{4}. \end{cases}$$

Case 2. when $\frac{1-\delta}{2} < c_h \le 1$, the manufacturer would choose decision 1 if $c = 0$, and choose choose decision 2 if $c = c_h$. Thus, the optimal expected quantities and expected profit of the manufacturer under in Case 2 are

$$\begin{cases} E\left(q_n^{TN*}\right) = \dfrac{\rho(1+\delta-c_h)}{2(1+3\delta)} + \dfrac{1-\rho}{2}, \\ E\left(q_r^{TN*}\right) = \dfrac{\rho(1+\delta-c_h)}{2(1+3\delta)}, \\ E\left(\pi^{TN*}\right) = \dfrac{\rho(1+\delta-c_h)^2}{4(1+3\delta)} + \dfrac{(1-\rho)}{4}. \end{cases}$$

Summarizing above two cases, we can obtain Lemma 1.

Now we calculate the results of model *TH*.

Under the model *TH*, the Lagrangean function and the KKT optimality conditions of the manufacturer are

$$L^{TH} = (p_n - c_0)q_n - p_r q_n - \lambda_1(-q_{r1}) - \lambda_2(q_r - q_n) \tag{A6}$$

$$\partial L^{TH} / \partial q_r = 0 \tag{A7}$$

$$\partial L^{TH} / \partial q_n = 0 \tag{A8}$$

$$\lambda_1 q_r = 0 \tag{A9}$$

$$\lambda_2(q_r - q_n) \tag{A10}$$

The solution process of Lemma 2 is very similar to Lemma 1, so we omit the details and present the optimal number of the manufacturer under the model *TH*, which are

(1) $q_n^{TH*} = \frac{1-\delta-c_0}{2(1-\delta)}$, $q_r^{TH*} = \frac{c_0}{2(1-\delta)}$, if $0 \le c_0 \le \frac{1-\delta}{2}$;

(2) $q_r^{TH*} = q_n^{TH*} = \frac{1+\delta-c_0}{2(1+3\delta)}$, if $\frac{1-\delta}{2} < c_0 \le 1$.

Correspondingly, we can obtain the optimal profit of the manufacturer under the model *TH*, which is

$$\pi^{TH*} = \begin{cases} \dfrac{(1-\delta) - 2(1-\delta)c_0 + {c_0}^2}{4(1-\delta)}, if \;\; 0 \le c \le \dfrac{1-\delta}{2}, \\ \dfrac{(1+\delta-c_0)^2}{4(1+3\delta)}, if \;\; \dfrac{1-\delta}{2} < c \le 1. \end{cases}$$

Now we calculate the optimal expected number and expected profit of the manufacturer.

Case 1. when $0 \le c_0 \le \frac{1-\delta}{2}$, the optimal expected quantities and expected profit of the manufacturer under in Case 1 are $E(q_n^{TH*}) = \frac{1-\delta-c_0}{2(1-\delta)}$, $E(q_r^{TH*}) = \frac{c_0}{2(1-\delta)}$, and $E(\pi^{TH*}) = \frac{(1-\delta)-2(1-\delta)c_0+{c_0}^2}{4(1-\delta)}$.

Case 2. when $\frac{1-\delta}{2} < c_0 \le 1$, the optimal expected quantities and expected profit of the manufacturer under in Case 2 are $E(q_r^{TH*}) = E(q_n^{TH*}) = \frac{1+\delta-c_0}{2(1+3\delta)}$, and $E(\pi^{TH*}) = \frac{(1+\delta-c_0)^2}{4(1+3\delta)}$.

Summarizing case 1 and case 2, we can obtain Lemma 2.

Proof of Proposition 1. Comparing the manufacturer's expected profits in model ***OH*** and model ***ON***, we have

$$E\left(\pi^{OH*}\right) - E\left(\pi^{ON*}\right) = E\left(\frac{(1-c_0)^2}{4}\right) - E\left(\frac{(1-c)^2}{4}\right)$$
$$= \frac{(1-c_0)^2}{4} - \left[\frac{(1-\rho c_h)^2}{4} + \frac{{c_h}^2\rho(1-\rho)}{4}\right]$$
$$= \frac{1}{4}c_h(2-c_h)\rho + \frac{1}{4}{c_0}^2 - \frac{c_0}{2}.$$

Since $c_h \in [0,1]$ in our model, $E(\pi^{OH*}) - E(\pi^{ON*})$ increases in ρ. When $\rho = 0$,

$$E\left(\pi^{OH*}\right) - E\left(\pi^{ON*}\right)|_{\rho=0} = -\frac{c_0(2-c_0)}{4} < 0$$

owing to $c_0 \in (0,1)$. When $\rho = 1$, we have

$$E\left(\pi^{OH*}\right) - E\left(\pi^{ON*}\right)|_{\rho=1} = \frac{(2-c_h-c_0)(c_h-c_0)}{4}$$

which satisfies $E(\pi^{OH*}) - E(\pi^{ON*}) \leq 0$ if $c_h \leq c_0$, and $E(\pi^{OH*}) - E(\pi^{ON*}) > 0$ if $c_h > c_0$. Therefore, when $c_h \leq c_0$, we have $E(\pi^{OH*}) - E(\pi^{ON*}) < 0$ for $\rho \in (0,1)$. When $c_h > c_0$, there exists a threshold $\rho_1 \in (0,1)$ such that $E(\pi^{OH*}) - E(\pi^{ON*}) < 0$ if $\rho \in (0,\rho_1)$, and $E(\pi^{OH*}) - E(\pi^{ON*}) > 0$ if $\rho \in (\rho_1, 1)$.

For a profit-oriented manufacturer, it is optimal for the manufacturer to choose cash hedging when $E(\pi^{OH*}) - E(\pi^{ON*}) > 0$, and not to choose hedge when $E(\pi^{OH*}) - E(\pi^{ON*}) < 0$. Therefore, it is optimal for the manufacturer to hedge its cash flow if $c_h > c_0$ and $\rho > \rho_1$, and not to hedge if 1) $c_h < c_0$, or 2) $c_h > c_0$ and $\rho < \rho_1$. Solving $E(\pi^{OH*}) - E(\pi^{ON*}) = 0$ for ρ, we can have the threshold

$\rho = \frac{c_0(2-c_0)}{c_h(2-c_h)} = \rho_1$.

Proof of Proposition 2. when the manufacturer does not engage in remanufacturing, we can calcualte the expected environmental impacts in model *ON* (i.e., $E(G^{ON*})$) and that in model *OH* (i.e., $E(G^{OH*})$), which are $E(G^{ON*}) = \frac{1-\rho c_h}{2}$, $E(G^{OH*}) = \frac{1-c_0}{2}$.

Comparing G^{ON*} and G^{OH*}, we have $E(G^{OH*}) - E(G^{ON*}) = (\rho c_h - c_0)/2$. $E(G^{OH*}) - E(G^{ON*})$ increases in ρ. When $\rho = 0$, we have $E(G^{OH*}) - E(G^{ON*}) < 0$. When $\rho = 1$, we have $E(G^{OH*}) - E(G^{ON*}) \leq 0$ if $c_h \leq c_0$, and $E(G^{OH*}) - E(G^{ON*}) > 0$ if $c_h > c_0$.

Therefore, when $c_h \leq c_0$, we have $E(G^{OH*}) - E(G^{ON*}) < 0$ for $\rho \in (0,1)$, which means the cash hedging has a positive impact on the environment. In addition, when $c_h > c_0$, there exists a threshold $\rho_2 \in (0,1)$ such that $E(G^{OH*}) - E(G^{ON*}) < 0$ if $\rho \in (0,\rho_2)$, and $E(G^{OH*}) - E(G^{ON*}) > 0$ if $\rho \in (\rho_2, 1)$. Solving $E(G^{OH*}) - E(G^{ON*}) = 0$, we can obtain $\rho_2 = c_0/c_h$.

In a sum, we can obtain Proposition 2.

Proof of Proposition 3. From Proposition 1, it is obvious that compared with no cash hedging, the cash hedging will increase the manufacturer's expected profit only if $c_h > c_0$ and $\rho > \rho_1$. However, we can infer from Proposition 2 that the cash hedging will increase environmental impacts of products if $c_h > c_0$ and $\rho > \rho_1$. Thus, the cash hedging cannot increase manufacturer's expected profit and decrease environmental impacts of products simultaneously if the manufacturer does not engage in remanufacturing.

Proof of Proposition 4. When comparing the manufacturer's expected profits in model *TH* and model *TN*, we need to discuss four cases:

Case 1. when $0 \leq c_0 \leq \frac{1-\delta}{2}$, and $0 \leq c_h \leq \frac{1-\delta}{2}$, we have $E(\pi^{TH*}) - E(\pi^{TN*}) = \rho c_h(2+2\delta-c_h) - c_0(2+2\delta-c_0)$.Obviously, $E(\pi^{TH*}) - E(\pi^{TN*})$ increases in ρ. When $\rho = 0$, we hve $E(\pi^{TH*}) - E(\pi^{TN*}) < 0$. When $\rho = 1$, we have

$$E\left(\pi^{TH*}\right) - E\left(\pi^{TN*}\right)|_{\rho=1} = \frac{(2(1-\delta)-c_h-c_0)(c_h-c_0)}{4}$$

Since $0 \leq c_0 \leq \frac{1-\delta}{2}$, and $0 \leq c_h \leq \frac{1-\delta}{2}$, we have $2(1-\delta) - c_h - c_0 > 0$. Thus $E(\pi^{TH*}) - E(\pi^{TN*})|_{\rho=1} > 0$ if $c_h > c_0$, and $E(\pi^{TH*}) - E(\pi^{TN*})|_{\rho=1} \leq 0$ if $c_h \leq c_0$.

In a sum, when $0 \leq c_0 \leq \frac{1-\delta}{2}$, and $0 \leq c_h \leq \frac{1-\delta}{2}$, we have following results: (a) when $c_h \leq c_0$, $E(\pi^{TH*}) - E(\pi^{TN*}) < 0$ for $\rho \in (0,1)$; (b) when $c_h > c_0$, there exists a threshold of $\rho_2^1 \in (0,1)$ such that $E(\pi^{TH*}) - E(\pi^{TN*}) < 0$ when $\rho \in (0,\rho_2^1)$, and $E(\pi^{TH*}) - E(\pi^{TN*}) > 0$ when $\rho \in (\rho_2^1, 1)$. Solving $E(\pi^{TH*}) - E(\pi^{TN*}) = 0$ for ρ, we can have the threshold $\frac{c_0(2(1-\delta)-c_0)}{c_h(2(1-\delta)-c_h)} = \rho_2^1$.

Case 2. when $0 \leq c_0 \leq \frac{1-\delta}{2}$, and $\frac{1-\delta}{2} \leq c_h \leq 1$, we have $E(\pi^{TH*}) - E(\pi^{TN*}) = \frac{\rho(1-\delta)(\delta-\delta^2+c_h(2+2\delta)-{c_h}^2)-c_0(1+3\delta)(2+2\delta-c_0)}{4(1+2\delta-3\delta^2)}$.

It is easy to obtain that $E(\pi^{TH*}) - E(\pi^{TN*})$ increases in ρ. In addition, we have $E(\pi^{TH*}) - E(\pi^{TN*})|_{\rho=0} < 0$ and $E(\pi^{TH*}) - E(\pi^{TN*})|_{\rho=1} > 0$. Thus, there exists a threshold $\rho_2^2 \in (0,1)$ such that $E(\pi^{TH*}) - E(\pi^{TN*}) < 0$ when $\rho \in (0,\rho_2^2)$, and $E(\pi^{TH*}) - E(\pi^{TN*}) > 0$ when $\rho \in (\rho_2^2, 1)$. Solving $E(\pi^{TH*}) - E(\pi^{TN*}) = 0$ for ρ, we can have the threshold $\rho = \frac{c_0(1+3\delta)(2+2\delta-c_0)}{(1-\delta)(\delta-\delta^2+c_h(2+2\delta)-{c_h}^2)} = \rho_2^2$.

Case 3. when $\frac{1-\delta}{2} < c_0 \leq 1$, and $0 \leq c_h \leq \frac{1-\delta}{2}$, we have

$$E\left(\pi^{TH*}\right) - E\left(\pi^{TN*}\right) = \frac{\rho(1+3\delta)c_h(2-2\delta-c_h) - (1-\delta)(\delta-\delta^2+c_0(2+2\delta)-{c_0}^2)}{4(1+2\delta-3\delta^2)}$$

It is easy to obtain that $E(\pi^{TH*}) - E(\pi^{TN*})$ increases in ρ. In addition, we have
$E(\pi^{TH*}) - E(\pi^{TN*})|_{\rho=0} < 0$ and $E(\pi^{TH*}) - E(\pi^{TN*})|_{\rho=1} < 0$. Thus, in case 3, we have $E(\pi^{TH*}) - E(\pi^{TN*}) < 0$.

Case 4. when $\frac{1-\delta}{2} < c_0 \leq 1$, and $\frac{1-\delta}{2} < c_h \leq 1$, we have

$$E\left(\pi^{TH*}\right) - E\left(\pi^{TN*}\right) = \frac{\rho(\delta-\delta^2+c_h(2+2\delta)-{c_h}^2) - (\delta-\delta^2+c_0(2+2\delta)-{c_0}^2)}{4(1+3\delta)}$$

It is easy to obtain that $E(\pi^{TH*}) - E(\pi^{TN*})$ increases in ρ. In addition, we have
$E(\pi^{TH*}) - E(\pi^{TN*})|_{\rho=0} < 0$ if $\rho = 0$. When $\rho = 1$, we have

$$E\left(\pi^{TH^*}\right) - E\left(\pi^{TN^*}\right)\big|_{\rho=1} = \frac{(2(1+\delta) - c_h - c_0)(c_h - c_0)}{4}$$

Since $\frac{1-\delta}{2} < c_0 \le 1$, and $\frac{1-\delta}{2} < c_h \le 1$, we have $2(1+\delta) - c_h - c_0 > 0$. Thus $E(\pi^{TH^*}) - E(\pi^{TN^*})\big|_{\rho=1} > 0$ if $c_h > c_0$, and $E(\pi^{TH^*}) - E(\pi^{TN^*})\big|_{\rho=1} \le 0$ if $c_h \le c_0$. In a sum, when $\frac{1-\delta}{2} < c_0 \le 1$ and $\frac{1-\delta}{2} < c_h \le 1$, we have following results. (a) When $c_h \le c_0$, $E(\pi^{TH^*}) - E(\pi^{TN^*}) < 0$ for $\rho \in (0,1)$; (b) when $c_h > c_0$, there exists a threshold $\rho_2^3 \in (0,1)$ such that $E(\pi^{TH^*}) - E(\pi^{TN^*}) < 0$ when $\rho \in (0,\rho_2^3)$, and $E(\pi^{TH^*}) - E(\pi^{TN^*}) > 0$ when $\rho \in (\rho_2^3, 1)$. Solving $E(\pi^{TH^*}) - E(\pi^{TN^*}) = 0$ for ρ, we can have the threshold

$$\rho = \frac{(\delta - \delta^2 + c_0(2+2\delta) - {c_0}^2)}{(\delta - \delta^2 + c_h(2+2\delta) - {c_h}^2)} = \rho_2^3$$

Define

$$\rho_2 = \begin{cases} \rho_2^1, if\ \ 0 \le c_0 < c_h \le \dfrac{1-\delta}{2}, \\ \rho_2^2, if\ \ 0 \le c_0 \le \dfrac{1-\delta}{2} < c_h \le 1, \\ \rho_2^3, if\ \ \dfrac{1-\delta}{2} < c_0 < c_h \le 1, \end{cases}$$

we have Proposition 4.

Proof of Proposition 5. when the manufacturer remanufactures, we can calcualte the expected environmental impacts in model *TN* (i.e., $E(G^{TN^*})$) and that in model *TH* (i.e., $E(G^{TH^*})$), which are

$$E\left(G^{TN^*}\right) = \begin{cases} \dfrac{1-\delta-(1-\alpha)\rho c_h}{2(1-\delta)}, if\ \ 0 \le c_h \le \dfrac{1-\delta}{2}, \\ \dfrac{1+3\delta+(\alpha-2\delta+\alpha\delta)\rho-(1+\alpha)\rho c_h}{2(1+3\delta)}, if\ \ \dfrac{1-\delta}{2} < c_h \le 1, \end{cases} \qquad E\left(G^{TH^*}\right) = \begin{cases} \dfrac{1-\delta-c_0+\alpha c_0}{2(1-\delta)}, if\ \ 0 \le c_0 \le \dfrac{1-\delta}{2}, \\ \dfrac{(1+\alpha)(1+\delta-c_0)}{2(1+3\delta)}, if\ \ \dfrac{1-\delta}{2} < c_0 \le 1. \end{cases}$$

Comparing $E(G^{TN^*})$ and $E(G^{TH^*})$, we need to discuss four cases.

Case 1. when $0 \le c_0 \le \frac{1-\delta}{2}$, and $0 \le c_h \le \frac{1-\delta}{2}$,

$$E\left(G^{TH^*}\right) - E\left(G^{TN^*}\right) = \frac{(1-\alpha)(\rho c_h - c_0)}{2(1-\delta)}$$

$E(G^{TH^*}) - E(G^{TN^*})$ increases in ρ. When $\rho = 0$, we have $E(G^{TH^*}) - E(G^{TN^*}) < 0$. When $\rho = 1$, we have $E(G^{OH^*}) - E(G^{ON^*}) \le 0$ if $c_h \le c_0$, and $E(G^{OH^*}) - E(G^{ON^*}) > 0$ if $c_h > c_0$.

Therefore, when $c_h \le c_0$, we have $E(G^{TH^*}) - E(G^{TN^*}) < 0$ for $\rho \in (0,1)$. However, when $c_h > c_0$, there exists a threshold $\rho_4^1 \in (0,1)$ such that $E(\pi^{OH^*}) - E(\pi^{ON^*}) < 0$ if $\rho \in (0,\rho_4^1)$, and $E(\pi^{OH^*}) - E(\pi^{ON^*}) > 0$ if $\rho \in (\rho_4^1, 1)$. Solving $E(G^{TH^*}) - E(G^{TN^*}) = 0$ for ρ, we have

$\rho = c_0/c_h = \rho_4^1$.

Case 2. when $0 \le c_0 \le \frac{1-\delta}{2}$, and $\frac{1-\delta}{2} \le c_h \le 1$, we have

$E(G^{TH^*}) - E(G^{TN^*}) = \frac{(1-\delta)(1+\alpha)\rho c_h - [\rho(2\delta+\alpha\delta^2-\alpha-2\delta^2)+(1-\alpha)(1+3\delta)c_0]}{2+4\delta-6\delta^2}$.$E(G^{TH^*}) - E(G^{TN^*})$ increases in ρ. When $\rho = 0$, we have $E(G^{TH^*}) - E(G^{TN^*}) < 0$. When $\rho = 1$, we have $E(G^{OH^*}) - E(G^{ON^*}) \le 0$ if $c_h \le c_0$, and $E(G^{OH^*}) - E(G^{ON^*}) > 0$ if $c_h > c_0$.

Therefore, when $c_h \le c_0$, we have $E(G^{TH^*}) - E(G^{TN^*}) < 0$ for $\rho \in (0,1)$. However, when $c_h > c_0$, there exists a threshold $\rho_4^2 \in (0,1)$ such that $E(\pi^{OH^*}) - E(\pi^{ON^*}) < 0$ if $\rho \in (0,\rho_4^2)$, and $E(\pi^{OH^*}) - E(\pi^{ON^*}) > 0$ if $\rho \in (\rho_4^2, 1)$. Solving $E(G^{TH^*}) - E(G^{TN^*}) = 0$ for ρ, we have

$$\rho = \frac{c_0(1+3\delta)(1-\alpha)}{(1-\delta)(2\delta + c_h - \alpha(1+\delta-c_h))} = \rho_4^2$$

Case 3. when $\frac{1-\delta}{2} < c_0 \le 1$, and $0 \le c_h \le \frac{1-\delta}{2}$, we have

$$E\left(G^{TH^*}\right) - E\left(G^{TN^*}\right) = \frac{(1-\alpha)(1+3\delta)\rho c_h - (1-\delta)(2\delta + c_0 - \alpha - \alpha\delta + \alpha c_0)}{2+4\delta-6\delta^2}$$

$E(G^{TH^*}) - E(G^{TN^*})$ increases in ρ. When $\rho = 1$, we have $E(G^{TH^*}) - E(G^{TN^*}) < 0$. Thus, $E(G^{TH^*}) - E(G^{TN^*}) < 0$ in case 3.

Case 4. when $\frac{1-\delta}{2} < c_0 \le 1$, and $\frac{1-\delta}{2} < c_h \le 1$,

$$E\left(G^{TH^*}\right) - E\left(G^{TN^*}\right) = \frac{\rho(1+\alpha)c_h - (1-\rho)[2\delta - \alpha(1+\delta)] - (1+\alpha)c_0}{2+6\delta}$$

$E(G^{TH^*}) - E(G^{TN^*})$ increases in ρ. When $\rho = 0$, we have $E(G^{TH^*}) - E(G^{TN^*}) < 0$. When $\rho = 1$, we have $E(G^{OH^*}) - E(G^{ON^*}) \le 0$ if $c_h \le c_0$, and $E(G^{OH^*}) - E(G^{ON^*}) > 0$ if $c_h > c_0$.

Therefore, when $c_h \le c_0$, we have $E(G^{TH^*}) - E(G^{TN^*}) < 0$ for $\rho \in (0,1)$. However, when $c_h > c_0$, there exists a threshold $\rho_4^3 \in (0,1)$ such that $E(\pi^{OH^*}) - E(\pi^{ON^*}) < 0$ if $\rho \in (0,\rho_4^3)$, and $E(\pi^{OH^*}) - E(\pi^{ON^*}) > 0$ if $\rho \in (\rho_4^3, 1)$. Solving $E(G^{TH^*}) - E(G^{TN^*}) = 0$ for ρ, we have $\rho = \frac{(2\delta + c_0 - \alpha(1+\delta-c_0))}{(2\delta + c_h - \alpha(1+\delta-c_h))} = \rho_4^3$

Summarizing case 1 to 4, and define

$$\rho_4 = \begin{cases} \rho_4^1, if \ \ 0 \le c_0 < c_h \le \dfrac{1-\delta}{2}, \\ \rho_4^2, if \ \ 0 \le c_0 \le \dfrac{1-\delta}{2} < c_h \le 1, \\ \rho_4^3, if \ \ \dfrac{1-\delta}{2} < c_0 < c_h \le 1, \end{cases}$$

we can obtain Proposition 5.

Proof of Proposition 6. Proposition 6 can be concluded from Proposition 4 and proposition 5.

References

Adam, T., Dasgupta, S., Titman, S., 2007. Financial constraints, competition, and hedging in industry equilibrium. J. Finance 62 (5), 2445–2473.

Adam, T., Nain, A., 2013. Strategic risk management and product market competition. In: Batten, J., Mackay, P., Wagner, N. (Eds.), Advances in Financial Risk Management. Palgrave Macmillan, London, pp. 3–29.

Agrawal, D., 1996. Effect of brand loyalty on advertising and trade promotions: a game theoretic analysis with empirical evidence. Market. Sci. 15 (1), 86–108.

Alizadeh-Basban, N., Taleizadeh, A.A., 2019. A hybrid circular economy - game theoretical approach in a dual-channel green supply chain considering sale's effort, delivery time, and hybrid remanufacturing. J. Clean. Prod. 250, 119521.

Amato, L.H., Zillante, A., Amato, C.H., 2015. Corporate environmental claims: a game theory model with empirical results. Soc. Responsib. J. 11 (1), 36–55.

Arellano, M., Bond, S., 1991. Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. Rev. Econ. Stud. 58 (2), 277–297.

Atasu, A., Sarvary, M., Van Wassenhove, L.N., 2008. Remanufacturing as a marketing strategy. Manag. Sci. 54 (10), 1731–1746.

Ba, S., Stallaert, J., Zhang, Z., 2012. Online price dispersion: a game-theoretic perspective and empirical evidence. Inf. Syst. Res. 23 (2), 575–592.

Bartram, S.M., 2019. Corporate hedging and speculation with derivatives. J. Corp. Finance 57, 9–34.

Bartram, S., Brown, G., Conrad, J., 2011. The effects of derivatives on firm risk and value. J. Financ. Quant. Anal. 46 (4), 967–999.

Ben, K.K., 2010. Do investors really value derivatives use? Empirical evidence from France. J. Risk Finance 11 (1), 62–74.

Berghöfer, B., Lucey, B., 2014. Fuel hedging, operational hedging and risk exposure –evidence from the global airline industry. Int. Rev. Financ. Anal. 34, 124–139.

Blundell, R., Bond, S., 2000. GMM estimation with persistent panel data: an application to production functions. Econom. Rev. 19 (3), 321–340.

Chod, J., Rudi, N., Van Mieghem, J.A., 2010. Operational flexibility and financial hedging: complements or substitutes? Manag. Sci. 56 (6), 1030–1045.

Cui, L., Jiang, F., 2012. State ownership effect on firms' FDI ownership decisions under institutional pressure: a study of Chinese outward-investing firms. J. Int. Bus. Stud. 43 (3), 264–284.

Disatnik, D.J., Duchin, R., Schmidt, B., 2014. Cash hedging and liquidity choices. Rev. Finance 18 (2), 715–748.

Dou, G.W., Cao, K.Y., 2020. A joint analysis of environmental and economic performances of closed-loop supply chains under carbon tax regulation. Comput. Ind. Eng. 146, 106624.

Elhorst, J.P., 2010. Dynamic panels with endogenous interaction effects when T is small. Reg. Sci. Urban Econ. 40 (5), 272–282.

Eisenberg, T., Sundgren, S., Wells, M.T., 1998. Larger board size and decreasing firm value in small firms. J. Financ. Econ. 48 (1), 35–54.

Ferguson, M.E., Fleischmann, M., Souza, G.C., 2011. A profit-maximizing approach to disposition decisions for product returns. Decis. Sci. J. 42 (3), 773–798.

Fok, R., Carroll, C., Chiou, M.C., 1997. Determinants of corporate hedging and derivatives: a revisit. J. Econ. Bus. 49 (6), 569–585.

Gamba, A., Triantis, A.J., 2014. Corporate risk management: integrating liquidity, hedging, and operating policies. Manag. Sci. 60 (1), 246–264.

Galbreth, M.R., Blackburn, J.D., 2010. Optimal acquisition quantities in remanufacturing with condition uncertainty. Prod. Oper. Manag. 19 (1), 61–69.

Géczy, C., Minton, B.A., Schrand, C., 1997. Why firms use currency derivatives. J. Finance 52, 1323–1354.

Geyer, R., Van Wassenhove, L.N., Atasu, A., 2007. The economics of remanufacturing under limited component durability and finite product life cycles. Manag. Sci. 53 (1), 88–100.

Ha, A.Y., Tian, Q., Tong, S.L., 2017. Information sharing in competing supply chains with production cost reduction. Manuf. Serv. Oper. Manag. 19 (2), 246–262.

Han, X.H., Wu, H.Y., Yang, Q.X., Shang, J., 2016. Reverse channel selection under remanufacturing risks: balancing profitability and robustness. Int. J. Prod. Econ. 182, 63–72.

He, Y., 2015. Acquisition pricing and remanufacturing decisions in a closed-loop supply chain. Int. J. Prod. Econ. 163, 48–60.

He, Y.J., 2017. Supply risk sharing in a closed-loop supply chain. Int. J. Prod. Econ. 183, 39–52.

He, Y., Zhang, J., 2008. Random yield risk sharing in a two-level supply chain. Int. J. Prod. Econ. 112, 769–781.

He, Z.L., Wong, P.K., 2004. Exploration vs. exploitation: an empirical test of the ambidexterity hypothesis. Organ. Sci. 15 (4), 481–494.

Helpman, E., Melitz, M.J., Yeaple, S.R., 2004. Export versus FDI with heterogeneous firms. Am. Econ. Rev. 94 (1), 300–316.

Heydari, J., Govindan, K., Sadeghi, R., 2018. Reverse supply chain coordination under stochastic remanufacturing capacity. Int. J. Prod. Econ. 202, 1–11.

Hoang, D., Ruckes, M., 2017. Corporate risk management, product market competition, and disclosure. J. Financ. Intermediation 30, 107–121.

Huang, H., Meng, Q.L., Xu, H.Y., Zhou, Y., 2019. Cost information sharing under competition in remanufacturing. Int. J. Prod. Res. 57 (21), 6579–6592.

Huang, Y.T., Wang, Z.J., 2018. Demand disruptions, pricing and production decisions in a closed loop supply chain with technology licensing. J. Clean. Prod. 191, 248–260.

Jin, M., Li, B., Xiong, Y., Chakraborty, R., Zhou, Y., 2022. Implications of coproduction technology on waste management: Who can benefit from the coproduct made of leftover materials? European Journal of Operational Research, in press.

Kouvelis, P., Turcic, D., 2021. Supporting operations with financial hedging: cash hedging vs. cost hedging in an automotive industry. Prod. Oper. Manag. 30 (3), 738–749.

Kouvelis, P., Wu, X.L., Xiao, Y.X., 2019. Cash hedging in a supply chain. Manag. Sci. 65 (8), 3470, 3469.

Krause, T.A., Tse, Y., 2016. Risk management and firm value: recent theory and evidence. Int. J. Account. Inf. Manag. 24 (1), 56–81.

Li, J., Strange, R., Ning, L., Sutherland, D., 2016. Outward foreign direct investment and domestic innovation performance: evidence from China. Int. Bus. Rev. 25 (5), 1010–1019.

Li, X., Yong, J., Cai, X.Q., 2015. Remanufacturing and pricing decisions with random yield and random demand. Comput. Oper. Res. 54, 195–203.

Liao, B., 2018. Warranty as a competitive dimension for remanufactured products under stochastic demand. J. Clean. Prod. 198, 511–519.

Ling, Y., Xia, S., Cao, M., He, K., Lim, M.K., Sukumar, A., Qian, X., 2021. Carbon emissions in China's thermal electricity and heating industry: an input-output structural decomposition analysis. Journal of Cleaner Production 329, 129608.

Liu, X., Hodgkinson, I.R., Chuang, F.M., 2014. Foreign competition, domestic knowledge base and innovation activities: evidence from Chinese high-tech industries. Res. Pol. 43 (2), 414–422.

Loss, F., 2012. Optimal hedging strategies and interactions between firms. J. Econ. Manag. Strat. 21 (1), 79–129.

Mackay, P., Moeller, S., 2007. The value of corporate risk management. J. Finance 62 (3), 1379–1419.

Master, H.P., Shen, N., Liao, H.L., Xue, H.Q., Wang, Q.W., 2020. Uncertainty factors, methods, and solutions of closed-loop supply chain-A review for current situation and future prospects. J. Clean. Prod. 254, 120032.

Mazahir, S., Verter, V., Boyaci, T., Van Wassenhove, L.N., 2019. Did europe move in the right direction on E-waste legislation? Prod. Oper. Manag. 28 (1), 121–139.

MIIT, 2009. https://www.miit.gov.cn/cms_files/filemanager/oldfile/miit/n1146285/n1146352/n3054355/n3057542/n3057544/c3864377/part/3864378.pdf. (Accessed 16 July 2022).

MIIT, 2016. https://www.miit.gov.cn/jgsj/jns/zyjy/art/2020/art_3550440adb194d168f1ff0a8e8869cdb.html. (Accessed 16 July 2022). Accessed:

MIIT, 2020. https://www.miit.gov.cn/zwgk/zcwj/wjfb/qt/art/2020/art_9dd4b785dda44159ab84da417e408528.html. (Accessed 16 July 2022). Accessed:

Milios, L., Beqiri, B., Whalen, K., Jelonek, S.H., 2019. Sailing towards a circular economy: conditions for increased reuse and remanufacturing in the Scandinavian maritime sector. J. Clean. Prod. 225, 227–235.

Nie, J.J., Shi, C.L., Xiong, Y., Xia, S.M., Liang, J.M., 2020. Downside of a carbon tax for environment: Impact of information sharing. Advances in Climate Change Research 11 (2), 92–101.

Ningsih, S., Sari, S.P., 2019. Analysis of the effect of liquidity ratios, solvability ratios and profitability ratios on firm value in go public companies in the automotive and component sectors. International Journal of Economics, Business and Accounting Research (IJEBAR) 3 (4), 351–359.

Niu, B., Chen, Z.L., Zhang, J., 2017. Punishing or subsidizing? Regulation analysis of sustainable fashion procurement strategies. Transport. Res. Part E 107, 81–96.

Przepiorka, W., Rutten, C., Buskens, V., Szekely, A., 2020. How dominance hierarchies emerge from conflict: a game theoretic model and experimental evidence. Soc. Sci. Res. 86, 102393.

Rampini, A.A., Sufi, A., Viswanathan, S., 2014. Dynamic risk management. J. Financ. Econ. 111 (2), 271–296.

Rampini, A.A., Viswanathan, S., Vuillemey, G., 2020. Risk management in financial institutions. J. Finan. 75 (2), 591–637.

Randall, T., Ulrich, K., 2001. Product variety, supply chain structure, and firm performance: analysis of the U.S. Bicycle industry. Manag. Sci. 47 (12), 1588–1604.

Raz, G., Souza, G.C., 2018. Recycling as a strategic supply source. Prod. Oper. Manag. 27 (5), 902–916.

Raz, G., Druehl, C.T., Blass, V., 2013. Design for the environment: life-cycle approach using a newsvendor model. Prod. Oper. Manag. 22 (4), 940–957.

Reimann, M., Xiong, Y., Zhou, Y., 2019. Managing a closed-loop supply chain with process innovation for remanufacturing. Eur. J. Oper. Res. 276, 510–518.

Roodman, D., 2009. How to do xtabond2: an introduction to difference and system GMM in Stata. STATA J. 9 (1), 86–136.

Roodman, D., 2020. Xtabond2: stata module to extend xtabond dynamic panel data estimator. Available at: https://econpapers.repec.org/software/bocbocode/s435901.htm.

Sarkar, B., Ullah, M., Kim, N., 2017. Environmental and economic assessment of closed-loop supply chain with remanufacturing and returnable transport items. Comput. Ind. Eng. 111, 148–163.

Savaskan, R.C., Bhattacharya, S., Van Wassenhove, L.N., 2004. Closed-loop supply chain models with product remanufacturing. Manag. Sci. 50 (2), 239–252.

Stock, G.N., Greis, N.P., Fischer, W.A., 2002. Firm size and dynamic technological innovation. Technovation 22 (9), 537–549.

Sun, H., Chen, W.D., Ren, Z.L., Liu, B.Y., 2017. Optimal policy in a hybrid manufacturing/remanufacturing system with financial hedging. Int. J. Prod. Res. 55 (19), 5728–5742.

Treanor, S.D., Simkins, B.J., Rogers, D.A., Carter, D.A., 2014. Does operational and financial hedging reduce exposure? Evidence from the US airline industry. Financ. Rev. 49 (1), 149–172.

Turcic, D., Kouvelis, P., Bolandifar, E., 2015. Hedging commodity procurement in a bilateral supply chain. Manuf. Serv. Oper. Manag. 17 (2), 221–235.

Wang, C., Hong, J., Kafouros, M., Wright, M., 2012. Exploring the role of government involvement in outward FDI from emerging economies. J. Int. Bus. Stud. 43 (7), 655–676.

Wang, L., Cai, G., Tsay, A.A., Vakharia, A.J., 2017. Design of the reverse channel for remanufacturing: must profit-maximization harm the environment? Prod. Oper. Manag. 26 (8), 1585–1603.

Wang, Z., He, Q., Xia, S., Sarpong, D., Xiong, A., Maas, G., 2020. Capacities of business incubator and regional innovation performance. Technol. Forecast. Soc. Change 158, 120125.

Wei, S., Tang, O., 2014. Real option approach to evaluate cores for remanufacturing in service markets. Int. J. Prod. Res. 53 (8), 2306–2320.

Wu, X.L., Zhou, Y., 2017. The optimal reverse channel choice under supply chain competition. Eur. J. Oper. Res. 259, 63–66.

Xia, S., Ling, Y., De Main, L., Lim, M.K., Li, G., Zhang, P., Cao, M., 2022. Creating a low carbon economy through green supply chain management: investigation of willingness-to-pay for green products from a consumer's perspective. International Journal of Logistics Research and Applications 1–31.

Xiong, Y., Zhou, Y., Li, G., Chan, H., Xiong, Z., 2013. Don't forget your supplier when remanufacturing. Eur. J. Oper. Res. 230 (1), 15–25.

Xu, J., Akhtar, M., Haris, M., Muhammad, S., Abban, O.J., Taghizadeh-Hesary, F., 2022. Energy crisis, firm profitability, and productivity: an emerging economy perspective. Energy Strategy Rev. 41, 100849.

Yenipazarli, A., 2016. Managing new and remanufactured products to mitigate environmental damage under emissions regulation. Eur. J. Oper. Res. 249, 117–130.

Yu, X., Zhang, W.G., Liu, Y.J., Wang, X., Wang, C., 2020. Hedging the exchange rate risk for international portfolios. Math. Comput. Simulat. 173, 85–104.

Zhang, X., Fang, W., Pi, Z., 2019. Interaction among information sharing, supply chain structure and performance. J. Coast Res. 93 (SI), 870–878.

Zhao, S., Zhu, Q., 2018. A risk-averse marketing strategy and its effect on coordination activities in a remanufacturing supply chain under market fluctuation. J. Clean. Prod. 171, 1290–1299.

Zhong, L., Nie, J., Lim, M.K., Xia, S., 2022. Agency or Self-Run: the effect of consumer green education on recyclers' distribution channel choice under platform economy. International Journal of Logistics Research and Applications 25 (4–5), 814–836.

Zhou, Y., Xiong, Y., Jin, M.Y., 2021. Less is more: consumer education in a closed-loop supply chain with remanufacturing. Omega 101, 102259.