

Research Article

Decision Analysis for the Remanufacturing System in the Presence of Carbon Cap and Trade Policy and Low-Carbon Consumers

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This paper considers a remanufacturing system in which an original equipment manufacturer (OEM) and an independent remanufacturer (IR) compete with each other. The paper conducts a model analysis for the optimal decisions in the remanufacturing system, taking into account the impacts of consumers' low-carbon awareness and carbon cap and trade (CCT) policy. With the studies, it is found that the effects of CCT and consumers' low-carbon awareness can be trading off sometimes on the remanufacturing system, and in this case, excessive cultivation of consumers' low-carbon awareness will weaken the beneficial effects of CCT on the remanufacturing system due to the resulted excessive consumers' willingness to pay for the remanufactured products.

1. Introduction

With the increasing environmental problems, much attention has been paid to carbon emission reduction. A typical policy that is used to control carbon emission is the carbon cap and trade (CCT) policy. With the CCT policy, the manufacturer is allocated a number of carbon allowances and he can buy or sell some certain carbon allowances via the carbon trading market according to the actual carbon emission amount needed for his production [1]. Obviously, the CCT policy can have an essential effect on the manufacturer's competitive position and the manufacturer who has a low carbon emission will gain a competitive advantage over those who have a high carbon emission.

It is widely recognized that the remanufactured product has a good low-carbon nature, which leads to an essential environmental and economic benefit. As reported by the United Nations Environment Programme, compared with a new product, the remanufactured product can generally save the use of new materials and reduce carbon emissions by

79%–99%. Due to the low-carbon advantage associated with remanufacturing, the remanufacturing industry is encouraged to a large extent in many countries. Typically, China initiated a plan for promoting the circular economy in the next five years in July 2021 with the aim to cultivate a group of leading remanufacturing enterprises. With this plan, more enterprises will enter into the remanufacturing market and become independent remanufacturers (IRs). Inevitably, this trend will lead to increasing competition between the original equipment manufacturer (OEM) and the IR [2, 3]. In addition, it is obvious that the level of low-carbon awareness of consumers has an essential effect on the remanufacturing industry [4]. With intuition, it can be known that an increase of the level of low-carbon awareness can promote more consumers to buy remanufactured products and enhance consumers' willingness to pay for the remanufactured products [5–7]. Besides, it should be noted that the CCT policy also has a positive effect on the remanufacturing industry and can attract more enterprises to participate in the remanufacturing business. It seems that

the CCT and the level of low-carbon awareness of consumers always have a consistently positive effect on the remanufacturing system. Is this true? That is, may their effects be trading off on a remanufacturing system? This should be an interesting and important issue for the operations management of the remanufacturing system.

Motivated by the above analysis, the paper is devoted to exploring a remanufacturing system in which an original equipment manufacturer (OEM) and an independent remanufacturer (IR) compete with each other. For resolving the above issue, the paper places the research emphasis on the operations management of the remanufacturing system with simultaneous consideration of the CCT policy and the level of the low-carbon awareness of consumers. As compared to the existing literature, a fundamental contribution of this paper lies in that it develops an analytical examination of how the CCT and the level of low-carbon awareness of consumers affect the remanufacturing decisions and how the CCT and the level of low-carbon awareness of consumers affect mutually on each other.

2. Literature Review

This paper mainly is related to two literature streams; the first is how the CCT policy affects the remanufacturing system, and the second concerns the impacts of low-carbon awareness on the remanufactured system.

For the first related research stream, the core issues have been placed on the examination of the optimal operations decisions for the remanufacturing system in the presence of the CCT policy. For example, Chang et al. [8]; Chang et al. [9]; and Chai et al. [10] studied a monopolist manufacturer who produces new products in the first period and produces both new and remanufactured products simultaneously in the second stage under the CCT policy. They analyzed the impacts of carbon emission-related parameters on the manufacturer's optimal operations decisions with the assumption that the new and remanufactured products are distinguishable. Gan et al. [11] and Yang et al. [12] explored the impacts of the CCT policy on remanufacturing with a supply chain comprising manufacturers and retailers (distributors). They explored the optimal decisions of how to improve manufacturers' profit targets and carbon emission targets. The above literature assumes that the remanufacturing is only carried out by the OEM, and the research focus is placed on the exploration of the cannibalization effect of remanufactured products on the new products. As a different research line, Chai et al. [13] examined the effects of CCT policy on remanufacturing with a remanufacturing system in which an OEM and an IR compete with each other. Their studies demonstrate that the OEM will suffer a loss from the free-riding behavior of the IR with the CCT policy. Hu et al. [1] explored the tradeoff between the carbon tax and the CCT mechanism in the remanufacturing system from the perspective of the government with numerical studies. All the above studies do not consider whether there exists a conflicting effect between the consumers' low-carbon awareness and the CCT policy, which is just the fundamental difference for this paper.

For the second related research stream, the research focus has been placed on the exploration of how the level of low-carbon awareness affects remanufacturing. For example, Wu and Zhou [14] and Mitra [15] exhibited that the target consumer group for remanufactured products are usually the green consumers who only choose the remanufactured products and the functional consumers who are willing to buy remanufactured products at a low price. Agrawal et al. [16] revealed that remanufactured products produced by third-party remanufacturers can improve consumers' perceived value on the new products. Zhu et al. [17] found that remanufacturers' adoption of warranty strategy can increase consumers' perceived value on the remanufactured products. In addition, there are some empirical pieces of evidence that show that some consumers are totally unwilling to buy remanufactured products [18]. Michaud et al. [19] pointed out that remanufactured products can be considered as green products because of the environmental benefits. And, unless consumers are informed of their impacts on the environment, they tend to pay less attention to remanufactured products than the traditional products. The questionnaire survey by Wang et al. [21] showed that consumers do not exhibit enough appreciation for the green concept of remanufactured products in Asia. All these studies advocated with an empirical approach that we should promote remanufacturing by strengthening the cultivation of consumers' low-carbon awareness and changing the perceptions of consumers [20]. Actually, there exists some literature exploring the effects of the cultivation of consumers' low-carbon awareness on remanufacturing. For example, recent research by Zhou et al. [22] incorporated low-carbon awareness cultivation into the remanufacturing system. Their studies demonstrated that excessive low-carbon awareness cultivation may make manufacturers withdraw from remanufacturing.

As compared with the above studies, the fundamental differences of this paper lie in two aspects as follows: i) This paper considers the remanufacturing system in the presence of competition between the OEM and the IR. (ii) This paper explores the remanufacturing system with simultaneous consideration of the effects resulted from the CCT policy and the consumers' low-carbon awareness. Furthermore, the paper also reveals how the CCT mechanism and the consumers' low-carbon awareness affect mutually each other.

3. Model Description

Consider a remanufacturing system comprising an OEM and an IR. The OEM produces the new products and the IR competes with the OEM and produces the remanufactured products by the recycled old products [23–25]. At the beginning of the period, the OEM and the IR receive the carbon allowance assigned by the carbon regulator and then they decide to buy or sell the carbon allowance based on their production quantity and their unit carbon emission [9]. In general, the carbon allowance allocation is based on two rules including the grandfathering and the bench-marking.

The common feature of both rules is that they allocate the carbon allowance according to the production quantity of the manufacturer. Let the unit carbon emission for the new and remanufactured products be e_n and e_r and the unit carbon allowance for the new and remanufactured products be g_n and g_r , respectively. Hence, the carbon allowance that needs to buy in the carbon trading market for each unit's new and remanufactured products are, respectively, $t_n = e_n - g_n$ and $\omega t_n = e_r - g_r$. As discussed in the Introduction section, given the low-carbon nature of the remanufactured products, it is reasonable to require that $\omega < 1$; that is, the carbon quota that needs to buy for each unit remanufactured product is lower than that of the unit new product. In addition, since the remanufactured products are produced with recycled old products, the production quantity for the remanufactured products should be bounded from above by the production quantity of the new products. That is, it should be required that $q_r^{ij} \leq \tau q_n^{ij}$, where τ is the recycle ratio of the used-old products. For clarity, we summarize all notations of the model in Table 1.

We divide the consumers into two types, namely, the functionality-oriented consumers (FOCs) and the newness-conscious consumers (NCCs). The FOCs choose both the new and remanufactured products and let their ratio be ϕ . The NCCs choose only the new products and let their ratio be $1 - \phi$ [26, 27]. Without loss of generality, we normalize the maximum WTP of consumers to 1 and require that the unit cost of the new product is $c_n < 1$. The FOCs with WTP being θ prefer the new product to the remanufactured product. The FOCs who treat the new and remanufactured products as the same can be expressed as $\theta - p_n^{ij} = \delta\theta - p_r^{ij}$, and so the marginal customers for the FOCs can be expressed as $\theta_{nr} = (p_n^{ij} - p_r^{ij})/(1 - \delta)$. The FOCs who have the same utility between buying the remanufactured product and buying nothing can be expressed as $\delta\theta - p_r^{ij} = 0$, and so the marginal customers for the FOCs can be expressed as $\theta_{rz} = p_r^{ij}/\delta$. Therefore, the FOCs' demand for remanufactured products is $\phi((p_n^{ij} - p_r^{ij})/(1 - \delta) - p_r^{ij}/\delta)$, and their demand for the new products is $\phi(1 - (p_n^{ij} - p_r^{ij})/(1 - \delta))$. For the NCCs, their WTP for the new products is θ and is zero for the remanufactured products. Thus, their net utility with purchasing the new products is $\theta - p_n^{ij}$ and is $-p_r^{ij}$ with buying the remanufactured products. Therefore, the NCCs' demand for the remanufactured products is 0 and is $(1 - \phi)(1 - p_n^{ij})$ for the new products. According to the results by Zhou et al. (2021), it can be obtained that $p_n^{ij} = 1 - q_n^{ij} - \delta q_r^{ij}$ and $p_r^{ij} = \delta(1 - q_n^{ij} - q_r^{ij}) - \delta(1 - \delta)q_r^{ij}/\phi$.

4. Model Analysis

4.1. Scenario 1: Analysis of the Model without CCT. In this section, we conduct the analysis for the model that does not consider the effect of CCT. For this case, the optimization problem for the OEM can be formulated as follows:

$$\max \pi_n^{i1}(q_n^{i1}) = (p_n^{i1} - c_n)q_n^{i1}. \quad (1)$$

And, the optimization problem for the IR can be formulated as follows:

$$\begin{aligned} \max \pi_r^{i1}(q_r^{i1}) &= (p_r^{i1} - c_r)q_r^{i1}, \\ \text{s.t.}, q_r^{i1} &\leq \tau q_n^{i1}. \end{aligned} \quad (2)$$

The following proposition characterizes the optimal production quantities of the new and remanufactured products for the OEM and the IR in response to different cost advantages of the remanufactured product.

Proposition 1. *The optimal production quantities of the new and remanufactured products for the OEM and the IR in scenario 1 can be characterized as follows:*

- (i) *When $r > \delta(1 + c_n)/2c_n$, the IR will adopt the no-remanufacturing strategy and the optimal production quantities of the new and remanufactured products for the IR and the OEM are $q_r^{i1} = 0$ and $q_n^{i1} = (1 + c_n)/2$, respectively.*
- (ii) *When $\delta(1 + c_n)/(2c_n) - ((-1 + c_n)\delta\tau(-4(1 + \phi) + \delta(4 + \phi)))/(2c_n(2 + \delta\tau)\phi) < r < \delta(1 + c_n)/(2c_n)$, the IR will adopt the partial remanufacturing strategy, i.e., $0 < q_r^{21} < \tau q_n^{21}$, and the optimal production quantities of the new and remanufactured products for the IR and the OEM are, respectively, as follows:*

$$\begin{aligned} q_r^{21} &= \frac{(\delta + c_n(-2r + \delta))\phi}{\delta(-4(1 + \phi) + \delta(4 + \phi))}, \\ q_n^{21} &= \frac{-2(1 + \phi) + \delta(2 + \phi) + c_n(2 - 2\delta + 2\phi - r\phi)}{-4(1 + \phi) + \delta(4 + \phi)}. \end{aligned} \quad (3)$$

- (iii) *When $r < \delta(1 + c_n)/(2c_n) - ((-1 + c_n)\delta\tau(-4(1 + \phi) + \delta(4 + \phi)))/(2c_n(2 + \delta\tau)\phi)$, the IR will adopt the full-remanufacturing strategy, i.e., $q_r^{31} = \tau q_n^{31}$, and the optimal production quantities of the new and remanufactured products for the IR and the OEM are, respectively, given by $q_r^{31} = \tau(1 - c_n)/(2 + \delta\tau)$ and $q_n^{31} = (1 - c_n)/(2 + \delta\tau)$.*

4.2. Scenario 2: Analysis of the Model with CCT. In this section, we will conduct the analysis for the model with CCT. For this case, the optimization problem for the OEM can be formulated as

$$\max \pi_n^{i2}(q_n^{i2}) = (p_n^{i2} - c_n - ct_n)q_n^{i2}. \quad (4)$$

And, the optimization problem for the IR can be formulated as follows:

$$\begin{aligned} \max \pi_r^{i2}(q_r^{i2}) &= (p_r^{i2} - c_r - c\omega t_n)q_r^{i2}, \\ \text{s.t.}, q_r^{i2} &\leq \tau q_n^{i2}. \end{aligned} \quad (5)$$

The following proposition characterizes the optimal production decisions for the OEM and the IR in the model with CCT.

Proposition 2. *The optimal production quantities of the new and remanufactured products for the OEM and the IR in scenario 2 can be characterized as follows:*

TABLE 1: Model notations.

Notations	Definitions
p_n^{ij}/p_r^{ij}	Price of the new/remanufactured product.
q_n^{ij}/q_r^{ij}	Demand for the new/remanufactured product, where $i = 1/2/3$ stands for no/partial/full remanufacturing and $j = 1, 2$ stands for the model without and with CCT, respectively.
$\phi/1 - \phi$	Ratio of the functionality-oriented consumers (FOCs)/the newness-conscious consumers (NCCs).
θ'/θ	The NCCs' willingness to pay (WTP) for each unit's new/remanufactured product.
$\theta/\delta\theta$	The FOCs' WTP for each unit new/remanufactured product, where $\delta \in (0, 1)$ indicates the discount factor of the FOCs' WTP for each unit remanufactured product.
π_n^{ij}/π_r^{ij}	Profit of the OEM/IR.
c_n/rc_n	Production cost per unit of the new/remanufactured product, where $r \in (0, 1)$ indicates the cost saving for the remanufactured product.
c	The unit price of the carbon trading.
g_n/g_r	Allocated carbon allowance per unit of new/remanufactured product.
e_n/e_r	Carbon emissions per unit of new/remanufactured product.
$t_n/\omega t_n$	The carbon trading volume of the OEM/IR, where $\omega < 1$ indicates the saving of the carbon emission for the remanufactured product.
τ	Collection ratio, where $\tau \in (0, 1)$.

- (i) When $r > (\delta(1 + c_n) + ct_n(\delta - 2\omega))/(2c_n)$, the IR will adopt the no-remanufacturing strategy and the optimal production quantities of the new and remanufactured products for the IR and the OEM are given, respectively, by $q_r^{12} = 0$ and $q_n^{12} = (1 - c_n)/2$.
- (ii) When $(\delta(1 + c_n) + ct_n(\delta - 2\omega))/(2c_n) - (-1 + c_n)\delta\tau / (-4(1 + \phi) + \delta(4 + \phi)) / (2c_n(2 + \delta\tau)\phi) < r < (\delta(1 +$

$c_n) + ct_n(\delta - 2\omega))/(2c_n)$, the IR will adopt the partial remanufacturing strategy, i.e., $0 < q_r^{22} < \tau q_n^{22}$, and the optimal production quantities of the new and remanufactured products for the IR and the OEM are as follows:

$$q_r^{22} = \frac{(\delta + c_n(-2r + \delta))\phi + ct_n(\delta - 2\omega)}{\delta(-4(1 + \phi) + \delta(4 + \phi))},$$

$$q_n^{22} = \frac{-2(1 + \phi) + \delta(2 + \phi) + c_n(2 - 2\delta + 2\phi - r\phi) + ct_n(2 - 2\delta + 2\phi - \phi\omega)}{-4(1 + \phi) + \delta(4 + \phi)}. \quad (6)$$

- (iii) When $r < (\delta(1 + c_n) + ct_n(\delta - 2\omega))/(2c_n) - (-1 + c_n)\delta\tau / (-4(1 + \phi) + \delta(4 + \phi)) / (2c_n(2 + \delta\tau)\phi)$, the IR will adopt the full remanufacturing strategy, i.e., $q_r^{32} = \tau q_n^{32}$, and the optimal production quantities of the new and remanufactured products for the IR and the OEM are given, respectively, by $q_r^{32} = \tau(1 - c_n - ct_n) / (2 + \delta\tau)$ and $q_n^{32} = (1 - c_n - ct_n) / (2 + \delta\tau)$.

$\delta > 2rc_n / (1 + c_n)$, $\delta/2 < \omega < \omega_2$, and $\omega_3 < \omega < \omega_1$, the IR's profit without CCT is higher than that with CCT, where $\omega_1 = (\delta(1 + ct_n) + c_n(\delta - 2r)) / (2ct_n) - (-1 + c_n + ct_n)t / (-4(1 + \phi) + \delta(4 + \phi)) / (2ct_n(-2 + \tau))$ and $\omega_2 = (\delta(1 + ct_n) + c_n(\delta - 2r)) / (2ct_n)$.

5. Effects of the CCT and the Low-Carbon Consumers

In this section, we conduct an analysis on the effects of the CCT based on the optimal decisions of the production quantity in response to different cost advantages of the remanufactured products. The main results are summarized in the following proposition.

5.1. Effects of CCT on the Profit of the IR

Proposition 3. (i) When $\delta < 2rc_n / (1 + c_n)$ and $\omega < \omega_2$ or when $\delta > 2rc_n / (1 + c_n)$, $\omega_1 < \omega < \delta/2$ and $\omega < \omega_3$, the IR's profit without CCT is lower than that with CCT. (ii) When

Figure 1(a) and 1(b) exhibit the results graphically in Proposition 3. The curve indicates the range in which the CCT policy will increase the IR's profit, and the thick line indicates the range in which the CCT policy will reduce the IR's profit. If $\delta < 2rc_n / (1 + c_n)$, as long as the IR enters the remanufacturing market, the CCT policy will help the IR increase profit. Actually, $\delta > 2rc_n / (1 + c_n)$ implies that the remanufacturing cost-saving factor satisfies $r < \delta(1 + c_n) / (2c_n)$, and for this case, the CCT can always increase the profit of the IR, regardless of the remanufacturing carbon cost.

If $\delta < 2rc_n / (1 + c_n)$, the CCT can increase the IR's profits for the small values of ω . Actually, $\delta < 2rc_n / (1 + c_n)$ implies that the remanufacturing cost-saving factor satisfies $r > \delta(1 + c_n) / (2c_n)$. And, when r is relatively large, the unit production cost of the remanufactured product is lower than that of the unit new product. As this is the case,

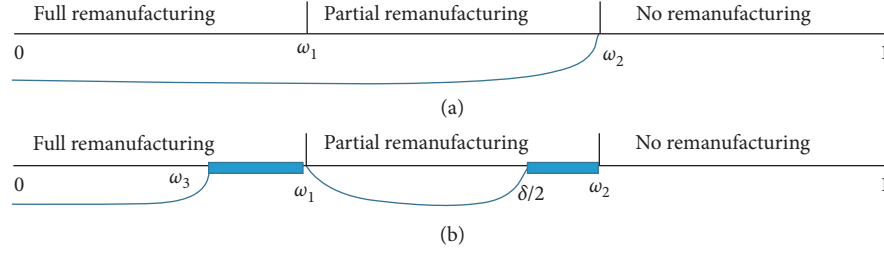


FIGURE 1: (a) Effects of CCT on the profit of the IR with $\delta < 2rc_n/(1 + c_n)$. (b) Effects of CCT on the profit of the IR with $\delta > 2rc_n/(1 + c_n)$.

the carbon cost will increase the cost of the remanufactured products with the implementation of CCT. Only when the carbon cost of the remanufactured product is lower than that of the new product, CCT can increase the IR's profit. When the carbon cost of the new products is lower than that of the remanufactured products, CCT will reduce the profit of the IR. Therefore, when δ is relatively low, an excessive increase of the discount factor of the remanufacturing products can do harm to the positive effects of CCT on the IR and the remanufacturing market. That is, the effects of CCT and consumers' low-carbon awareness can be trading off sometimes on the remanufacturing system, and in this case, an excessive cultivation of consumers' low-carbon awareness will weaken the beneficial effects of CCT on the remanufacturing system due to the resulted excessive consumers' WTP for the remanufactured products.

5.2. Sensitivity Analysis of the CCT

Proposition 4

- (i) For the case of partial remanufacturing, it is derived that $\partial\pi_r/\partial\omega > 0$, and if $\omega < \min\{\delta/2, \omega_2\}$, then $\partial\pi_r/\partial c > 0$, $\partial\pi_r/\partial t_n > 0$; if $\delta > 2rc_n/(1 + c_n)$ and $\delta/2 < \omega < \omega_2$, then $\partial\pi_r/\partial c > 0$ and $\partial\pi_r/\partial t_n < 0$
- (ii) For the case of full remanufacturing, it is derived that $\partial\pi_r/\partial\omega < 0$, and if $\omega < \omega_3$, then $\partial\pi_r/\partial c > 0$ and $\partial\pi_r/\partial t_n > 0$; if $\omega > \omega_3$, then $\partial\pi_r/\partial c < 0$ and $\partial\pi_r/\partial t_n < 0$, where $\omega_3 = (-2c_n r \phi + \delta^2 \tau (2 - 2c_n - ct_n + \phi) + \delta((2c_n + ct_n)\phi + (-2 + ct_n)\tau(1 + \phi) + c_n \tau(2 - (-2 + r)\phi)))/((-1 + c_n + ct_n)(2 + \delta\tau)\phi)$.

The results in Proposition 4 can be exhibited by Figures 1(a) and 1(b). To be specific, when $\delta < 2rc_n/(1 + c_n)$, as long as the IR enters the remanufacturing market, an increase in c and t_n will lead to an increase in profit. Actually, when δ is relatively small, it implies that r is relatively large. Therefore, the cost of the remanufactured products is relatively high and the remanufactured product has a relatively small cost advantage relative to the new product. It can be explained in a similar way for the case of $\delta > 2rc_n/(1 + c_n)$. Similar to Proposition 3, if the FOCs' WTP for the remanufactured products is too high, it will do harm to the synergistic effects between the low-carbon awareness cultivation and the CCT policy.

5.3. Sensitivity Analysis of the Ratio of Consumers

Proposition 5. For the case of partial remanufacturing, it is derived that $\partial\pi_r/\partial\phi > 0$, and for the case of full remanufacturing, it is derived that $\partial\pi_r/\partial\phi > 0$.

The results in Proposition 5 show that an increase in the proportion of the FOCs will lead to an increase in the profit with the partial and full remanufacturing scenarios. Given the important role of consumers' low-carbon awareness cultivation in increasing the functional consumers, it can be seen that the cultivation of consumers' low-carbon awareness is beneficial to the profit of the IR. Even so, it should be noted that an excessive cultivation of consumers' low-carbon awareness can sometimes weaken the beneficial effects of CCT on the remanufacturing system. As a result, it is necessary to balance the effects of the CCT and the cultivation of consumers' low-carbon awareness on the remanufacturing system.

6. Conclusion

This paper examines a remanufacturing system with competition between the OEM and the IR. We have developed a model analysis for the effects of the CCT policy and the consumers' low-carbon awareness on the remanufacturing system and have examined the optimal decisions for the remanufacturing system in the presence of carbon cap and trade policy and low-carbon consumers. A particularly interesting result derived from the studies is that the CCT and the consumers' low-carbon awareness can have a trading-off effect sometimes on the remanufacturing system. Therefore, it is necessary to conduct an appropriate cultivation on the low-carbon awareness of consumers in the remanufacturing system in the presence of CCT policy. In the conclusion, it should be pointed out that there exist some limitations for this study and these limitations can inspire some topics for future research. For example, it is assumed in the model that the OEM does not engage in remanufacturing. Actually, it is common in reality that the OEM participates in the competition of remanufacturing market. Hence, it is worthwhile to extend the model to consider that the OEM produces both the new and remanufactured products at the same time. In addition, it should be noted that after-sales services associated with the remanufactured products are usually different from those associated with the new products. Hence, it is also significant to extend the model to consider the effects of after-sales services on the remanufacturing system.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Authors' Contributions

Xiaoge Meng, Shushu Xie, and Yingxue Zhao contributed to model development and analysis. Xiaoge Meng, Shushu Xie, and Menghao Xi contributed to basic writing of the paper. Shushu Xie is responsible for conducting the research.

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