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Analysis of Environmental Policy's Impact on Remanufacturing Decision Under the Effect of Green Network Using Differential Game Model

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ABSTRACT Consumers' environmental protection awareness promotes the quality of green products produced by remanufacturers, which requires higher input cost and more efforts but wins environmental reputation in return. In order to encourage remanufacturers to produce products with less pollution, government enacts environmental policy to subsidy the production of remanufacturing. This paper aims to analyze the impact of subsidy on remanufacturing decision and identify the optimal decisions under the effect of green network using a differential game model. First, both government and remanufacturer's cost functions are established with their own environmental effort, respectively. Then, their benefit functions are built to represent their own reward, in which multiple factors are taken into account including but not limited to the environmental reputation of remanufacturer and consumers' demand for remanufactured products. Using the models of Nash-non cooperative game, Stackelberg master-slave game and cooperative game, their benefits are calculated and compared. The equilibrium results show that the improvement level of products' environmental quality is equal to the level of subsidies, and subsidies will increase with the improvement of products' environmental quality. In addition, with the support of the government, remanufactures are able to produce the most environmentally friendly products with the most benefit. Finally, a case study is given to prove the theorems obtained in this paper.

INDEX TERMS Remanufacturer, environmental policy, government subsidy, green network, differential game model.

I. INTRODUCTION

In the recent years, the market share of environmental products have been constantly growing with the shortage of resources and the aggravation of environmental pollution problems [1]. At the same time, enterprises' awareness of environmental protection has been gradually enhanced. As for remanufacturers whose work involves parts recycling, the production-batch disassembly, restoration to like-new condition and reassembly of used products, they offers significant environmental benefits by retaining the energy, as well as material, embodied in the product during original

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manufacture, while diverting solid waste from landfills [2]. They aim to develop more environmental products or techniques to reduce pollution, which requires more cost in development. As a key means to achieve the coordinated development of environmental protection and economic development, green product innovation is still in the lead-in period in China; since it is difficult to achieve rapid development only by relying on market forces, it needs government intervention and regulation [3]. Therefore, it is necessary for government to take some financial measures, including but not limited to environmental taxes, subsidies, to encourage remanufacturers to shoulder the responsibility of recycling waste products [4]–[8] and remanufacturing [9]–[12]. Besides, the necessity of environmental protection and green purchase behavior is addressed by the increasing consumers [13]. According to a survey from Brecard [1], 83% of Europeans pay great attention to the impact of products on the environment when they buy products, and 75% are ''more willing to buy environmentally-friendly products, even if they are slightly more expensive''. With consumers' preference for green productions, remanufacturers and the government are supposed to spare no efforts on environmental protection during manufacturing process.

Green network effect refers to the impact of consumers' green payment preferences on green purchase in low-carbon environment [14]. According to this definition, Grilo *et al.* [15] formalized the impact of consumer vanity and consumer herd mentality on product differentiation and competition among consumers. In addition, the European Commission (2008) stressed that under the green network effect, if the price of green products is the same as that of high pollution products, most consumers will turn to green products. Under this assumption, Brecard [1] points out that ''green network effect'' has a considerable impact on the environmental quality and price competition of enterprises. Wang *et al.* [12] analyzed the effects of consumer green preference on enterprises' optimal decisions and found that consumer green preference significantly influences the product green level of the manufacturer and the supplier and has intricate effects on the speed of the adjustment of the boundedly rational supply chain which directly affects the social stability. In the sense of remanufacturing, public environmental protection consciousness on the products of an enterprise is described by the expectation of used product collection and remanufacturing rate, and customer demand sensitivity to environmental impact of the products. Based on this, Qiao *et al.* [16] developed a model to analyze the impact of public environmental consciousness on an enterprise's remanufacturing decision. It is found that an enterprise's remanufacturing rate would increase with increasing of demand sensitivity, resulting in the reverse logistics. It can be seen that public environmental protection consciousness has a great impact on the products manufacturing.

Due to the increasing environmental pollution, the government plays a more and more important role in the production of enterprises. The high-quality development of the environmental protection industry requires the support of the corresponding industrial policy system [17]. Based on the existence of consumer awareness of environmental protection, Bransal *et al.* [18], [19] considered two policies of government taxes and subsidies to encourage manufacturers to deploy green production strategies. On this basis, Krass *et al.* [5] studied several important aspects, including the use of environmental taxes to stimulate innovation and the choice of ''green'' emission reduction technologies, as well as the role of fixed cost subsidies and consumption tax rebates. In order to curb carbon emissions and maintain sustainable economic development, Miao *et al.* [8] solved the issue of remanufacturing discount trading under carbon tax, carbon quota and trading and other carbon emission regulations and government subsidy mechanism, resulting in the reduction of total emissions. Song *et al.* [3] analyzed the effect of environmental regulation and R&D tax incentives on green product innovation from a disciplinary and incentive perspective, which not only identified the determinants of green product innovation but also provide a theoretical and decision-making framework for the industrial development and promotion of green product innovation in China. With consumers' preference on green productions, remanufacturers and the government are supposed to spare no efforts on environmental protection during manufacturing process.

This paper aims to analyze the impact of environmental policy on remanufacturing decision under the effect of green network using differential game model, which has the basis of previous researches. Zhen *et al.* [20] established a two-stage game model for the government's optimal price subsidy. It found that government subsidy efectively stimulates the demand for remanufactured products, reduces the price of both new and remanufactured products, and promotes the remanufacturing industry. Wei *et al.* [21] considered a two-period competition model of a remanufacturing supply chain consisting of three members: a new product manufacturer, a recycler and a remanufacturer. With consumer awareness of environmental protection taken into account, the effects of government subsidy and tax and their asymmetric use on manufacturers' and remanufacturers' decision-making variables and competitive performance have been analyzed. Song *et al.* [22] considered the recycling of used products for environmental sustainability and took into account profit donation as a corporate social responsibility (CSR) investment. Based on Stackelberg Game analysis, the results showed that government subsidy is not only conducive to expanding market demand and increasing waste recycling rates, but also to improving CSR investment levels. Zhao *et al.* [23] set up a decision-making model with considering both consumers' environmental preference and the subsidy policy, which concluded that if a remanufacturer shares a percentage of the subsidy with consumers, it can get more profit due to the increased market. Yu *et al.* [24] developed an optimization model under oligopolistic competition considering green preferences and subsidies, with the objective of profit maximization for the manufacturers.

Numerical results showed that an increase of consumer environmental awareness will incentivize manufacturers to produce more green products with higher green levels, and a well-designed subsidy policy can not only generate more profits for manufacturers, but also save subsidy investment for the government. However, this paper considers a government system and a remanufacturer as two players in the game and compares the decision making in different situations, which is from a distinctive perspective.

This paper uses differential game model which pays attention to the dynamic impact of time on the research objects. Some researchers have applied differential game model to many fields. Gao *et al.* [25] used differential game model to study the ecological compensation mechanism of the river basin in 2019. In the same year, Xu and Han [26] used differential game model to provide theoretical reference for supply chain cooperative emission reduction and government subsidy strategies. Wang *et al.* [27] used differential game model to explore government-enterprise cooperation disaster relief strategies in 2018. Zhao *et al.* [28] used differential game model to study the technology sharing in the system in the field of military-civilian integration and collaborative innovation in 2017. However, few studies have applied the differential game model on the field of remanufacturing.

Based on the previous work, this paper focuses on the impact of environmental policy on remanufacturing decision under the effect of green network, in which a differential game model is presented to formulate the dynamics of the effort and reward of both government and remanufacturer. Then their computational results in the three models of Nash-non cooperative game, Stackelberg master-slave game and cooperative game can be calculated. By comparing their results we can obtain the optimal remanufacturing decision, which also demonstrates the superiority of the environmental policy on remanufacturing. In addition, some factors influencing the efforts and rewards of government and remanufacturer are also discussed.

The remainder of the paper is organized as follows. In Section 2, the problem statement and model formulation are given in detail. In Section 3, the decisions and benefits of remanufacturer and government are discussed using three models of Nash-non cooperative game, Starkelberg game and cooperative game. Section 4 gives a comparative analysis of equilibrium results. In Section 5, a case study is given to verify the theorems obtained in this paper. At last, a summary is made in Section 6.

II. PROBLEM STATEMENT AND MODEL FORMULATION

A. PROBLEM STATEMENT

In this study, the government and a remanufacturing enterprise are taken as the research object to explore the impact of government enterprise cooperation on remanufacturing enterprise's production strategy and revenue under the green network effect (for short GNE). Government enterprise cooperation can bring environmental protection subsidy to remanufacturers, whose purpose is to improve the production cost of remanufacturers and environmental protection quality of products, so as to achieve the effect of environmental protection. Independent of government development, remanufacturer will reduce production costs due to lack of subsidies, and the environmental protection quality of its products will also decline. At the same time, the level of product environmental protection quality will cause the impact of GNE on remanufacturer's revenue. Consumers will pay more attention to the products with high environmental protection quality. The decision-making process is as follows. First, the government decides its own environmental protection subsidies to remanufacturers. Second, remanufacturers decide their own environmental protection efforts (for short EPE) to produce products. In this process, the government's benefit function includes two parts. One is the social benefits brought by manufacturing enterprises' active participation in digital twin technology to promote the development of China's manufacturing industry. The other is the change of consumer demand caused by the GNE of remanufacturer's behavior, thus promoting the government's tax gain. Figure 1 depicts the decision process.

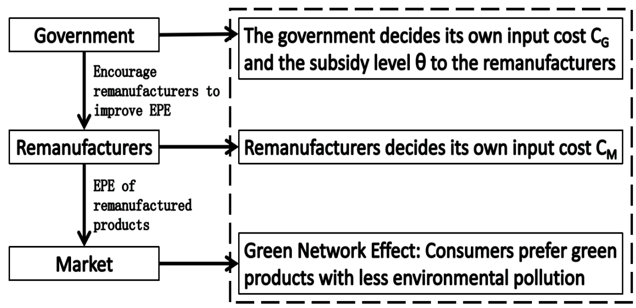

FIGURE 1. Game decision diagram of government and enterprise.

B. DIFFERENTIAL GAME MODEL FORMULATION

1) ASSUMPTION 1

The cost invested by the government and enterprises in the production of remanufactured products is related to the EPE. Considering the convexity of the cost, the cost [28], [29] invested by the government and enterprises in the remanufactured products at time t is respectively

$$C_G(t) = \frac{1}{2}k_G E_G^2(t),\ C_M(t) = \frac{1}{2}k_M E_M^2(t)$$

Let $C_G(t), C_M(t)$ respectively represent the input cost of the government and the enterprise at time t. Let $k_G, k_M \geq 0$ denote the input cost coefficient of the government and the enterprise. Let $E_G(t), E_M(t) \geq 0$ denote the environmental protection intensity of the government and the enterprise for the production of remanufactured products at time t.

2) ASSUMPTION 2

In order to encourage the remanufacturer to increase input costs to produce green products, the government will provide environmental protection subsidies to them. Let $\theta(t)$ represent the proportion of costs which the government will share for enterprise, $\theta(t) \in [0, 1]$.

3) ASSUMPTION 3

Due to the consideration of GNE and the consumers' preferences of greater EPE products, the environmental reputation of enterprises will be affected by the EPE of enterprises' own investment in remanufactured products production and the EPE of government investment. And it will form a continuous and dynamic impact process. The dynamic equation of Nerlove-Arrow goodwill model is adopted, and the differential equation of environmental reputation change of enterprises $L(t)$ can be expressed as

$$\frac{dL(t)}{dt} = \alpha E_G(t) + \beta E_M(t) - \delta L(t), L(0) = L_0 \tag{1}$$

L_0 denotes the environmental reputation of the enterprise at the initial moment. Let $\alpha, \beta > 0$ respectively represent the influence coefficient of the EPE invested by the government and the enterprise in the remanufacturing process on the environmental reputation of the enterprise. Let $\delta > 0$ represent the decay rate of the environmental reputation of the enterprise over time due to different external factors.

4) ASSUMPTION 4

Assuming that the purchase behavior of consumers is affected by the EPE, reputation and price of remanufactured products invested by the government and the enterprise, the demand function of consumers for remanufactured products can be expressed as

$$D(t) = \mu_1 E_G(t) + \mu_2 E_M(t) + \nu L(t) - \varphi P(t) \tag{2}$$

Let μ_1, μ_2 respectively represent the influence coefficient of the EPE invested by the government and the enterprise on the consumer demand. ν denotes the influence coefficient of the environmental protection reputation of the enterprise on the consumer demand. φ denotes the influence coefficient of the product price on the consumer demand. Let $P(t)$ represent the price of the remanufactured product at the current time.

Let ρ represent the same positive discount rate of the government and the enterprise. They seek the goal of maximizing their own interests in an unlimited time range. Among them, the objective function of the government is the sum of the social benefits affected by the EPE invested by the enterprises and the marginal benefits generated by their own investment, minus the cost of investment and subsidies. The objective function of an enterprise is directly obtained by subtracting the input cost from the marginal income generated by its own input. Then the objective functions of government and enterprise can be expressed as

$$\max_{E_G,\theta} J_G = \int_0^{\infty} e^{-\rho t} \left[\lambda_0 E_M(t) + \lambda_1 D(t) - C_G(t) - \theta(t) C_M(t)\right] dt \tag{3}$$

$$\max_{E_M} J_M = \int_0^{\infty} e^{-\rho t} \left[\lambda_2 D(t) - (1-\theta(t)) C_M(t)\right] dt \tag{4}$$

$\lambda_0 > 0$ denotes the influence coefficient of EPE invested by enterprises for production on social benefits. $\lambda_1, \lambda_2 > 0$ respectively denotes the marginal income coefficient of government and enterprises.

In this paper, government and a remanufacturer, as two players, launch differential games. Due to the existence of dynamic parameters in differential games, it is difficult to solve them. Therefore, the parameters in the model are assumed to be time independent constants [29], [30]. The variables in the paper $E(t), D(t), C(t), \theta(t), L(t), P(t)$ are respectively simplified as E, D, C, θ, L, P.

For ease of understanding, most of the notations mentioned in this paper are shown in the table 1.

III. MODEL ANALYSIS

A. NASH NON COOPERATIVE GAME MODEL

In the Nash-non cooperative game model, the government and the enterprise develop independently and decide their own EPE for the remanufactured product production investment independently. And the government does not provide environmental protection subsidies to the enterprise, which means $\theta = 0$. In this case, the objective function of government and enterprise can be expressed as

$$\max_{E_G} J_G^N = \int_0^{\infty} e^{-\rho t} \left[\lambda_0 E_M + \lambda_1 D - C_G\right] dt \tag{5}$$

$$\max_{E_M} J_M^N = \int_0^{\infty} e^{-\rho t} \left[\lambda_2 D - C_M\right] dt \tag{6}$$

Theorem 1: In the case of Nash-non cooperative game, in order to maximize the interests of both parties, the optimal EPE invested by the government and enterprises for remanufactured product production should be

$$E_G^{N*} = \frac{\mu_1 \lambda_1 (\rho + \delta) + \alpha \lambda_1 \nu}{(\rho + \delta) k_G} \tag{7}$$

$$E_M^{N*} = \frac{\mu_2 \lambda_2 (\rho + \delta) + \beta \lambda_2 \nu}{(\rho + \delta) k_M} \tag{8}$$

Prove: According to Bellman's continuous dynamic programming theory, continuous bounded revenue function $V_G(L)$, $V_M(L)$, for any $L \geq 0$, must satisfy Hamilton-Jacobi-Bellman (for short HJB) equation

$$\rho V_G^N = \max_{E_G} \left\{ \lambda_0 E_M + \lambda_1 D - C_G + \frac{\partial V_G^N}{\partial L} (\alpha E_G + \beta E_M - \delta L) \right\} \tag{9}$$

$$\rho V_M^N = \max_{E_M} \left\{ \lambda_2 D - C_M + \frac{\partial V_M^N}{\partial L} (\alpha E_G + \beta E_M - \delta L) \right\} \tag{10}$$

TABLE 1. Notation declaration.

Notation	Meaning
$C_G(t)$	the input cost of the government
$C_M(t)$	the input cost of the enterprise
$E_G(t)$	the environmental protection intensity of the government
$E_M(t)$	the environmental protection intensity of the enterprise
k_G	the input cost coefficient of the government
k_M	the input cost coefficient of the enterprise
$\theta(t)$	the proportion of government subsidies
$L(t)$	the environmental reputation of the enterprise
α	the influence coefficient of the EPE invested by the government on the environmental reputation of the enterprise
β	the influence coefficient of the EPE invested by the enterprise on the environmental reputation of the enterprise
δ	the decay rate of the environmental reputation of the enterprise
μ_1	the influence coefficient of the EPE invested by the government on the consumer demand
μ_2	the influence coefficient of the EPE invested by the enterprise on the consumer demand
v	the influence coefficient of the environmental protection reputation of the enterprise on the consumer demand
φ	the influence coefficient of the product price on the consumer demand
$P(t)$	the price of the remanufactured product
$D(t)$	the demand function of
	consumers for remanufactured products
ρ	the same positive discount rate of the government and the enterprise
λ_0	the influence coefficient of EPE invested by the enterprise for production on social benefits
λ_1	the marginal income coefficient of the government
λ_2	the marginal income coefficient of the enterprise
$V_G(L)$	the benefits of the government
$V_M(L)$	the benefits of the enterprise

To solve the right end of HJB equation, the condition to maximize it is to find the first-order partial derivative for equation (9). Find the first-order partial derivative of E_M for equation (10), and make it zero, which can be obtained

$$E_G = \frac{\mu_1\lambda_1 + \alpha V_G'^N}{k_G}, E_M = \frac{\mu_2\lambda_2 + \beta V_M'^N}{k_M} \tag{11}$$

where $\frac{\partial V_G^N}{\partial L} = V_G'^N$, $\frac{\partial V_M^N}{\partial L} = V_M'^N$, substitute (11) into formula (9) and formula (10), we can get

$$\begin{aligned}\rho V_G^N &= \left(\lambda_1 v - \delta V_G'^N\right) L \\ &+ \frac{\left(\lambda_0 + \mu_2\lambda_1 + \beta V_G'^N\right)\left(\mu_2\lambda_2 + \beta V_M'^N\right)}{k_M} \\ &+ \frac{\left(\mu_1\lambda_1 + \alpha V_G'^N\right)^2}{2k_G} - \lambda_1\varphi P \end{aligned}\tag{12}$$

$$\begin{aligned}\rho V_M^N &= \left(\lambda_2 v - \delta V_M'^N\right) L + \frac{\left(\mu_2\lambda_2 + \beta V_M'^N\right)^2}{2k_M} \\ &+ \frac{\left(\mu_1\lambda_1 + \alpha V_G'^N\right)\left(\mu_1\lambda_2 + \alpha V_M'^N\right)}{k_G} - \lambda_2\varphi P \end{aligned}\tag{13}$$

From the structure of formula (12) and formula (13), it can be seen that the univariate primary function formula with L as the independent variable is the solution of HJB equation, satisfying

$$V_G^N(L) = f_1 L + f_2, V_M^N(L) = g_1 L + g_2 \tag{14}$$

where f_1, f_2, g_1, g_2 are the constants to be solved, we can get

$$V_G'^N(L) = \frac{dV_G^N(L)}{dL} = f_1 , \quad V_M'^N(L) = \frac{dV_M^N(L)}{dL} = g_1 \tag{15}$$

Substituting equations (14), (15) into equations (12), (13), we can get

$$\begin{aligned}\rho(f_1 L + f_2) &= (\lambda_1 v - \delta f_1) L \\ &+ \frac{(\lambda_0 + \mu_2\lambda_1 + \beta f_1)(\mu_2\lambda_2 + \beta g_1)}{k_M} \\ &+ \frac{(\mu_1\lambda_1 + \alpha f_1)^2}{2k_G} - \lambda_1\varphi P \end{aligned}\tag{16}$$

$$\begin{aligned}\rho(g_1 L + g_2) &= (\lambda_2 v - \delta g_1) L \\ &+ \frac{(\mu_1\lambda_1 + \alpha f_1)(\mu_1\lambda_2 + \alpha g_1)}{k_G} \\ &+ \frac{(\mu_2\lambda_2 + \beta g_1)^2}{2k_M} - \lambda_2\varphi P \end{aligned}\tag{17}$$

It can be seen from the previous assumption that all $L \geq 0$ should be satisfied with $V_G(L)$, $V_M(L)$, so the values that can be obtained from f_1, f_2, g_1, g_2 are

$$\begin{cases} f_1 = \dfrac{\lambda_1 v}{\rho + \delta} \\ f_2 = \dfrac{[(\rho+\delta)\mu_1\lambda_1 + \lambda_1 v\alpha]^2}{2k_G\rho(\rho+\delta)^2} \\ \quad + \dfrac{[(\lambda_0 + \mu_2\lambda_1)(\rho+\delta) + \beta\lambda_1 v][\mu_2\lambda_2(\rho+\delta) + \beta\lambda_2 v]}{k_M\rho(\rho+\delta)^2} \\ \quad - \dfrac{\lambda_1\varphi P}{\rho} \end{cases}$$

$$\begin{cases} g_1 = \dfrac{\lambda_2 \nu}{\rho+\delta} \\ g_2 = \dfrac{[(\rho+\delta)\mu_1\lambda_1+\lambda_1\nu\alpha][(\rho+\delta)\mu_1\lambda_2+\lambda_2\nu\alpha]}{k_G\rho(\rho+\delta)^2} \\ \quad +\dfrac{[\mu_2\lambda_2(\rho+\delta)+\beta\lambda_2\nu]^2}{2k_M\rho(\rho+\delta)^2} - \frac{\lambda_2\varphi P}{\rho} \end{cases}$$

Substituting f_1, g_1 into equation (11) can respectively obtain the optimal EPE invested by the government and enterprises for remanufactured product production, as shown in equation (7), equation (8). By substituting f_1, f_2, g_1, g_2 into equation (14), the expression of the optimal revenue function of government and manufacturing enterprise can be obtained respectively

$$V_M^{N*} = \frac{\lambda_2\nu}{\rho+\delta}L + \frac{[(\rho+\delta)\mu_1\lambda_1+\lambda_1\nu\alpha][(\rho+\delta)\mu_1\lambda_2+\lambda_2\nu\alpha]}{k_G\rho(\rho+\delta)^2} + \frac{[\mu_2\lambda_2(\rho+\delta)+\beta\lambda_2\nu]^2}{2k_M\rho(\rho+\delta)^2} - \frac{\lambda_2\varphi P}{\rho} \tag{18}$$

$$V_G^{N*} = \frac{\lambda_1\nu}{\rho+\delta}L + \frac{[(\rho+\delta)(\lambda_0+\mu_2\lambda_1)+\lambda_1\nu\beta][(\rho+\delta)\mu_2\lambda_2+\lambda_2\nu\beta]}{k_M\rho(\rho+\delta)^2} + \frac{[\mu_1\lambda_1(\rho+\delta)+\alpha\lambda_1\nu]^2}{2k_G\rho(\rho+\delta)^2} - \frac{\lambda_1\varphi P}{\rho} \tag{19}$$

B. STACKELBERG MASTER-SLAVE GAME MODEL

In Stackelberg master-slave game model, in order to encourage remanufacturers to achieve green manufacturing, the government actively provides environmental protection subsidies for remanufacturers. So the government can be regarded as the leading Party in the game, and the enterprise can be regarded as the follower. In this case, the government will take the maximization of its own interests as the goal, preferentially determine its share proportion of the production cost of the enterprise, and then determine the optimal EPE invested in the production of remanufactured products. The enterprise will determine the optimal EPE invested in the production of remanufactured products based on the environmental protection subsidies provided by the government and the maximization of its own interests as the goal. Assuming that the government and the enterprise both have the optimal EPE, the revenue function $V_G(L)$, $V_M(L)$, and are continuously bounded and differentiable, all $L \geq 0$ must satisfy the HJB equation.

Theorem 2: In Stackelberg master-slave game model, in order to maximize the interests of both sides, the optimal EPE invested by the government and the enterprise for remanufactured products production and the optimal environmental protection subsidy from the government to the enterprise should be

$$E_G^{D*} = \frac{\mu_1\lambda_1(\rho+\delta)+\alpha\lambda_1\nu}{(\rho+\delta)k_G} \tag{20}$$

$$E_M^{D*} = \frac{(2\lambda_0+2\mu_2\lambda_1+\mu_2\lambda_2)(\rho+\delta)+(2\lambda_1+\lambda_2)\nu\beta}{2(\rho+\delta)k_M} \tag{21}$$

$$\theta^* = \frac{2\lambda_0+(2\lambda_1-\lambda_2)\left(\mu_2+\frac{\beta\nu}{\rho+\delta}\right)}{2\lambda_0+(2\lambda_1+\lambda_2)\left(\mu_2+\frac{\beta\nu}{\rho+\delta}\right)} \tag{22}$$

Prove: By using the reverse induction method, the optimal objective function of the enterprise is solved firstly. The HJB equation of its optimal objective function is

$$\rho V_M^D = \max_{E_M}\left\{\lambda_2 D-(1-\theta)C_M+\frac{\partial V_M^D}{\partial L}(\alpha E_G+\beta E_M-\delta L)\right\} \tag{23}$$

To solve the right end of HJB equation, the condition to maximize it is to find the first partial derivative of equation (23) for E_M, and make it zero. The solution can obtain

$$E_M = \frac{\mu_2\lambda_2+\beta V_M'^D}{(1-\theta)k_M} \tag{24}$$

According to equation (24), the enterprise will determine its EPE E_M for the production input of remanufactured products. The government will determine its environmental protection intensity and the proportion of environmental protection subsidies for the production input of remanufactured products based on the rational decision of the enterprise, so as to maximize its own interests. In this case, the HJB equation of the optimal objective function of the government is

$$\rho V_G^D = \max_{E_G,\theta}\left\{\lambda_0 E_M+\lambda_1 D-C_G-\theta C_M + \frac{\partial V_G^D}{\partial L}(\alpha E_G+\beta E_M-\delta L)\right\} \tag{25}$$

Substituting equation (24) into equation (25), and solving the right part of equation (25) to maximize it, the condition is that equation (25) calculates the first-order partial derivatives for E_G and θ respectively, and makes them all zero. The solution can obtain

$$E_G = \frac{\mu_1\lambda_1+\alpha V_G'^D}{k_G} \tag{26}$$

$$\theta = \begin{cases} \dfrac{2\left(\lambda_0+\mu_2\lambda_1+V_G'^D\beta\right)-\left(\mu_2\lambda_2+\beta V_M'^D\right)}{2\left(\lambda_0+\mu_2\lambda_1+V_G'^D\beta\right)+\left(\mu_2\lambda_2+\beta V_M'^D\right)}, & 2B > A \\ 0, & 2B \leq A \end{cases}$$

where $\frac{\partial V_G^D}{\partial L} = V_G'^D$, $\frac{\partial V_M^D}{\partial L} = V_M'^D$, satisfying $A = \left(\mu_2\lambda_2+\beta V_M'^D\right)$, $B = \left(\lambda_0+\mu_2\lambda_1+V_G'^D\beta\right)$.

In order to ensure the existence and rationality of the share proportion, satisfying $2B > A$, namely

$$\theta = \frac{2\left(\lambda_0+\mu_2\lambda_1+V_G'^D\beta\right)-\left(\mu_2\lambda_2+\beta V_M'^D\right)}{2\left(\lambda_0+\mu_2\lambda_1+V_G'^D\beta\right)+\left(\mu_2\lambda_2+\beta V_M'^D\right)} \tag{27}$$

By substituting equations (24), (26) and (27) into equations (23) and (25), we can obtain

$$\rho V_M^D = \frac{A(2B+A)}{4k_M} + \left(\lambda_2\nu - \delta V_M'^D\right)L + \frac{\left(\mu_1\lambda_1+\alpha V_G'^D\right)\left(\mu_1\lambda_2+\alpha V_M'^D\right)}{k_G} - \lambda_2\varphi P \quad (28)$$

$$\rho V_G^D = \frac{(2B+A)^2}{8k_M} + \left(\lambda_1\nu - \delta V_G'^D\right)L + \frac{(\mu_1\lambda_1+\alpha V_G'^D)^2}{2k_G} - \lambda_1\varphi P \quad (29)$$

From the structure of equations (28) and (29), it can be seen that the 1 yuan function with L as independent variable is the solution of HJB equation

$$V_G^D(L) = (f_1L+f_2),\ V_M^D(L) = (g_1L+g_2) \quad (30)$$

where f_1, f_2, g_1, g_2 are the constants to be solved. We can get

$$V_G'^D(L) = \frac{dV_G^D(L)}{dL} = f_1,\ V_M'^D(L) = \frac{dV_M^D(L)}{dL} = g_1 \quad (31)$$

Substituting formula (30), (31) into formula (28), (29), we can get

$$\rho(f_1L+f_2) = \frac{[2(\lambda_0+\mu_2\lambda_1+f_1\beta)+(\mu_2\lambda_2+\beta g_1)]^2}{8k_M} + (\lambda_1\nu-\delta f_1)L + \frac{(\mu_1\lambda_1+\alpha f_1)^2}{2k_G} - \lambda_1\varphi P \quad (32)$$

$$\rho(g_1L+g_2) = \frac{[2(\lambda_0+\mu_2\lambda_1+f_1\beta)+(\mu_2\lambda_2+\beta g_1)]}{4k_M} \times (\mu_2\lambda_2+\beta g_1) + (\lambda_2\nu-\delta g_1)L - \lambda_2\varphi P + \frac{(\mu_1\lambda_1+\alpha f_1)(\mu_1\lambda_2+\alpha g_1)}{k_G} \quad (33)$$

From the previous assumption, equation $V_G^D(L), V_M^D(L)$ should satisfy all $L \geq 0$, so the values of f_1, f_2, g_1, g_2 are

$$\begin{cases} f_1 = \dfrac{\lambda_1\nu}{\rho+\delta} \\ f_2 = \dfrac{[(2\lambda_0+2\mu_2\lambda_1+\mu_2\lambda_2)(\rho+\delta)+\beta(2\lambda_1\nu+\lambda_2\nu)]^2}{8k_M\rho(\rho+\delta)^2} + \dfrac{[\mu_1\lambda_1(\rho+\delta)+\lambda_1\nu\alpha]^2}{2k_G\rho(\rho+\delta)^2} - \dfrac{\lambda_1\varphi P}{\rho} \end{cases}$$

$$\begin{cases} g_1 = \dfrac{\lambda_2\nu}{\rho+\delta} \\ g_2 = \dfrac{[(2\lambda_0+2\mu_2\lambda_1+\mu_2\lambda_2)(\rho+\delta)+\beta(2\lambda_1\nu+\lambda_2\nu)]}{4k_M\rho(\rho+\delta)^2} \times [\mu_2\lambda_2(\rho+\delta)+\beta\lambda_2\nu] - \frac{\lambda_2\varphi P}{\rho} + \dfrac{[\mu_1\lambda_1(\rho+\delta)+\alpha\lambda_1\nu][\mu_1\lambda_2(\rho+\delta)+\alpha\lambda_2\nu]}{k_G\rho(\rho+\delta)^2} \end{cases}$$

Substituting f_1, g_1 into formula (24), (26), (27), we can obtain the EPE of government and enterprise for remanufactured product production investment and the optimal environmental protection subsidy proportion of government to enterprise, as shown in formula (20), (21), (22).

By substituting f_1, f_2, g_1, g_2 into equations (32) and (33), we can obtain the optimal return functions of government and enterprise respectively

$$V_G^{D*} = \frac{[(2\lambda_0+2\mu_2\lambda_1+\mu_2\lambda_2)(\rho+\delta)+\beta\nu(2\lambda_1+\lambda_2)]^2}{8k_M\rho(\rho+\delta)^2} + \frac{[\mu_1\lambda_1(\rho+\delta)+\lambda_1\nu\alpha]^2}{2k_G\rho(\rho+\delta)^2} - \frac{\lambda_1\varphi P}{\rho} + \frac{\lambda_1\nu}{\rho+\delta}L \quad (34)$$

$$V_M^{D*} = \frac{[(2\lambda_0+2\mu_2\lambda_1+\mu_2\lambda_2)(\rho+\delta)+\beta\nu(2\lambda_1+\lambda_2)]}{4k_M\rho(\rho+\delta)^2} \times [\mu_2\lambda_2(\rho+\delta)+\lambda_2\nu\beta] - \frac{\lambda_2\varphi P}{\rho} + \frac{\lambda_2\nu}{\rho+\delta}L + \frac{[\mu_1\lambda_1(\rho+\delta)+\lambda_1\nu\alpha][\mu_1\lambda_2(\rho+\delta)+\lambda_2\nu\alpha]}{k_G\rho(\rho+\delta)^2} \quad (35)$$

C. COOPERATIVE GAME MODEL

In the case of cooperative game, the government and the enterprise will be regarded as a whole. The system will take the overall economic and social benefits as the goal to maximize, and jointly determine the EPE of the two for remanufactured product production investment. At this time, the environmental protection subsidies provided by the government for enterprises will be regarded as the fund transfer within the system.

Theorem 3: In the case of cooperative game, in order to maximize the interests of both sides, the optimal EPE invested by the government and the enterprise for remanufactured product production should be

$$E_G^{C*} = \frac{\mu_1(\lambda_1+\lambda_2)(\rho+\delta)+(\lambda_1+\lambda_2)\nu\alpha}{(\rho+\delta)k_G} \quad (36)$$

$$E_M^{C*} = \frac{(\lambda_0+\mu_2(\lambda_1+\lambda_2))(\rho+\delta)+(\lambda_1+\lambda_2)\nu\beta}{(\rho+\delta)k_M} \quad (37)$$

Prove: In this case, the objective function is

$$\max_{E_M,E_G} J^C = \int_0^\infty e^{-\rho t}[\lambda_0E_M+(\lambda_1+\lambda_2)D-C_G-C_M]\,dt \quad (38)$$

Its optimal benefit function satisfies HJB equation, which is

$$\rho V^C = \max_{E_M,E_G}\{\lambda_0E_M+(\lambda_1+\lambda_2)D-C_G-C_M + \frac{\partial V^C}{\partial L}(\alpha E_G+\beta E_M-\delta L)\} \quad (39)$$

To solve the right end of HJB equation, the condition to maximize it is to find the first-order partial derivatives of E_G, E_M, and make them get zero, and the solution can get

$$E_G = \frac{\mu_1(\lambda_1+\lambda_2)+\alpha V'^C}{k_G},\quad E_M = \frac{\lambda_0+\mu_2(\lambda_1+\lambda_2)+\beta V'^C}{k_M} \quad (40)$$

where $\frac{\partial V^C}{\partial L} = V'^C$, substituting equation (40) into equation (39) can obtain

$$\rho V^C = [(\lambda_1+\lambda_2)\nu - \delta V'^C]L + \frac{\left(\mu_1(\lambda_1+\lambda_2)+\alpha V'^C\right)^2}{2k_G} + \frac{[\lambda_0+\mu_2(\lambda_1+\lambda_2)+\beta V'^C]^2}{2k_M} - (\lambda_1+\lambda_2)\varphi P \tag{41}$$

It can be seen from the structure of equation (41) that the solution of the univariate primary function HJB equation with L as the independent variable, so that

$$V^C(L) = f_1 L + f_2 \tag{42}$$

f_1 and f_2 denote the constant to be solved, which is

$$\begin{cases} f_1 = \dfrac{\nu(\lambda_1+\lambda_2)}{\rho+\delta} \\ f_2 = \dfrac{[(\lambda_0+\mu_2(\lambda_1+\lambda_2))(\rho+\delta)+(\lambda_1+\lambda_2)\nu\beta]^2}{2k_M\rho(\rho+\delta)^2} \\ \quad + \dfrac{[\mu_1(\lambda_1+\lambda_2))(\rho+\delta)+(\lambda_1+\lambda_2)\nu\alpha]^2}{2k_G\rho(\rho+\delta)^2} \end{cases} \tag{43}$$

Substituting equation (43) into equation (40) can respectively obtain the optimal EPE invested by the government and enterprises for the production of remanufactured products, as shown in equations (36), (37). By substituting equation (43) into equation (42), we can get the expression of income function $V^C(L)$ of the whole system when the government and the enterprise cooperate

$$V^{C*} = \frac{[(\lambda_0+\mu_2(\lambda_1+\lambda_2)(\rho+\delta)+(\lambda_1+\lambda_2)\nu\beta]^2}{2k_M\rho(\rho+\delta)^2} + \frac{[\mu_1(\lambda_1+\lambda_2)(\rho+\delta)+(\lambda_1+\lambda_2)\nu\alpha]^2}{2k_G\rho(\rho+\delta)^2} + \frac{(\lambda_1+\lambda_2)\nu}{\rho+\delta}L - \frac{(\lambda_1+\lambda_2)\varphi P}{\rho} \tag{44}$$

IV. COMPARATIVE ANALYSIS OF EQUILIBRIUM RESULTS

Through the comparison of the optimal EPE, the optimal income situation and the optimal income of the whole cooperation between the government and the enterprise for remanufactured product production, the following conclusions can be drawn.

Theorem 4: Under Stackelberg master-slave game model, the optimal EPE invested by enterprises in remanufactured product production is significantly improved compared with Nash-non cooperative game. The improvement intensity is equal to the proportion of environmental protection subsidies provided by the government, which is also called the optimal cost sharing proportion. This shows that environmental protection subsidies can encourage enterprises to increase cost input to improve product quality, so as to achieve the effect of environmental protection and green production. In these two non cooperative game situations, the optimal EPE invested by the government for remanufactured product production remains unchanged. When the government and the enterprise reach a cooperative cooperation, the optimal EPE invested by both sides for remanufactured product production reaches the maximum respectively, and is superior to the non cooperative game situation. We can get

$$E_G^{N*}=E_G^{D*}<E_G^{C*}, E_M^{N*}<E_M^{D*}<E_M^{C*}, E_M^{D*}-E_M^{N*}=E_M^{D*}*\theta$$

Prove: From formula (7), (8), (20), (21), (36), (37),we can get

$$\begin{aligned} E_G^{D*}-E_G^{N*} &= 0 \\ E_G^{C*}-E_G^{D*} &= \frac{\mu_1\lambda_2(\rho+\delta)+\alpha\lambda_2\nu}{(\rho+\delta)k_G} > 0 \\ E_M^{D*}-E_M^{N*} &= \frac{(2\lambda_0+2\mu_2\lambda_1-\mu_2\lambda_2)(\rho+\delta)+(2\lambda_1-\lambda_2)\nu\beta}{2(\rho+\delta)k_M} \\ &= E_M^{D*}*\theta > 0 \\ E_M^{C*}-E_M^{D*} &= \frac{\mu_2\lambda_2(\rho+\delta)+\lambda_2\nu\beta}{2(\rho+\delta)k_M} > 0 \end{aligned}$$

Theorem 4 is proved.

Theorem 5: In Stackelberg master-slave game model, the optimal returns of government and enterprise are higher than that of Nash-non cooperative game. This shows that compared with their independent development, it is more beneficial for both sides to form a master-slave relationship between enterprises and the government. We can get $V_M^{N*} < V_M^{D*}$, $V_G^{N*} < V_G^{D*}$.

Prove: In order to ensure the existence and reasonableness of the share proportion, satisfy $2B > A$. For the convenience of analysis, satisfy

$$B = \lambda_0+\mu_2\lambda_1+\frac{\lambda_1\nu\beta}{\rho+\delta}, A = \mu_2\lambda_2+\frac{\lambda_2\nu\beta}{\rho+\delta}.$$

From formula (18), (19), (34), (35), we can get

$$\begin{aligned} V_G^{D*}-V_G^{N*} &= \frac{[(2\lambda_0+2\mu_2\lambda_1-\mu_2\lambda_2)(\rho+\delta)+(2\lambda_1-\lambda_2)\nu\beta]^2}{8k_M\rho(\rho+\delta)^2} \\ &= \frac{(2B-A)^2}{8k_M\rho} > 0 \\ V_M^{D*}-V_M^{N*} &= \frac{[(2\lambda_0+2\mu_2\lambda_1-\mu_2\lambda_2)(\rho+\delta)+(2\lambda_1-\lambda_2)\nu\beta]}{4k_M\rho(\rho+\delta)^2} \\ &\quad \times [\mu\lambda_2(\rho+\delta)+\nu\beta\lambda_2] \\ &= \frac{(2B-A)A}{4k_M\rho} > 0 \end{aligned}$$

Theorem 5 is proved.

Theorem 6: The total optimal revenue of government and enterprise is the highest in the cooperative game, followed by Stackelberg master-slave game and Nash-non cooperative game. This shows that the most favorable choice for both sides is to reach a cooperative cooperation between the government and enterprises, which means $V^{N*} < V^{D*} < V^{C*}$.

Prove: From formula (34), (35), (44), we can get

$$V^{D*} = (V_G^{D*} + V_M^{D*})$$

$$V^{C*} - V^{D*} = \frac{[\mu_1\lambda_2(\rho+\delta)+\alpha\lambda_2\nu]^2}{2k_G\rho(\rho+\delta)^2} + \frac{[\mu_2\lambda_2(\rho+\delta)+\nu\beta\lambda_2]^2}{8k_M\rho(\rho+\delta)^2} > 0$$

It can be seen from theorem 5 that $V^{N*} = (V_G^{N*} + V_M^{N*}) < V^{D*}$, and $V^{N*} < V^{D*} < V^{C*}$.

Theorem 6 is proved.

V. CASE STUDY

According to the above analysis, the function expressions of the optimal EPE invested by the government and enterprises for remanufactured products production and the sum of their respective optimal income and the optimal income of both parties have been obtained. Now refer to the relevant literature [31] to give specific values to the model parameters for calculation and analysis.

Suppose the parameters in the model are set to:

$$\rho = 0.1, \delta = 0.4, \lambda_0 = \lambda_1 = 0.4, \lambda_2 = 0.6, \mu_1 = \mu_2 = 0.5,$$
$$\nu = 0.5, \varphi = 0.7, k_M = 0.4, k_G = 0.2, \alpha = 0.2, \beta = 0.3,$$
$$P = 1, L_0 = 1.$$

It can be solved as follows:

$$E_G^{N*} = 1.4, E_M^{N*} = 1.2;$$
$$E_G^{D*} = 1.4, E_M^{D*} = 2.4, \theta = 0.5;$$
$$E_G^{C*} = 3.5, E_M^{C*} = 3$$

and satisfying:

$$E_G^{N*} = E_G^{D*} < E_G^{C*}, E_M^{N*} < E_M^{D*} < E_M^{C*}, \frac{E_M^{D*} - E_M^{N*}}{E_M^{D*}} = \theta = 0.5,$$

consistent with the conclusion of theorem 4.

Using MATLAB software to draw the optimal income of the government and the enterprise with time in the case of Nash-non cooperative game and Stackelberg master-slave game (Figure 2), we explore the improvement effect of environmental protection subsidy in Stackelberg master-slave game on the income in the case of Nash-non cooperative game. Secondly, we draw the environmental protection subsidy θ according to the change of the impact coefficient λ_0 of the EPE invested by the enterprise for production on social benefits, and explore the impact of parameter λ_0 on environmental protection subsidy θ (Figure 3). Finally, we draw the sum of the optimal benefits of the government and the enterprise with time in the case of Nash-non cooperative game, Stackelberg master-slave game and cooperative game, so as to compare the most favorable game situation for both the government and the enterprise (Figure 4).

(1) As it can be seen from Figure 2, compared with the situation without environmental protection subsidies, when the government provides environmental protection subsidies for enterprises, the benefits of both sides have been improved, which is consistent with the conclusion of theorem 5.

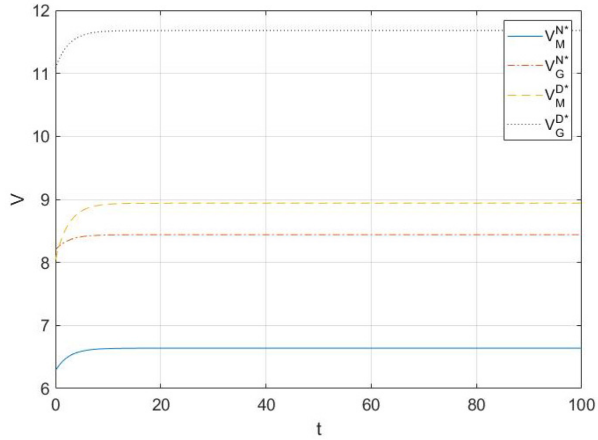

FIGURE 2. Comparison of government and enterprise income with time before and after providing environmental protection subsidies.

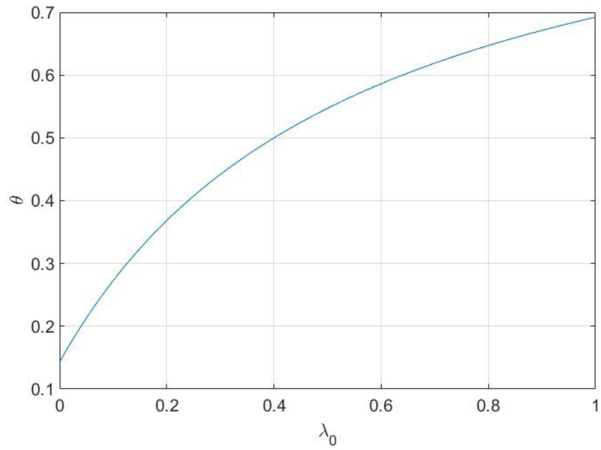

FIGURE 3. Impact of parameter λ_0 on environmental protection subsidy θ.

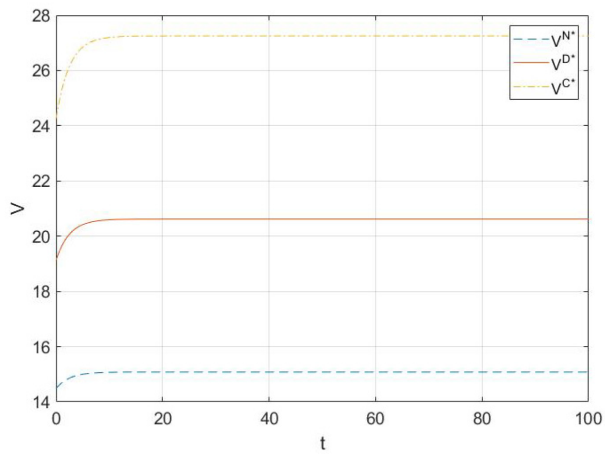

FIGURE 4. Comparison of the total optimal returns of government and enterprises with time in three game situations.

(2) It can be seen from Figure 3 that with the increase of the influence coefficient λ_0 of the EPE invested by enterprises for production on social benefits, the environmental protection subsidy θ provided by the government for enterprises will also increase.

(3) It can be seen from Figure 4 that the total optimal income of the government and the enterprise in three cases is: the total optimal income is the largest in the case of cooperative game, the next in the case of Stackelberg master-slave game, and the smallest in the case of Nash-non cooperative game, which is consistent with the conclusion of theorem 6.

It can be seen that the government can reduce the harm of remanufactured products to the environment by sharing part of the production cost for remanufacturers, and improve the respective benefits of the government and enterprises. Therefore, the rationality of the government's measures to provide environmental protection subsidies for enterprises has been verified. Secondly, the EPE invested by enterprises in remanufactured product production will have an impact on their social benefits, and the impact coefficient of their social benefits is positively related to the environmental protection subsidies provided by the government. It indicates that the improvement of environmental protection subsidies and the improvement of the environmental protection quality of remanufactured products form a positive promotion cycle. The superiority of the government's environmental protection subsidies for enterprises has been verified. Finally, when the government and the enterprise achieve cooperative cooperation, the sum of the optimal revenue and the optimal revenue of both sides are strictly superior to the non cooperative situation. It shows that the government enterprise cooperation is the best choice for the remanufacturing enterprise with the goal of maximizing the benefits.

VI. SUMMARY

This paper analyzes the impact of environmental policy on decision made by remanufacturers with the effect of green network using differential game model. Both government and remanufacturer's cost functions are established with their own environmental effort, respectively. Then their benefit functions are built, in which many factors including but not limited to the environmental reputation of remanufacturer and consumers' demand for remanufactured products can influence the final benefit. Using the model of Nash-non cooperative game, Stackelberg master-slave game and cooperative game, their benefits are calculated and compared.

The equilibrium results show that the improvement level of products' environmental quality is equal to the level of subsidies, and subsidies will increase with the improvement of products' environmental quality. In addition, they can gain the most benefits in cooperative-game.

This paper regarded a government system and a remanufacturer as two players in the game, however, the cooperation between the government and the enterprise in life always involves more complex relationships. The future research is supposed to concentrate on the game with more government systems or remanufacturers as players to explore the impact of environmental policy deeper. Further, parameters in this paper are set to be time-independent in order to be solved easily. Thus, it also can be one of future research directions to apply differential game model to solve nondegenerate problems.

REFERENCES

[1] D. Brécard, "Environmental quality competition and taxation in the presence of green network effect among consumers," *Environ. Resour. Econ.*, vol. 54, no. 1, pp. 1–19, Jan. 2013.
[2] J. Williams and L. H. Shu, "Analysis of remanufacturer waste streams for electronic products," in *Proc. IEEE Int. Symp. Electron. Environ.*, Denver, CO, USA, Jul. 2001, pp. 279–284.
[3] M. Song, "Could environmental regulation and R&D tax incentives affect green product innovation?" *J. Cleaner Prod.*, vol. 258, Jun. 2020, Art. no. 120849.
[4] Q. H. Zhu and Y. J. Dou, "Game model of green supply chain management based on government subsidy," *J. Manage. Sci.*, vol. 14, no. 6, pp. 90–99, 2011.
[5] D. Krass, T. Nedorezov, and A. Ovchinnikov, "Environmental taxes and the choice of green technology," *Prod. Oper. Manage.*, vol. 22, no. 5, pp. 1035–1055, 2013.
[6] Z. K. Xiong and R. Y. He, "Analysis of the impact of downstream enterprise supervision and government intervention on supplier emission reduction," *J. Ind.*, vol. 31, no. 1, pp. 93–101, 2017.
[7] Z. Liu, J. Tang, B.-Y. Li, and Z. Wang, "Trade-off between remanufacturing and recycling of WEEE and the environmental implication under the chinese fund policy," *J. Cleaner Prod.*, vol. 167, pp. 97–109, Nov. 2017.
[8] Z. Miao, H. Mao, K. Fu, and Y. Wang, "Remanufacturing with tradeins under carbon regulations," *Comput. Oper. Res.*, vol. 89, pp. 253–268, Jan. 2018.
[9] A. Ovchinnikov, V. Blass, and G. Raz, "Economic and environmental assessment of remanufacturing strategies for product + service firms," *Prod. Oper. Manage.*, vol. 23, no. 5, pp. 744–761, May 2014.
[10] H. Guo, M. Chen, R. Zhang, J. Li, T. Qu, C. Li, G. Huang, Z. He, and Y. Zeng, "Research on improvement of truck vibration based on systematic G8D," *Shock Vib.*, Vol. 2019, Jun. 2019, Art. no. 1416340.
[11] K. Yang and X. Y. Liu, "Supply chain carbon emission reduction decision based on consumer low-carbon preference and internal financing," *Syst. Eng.*, vol. 34, no. 11, pp. 87–97, 2016.
[12] A. Yenipazarli, "Managing new and remanufactured products to mitigate environmental damage under emissions regulation," *Eur. J. Oper. Res.*, vol. 249, no. 1, pp. 117–130, Feb. 2016.
[13] Y. Wang and G. Hou, "A duopoly game with heterogeneous green supply chains in optimal price and market stability with consumer green preference," *J. Cleaner Prod.*, vol. 255, May 2020, Art. no. 120161.
[14] Q. Li and W. Chen, "The optimal production for remanufacturing products and competition among consumers in the presence of green network effect[J/OL]," in *Proc. Control Decision*, 2020, pp. 1–10.
[15] I. Grilo, O. Shy, and J.-F. Thisse, "Price competition when consumer behavior is characterized by conformity or vanity," *J. Public Econ.*, vol. 80, no. 3, pp. 385–408, Jun. 2001.
[16] F. Qiao-Hong, "On the impact of public environmental protection consciousness on remanufacturing decision," *Ind. Eng. J.*, vol. 13, no. 1, pp. 47–51, 2010.
[17] R. Wang, Y. Tian, and X. He, "Technical efficiency characteristics and the policy sensitivity of environmental protection enterprises: Micro evidence from China," *J. Cleaner Prod.*, vol. 256, May 2020, Art. no. 120752.
[18] S. Bansal and S. Gangopadhyay, "Tax/subsidy policies in the presence of environmentally aware consumers," *J. Environ. Econ. Manage.*, vol. 45, no. 2, pp. 333–355, 2003.
[19] X. Zhang, X. Xu, and P. He, "New product design strategies with subsidy policies," *J. Syst. Sci. Syst. Eng.*, vol. 21, no. 3, pp. 356–371, Sep. 2012.
[20] Z. Li, J. Zhang, Q. Meng, W. Zheng, and J. Du, "Influence of government subsidy on remanufacturing decision under different market models," *Math. Problems Eng.*, vol. 2019, pp. 1–16, Jul. 2019.
[21] Z. Li, W. Zheng, Q. Meng, and S. Jin, "The impact of government subsidy and tax policy on the competitive decision-making of remanufacturing supply chains," *Int. J. Sustain. Eng.*, vol. 12, no. 1, pp. 18–29, Jan. 2019.

[22] L. Song, Y. Yan, and F. Yao, "Closed-loop supply chain models considering government subsidy and corporate social responsibility investment," *Sustainability*, vol. 12, no. 5, p. 2045, Mar. 2020.
[23] S. Zhao, Q. Zhu, and L. Cui, "A decision-making model for remanufacturers: Considering both consumers' environmental preference and the government subsidy policy," *Resour., Conservation Recycling*, vol. 128, pp. 176–186, Jan. 2018.
[24] Y. Yu, X. Han, and G. Hu, "Optimal production for manufacturers considering consumer environmental awareness and green subsidies," *Int. J. Prod. Econ.*, vol. 182, pp. 397–408, Dec. 2016.
[25] H. Gao, H. Xu, L. Zhang, and X. Zhou, "A differential game model for data utility and privacy-preserving in mobile crowdsensing," *IEEE Access*, vol. 7, pp. 128526–128533, 2019.
[26] S. Xu and C. Han, "Study on basin ecological compensation mechanism based on differential game theory," *Chin. J. Manage. Sci.*, vol. 27, no. 8, pp. 199–207, 2019.
[27] D. Wang, T. Wang, and B. Zhang, "Reduce emissions in cooperation and government subsidies strategies in supply chain based on differential game," *Control Decis.*, vol. 34, no. 8, pp. 1733–1744, 2019.
[28] J. Zeng and B. Li, "Research on cooperation strategy between government and green supply chain based on differential game," *Open Math.*, vol. 17, no. 1, pp. 828–855, Aug. 2019.
[29] A. Atasu, L. B. Toktay, and W. L. N. Van, "How collection cost structure drives a manufacturer's reverse channel choice," *Prod. Oper. Manage.*, vol. 22, no. 5, pp. 1089–1102, 2013.
[30] S. C. Bulmuý, S. X. Zhu, and R. H. Teunter, "Optimal core acquisition and pricing strategies for hybrid manufacturing and remanufacturing systems," *Int. J. Prod. Res.*, vol. 52, no. 22, pp. 6627–6641, Nov. 2014.
[31] D. O. Ward, C. D. Clark, K. L. Jensen, and S. T. Yen, "Consumer willingness to pay for appliances produced by green power partners," *Energy Econ.*, vol. 33, no. 6, pp. 1095–1102, Nov. 2011.

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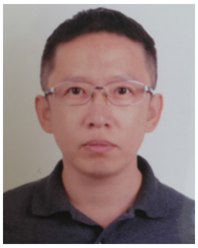

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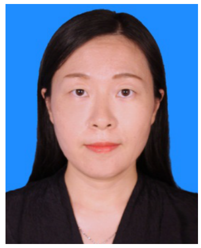

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