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Duopoly Game with Green Efficiency Based on Ecological Modernization Theory

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Abstract: Since the birth of ecological modernization theory in 1982, the problem of enterprise benefit and environmental protection has entered the field of view of academia and industry. Ecological modernization theory discusses the influence of government policy intervention (subsidy or penalty) on enterprise green innovation and then explains the possibility of enterprise revenue and enterprise green coexistence. Firstly, this paper gives a simple explanation of the theory of ecological modernization and then establishes several simple duopoly game models through multiple hypotheses. Moreover, through comparative static analysis, it discusses the influence of government policies on enterprise carbon emissions and the influence of enterprise carbon emission decisions on enterprise green efficiency. The analysis shows that the government's policy intervention can effectively reduce the carbon emissions of enterprises. Meanwhile, in the same market, a number of carbon emission enterprises will reduce their own carbon emission levels according to the carbon emission situation of oligopolies with carbon emission initiatives.

Keywords: Ecological Modernization; Green Supply Chain Management; Green Logistics Strategies; Comparative Static Analysis; Carbon Emissions

1. Introduction

With the development of global economy, the natural environment has become one of the most important issues concerned by governments and leading enterprises in the last 30 years. Whether it is climate warming or environmental pollution, natural environmental issues have become a topic closely related to everyone on earth. On the premise of ensuring the economic benefits of both enterprises and the country, sustainable development is a pressing and important choice. Therefore, green logistics and green supply chain management have suddenly become hot research topics. Various countries and regions are paying attention to this major issue, from the upstream and downstream design of the supply chain [1] and enterprise greening evaluation [2-3] to the discharge and collection of waste water, waste gas, and residues [4], and then to policy making based on relevant green industries [5-7]. Since 2013, the United Nations Environment Programme[1] has called on governments to focus on implementing environmental legislation. In 2019, the State Council of China issued Opinions on Promoting High-Quality Development of Logistics and Forming a Strong Domestic Market[2], which also mentioned in Article 14: "To accelerate the development of green

[1] UNEP/GC.27/9 https://www.un.org/zh/documents/view_doc.asp?symbol=UNEP/GC.27/17

[2] Opinions on Promoting High-Quality Development of Logistics and Forming a Strong Domestic Market http://www.ndrc.gov.cn/zcfb/zcfbtz/201903/t20190301_929841.html

logistics, we should take green logistics as a breakthrough and drive upstream and downstream enterprises to develop green supply chains."

Ecological modernization theory was first proposed by Huber [8-10] in the 1980s, aiming at discussing the relationship between the development of enterprises and the ecological environment. In the following 20 years, the concept of ecological modernization theory has been discussed continuously and has been regarded by relevant scholars as an important theoretical basis for solving ecological problems. However, how to measure the role of ecological modernization theory [5] has become a new object of discussion, including the government's policy decisions, the level of innovation and development of enterprises, the green standards of enterprises, and the profits of enterprises. The concept and development of relevant issues will be briefly reviewed in this paper based on ecological modernization theory and then explained through the establishment of a simple mathematical model. Furthermore, it is hoped that an understanding of enterprise behavior or decisions, as well as future planning suggestions, will be obtained based on the ecological modernization theory.

2. Literature Review

2.1. Ecological Modernization

Sustainable development is a way of achieving both enterprise benefits and environmental protection. The problems that need to be considered in sustainable development usually include the recycling of resources, the replacement of non-renewable resources, and the control and management of waste water, waste gas, and residues. The theory of ecological modernization provides a new angle, shows the new stage of enterprise development and innovation, and introduces the policy factors of the government to solve the problem of sustainable development. At present, the theory of ecological modernization usually refers to encouraging enterprise innovation and technological development through government policy regulation so as to realize enterprise development and environmental protection [5, 11-12].

In the 1980s, the concept of ecological modernization theory was first put forward. In the first stage of ecological modernization theory, enterprises should start from within themselves to solve the "dirty, messy, and bad" phenomenon inside enterprises so as to make innovations in the enterprise ecology [10]. Later, the theory of ecological modernization entered the research horizon of more scholars and was redefined as the theory "related to the national macroeconomic level" and "related to the technological composition of enterprises and the national macroeconomic structure" [13-17]. By the 1990s, relevant studies had shown that the development and implementation of ecological modernization theory were significantly related to policy orientation and the purpose of policy issuance [18-19]. Since the beginning of the 21st century, relevant scholars have started to study how "environmental or green-related policies will affect enterprise decision-making" [6, 20-21]. The influence of government policies is mainly reflected in two aspects, namely, policy support and policy supervision. Policy support and regulation help enterprises increase their innovation, which is specifically reflected in enabling innovative enterprises to better obtain market dominance. At the same time, the government exerts innovation pressure on non-innovative enterprises by increasing business risks [11].

2.2. Innovative Development of Enterprises

An enterprise's ecological innovation capability is equally important as its supply chain management capability [5, 22-23]. The innovation and development ability of an enterprise often has a strong correlation with its investment in research and development (R&D). In an enterprise, the higher the proportion of investment in green innovation or ecological innovation in R&D, the more ideal the

enterprise's green output will be [24]. Specifically, R&D expenditure is directly proportional to the degree of environmental management system construction [25] and inversely proportional to the pollutant emissions of enterprises [26].

Enterprise ecological innovation can be divided into external ecological innovation and internal ecological innovation. The external ecological innovation of enterprises refers to all the external green behaviors of relevant enterprises, such as the interaction with the upstream and downstream of the supply chain, government agencies, and the market. The internal ecological innovation of enterprises refers to improving the management efficiency of internal green innovation, such as the research and development of related new green products [27-28]. From another perspective, enterprise ecological innovation can also be divided into hard ecological innovation and soft ecological innovation. The hard ecological innovation of enterprises exists in the green innovation of specific products or equipment, such as terminal equipment that can effectively reduce the emission of pollutants. Similar to the internal ecological innovation mentioned above, soft ecological innovation in enterprises mainly exists in the management efficiency of the green innovation process [29]. On this basis, some scholars put forward concepts such as "green human resources" [30].

2.3. The Definition of Enterprise Greening

There is no precise definition of enterprise greening. In different research scenarios and for different research problems, scholars will give different explanations for enterprise greening. In a general sense, enterprise greening refers to the extent to which enterprises can get along well with the natural environment while considering their economic benefits. For example, in most scenarios, enterprise greening refers to the control of pollutant emissions by enterprises or the extent to which enterprises use clean or relatively clean energy as substitutes for the same production purpose [5]. Studies show that among green supply chain problems, the most common environmental problems are the disposal of hazardous waste and solid waste [31]. To solve environmental problems, the criteria for judging the greening degree of enterprises are the 3R principles (Recycling, Reducing, and Reusing), that is, using renewable energy, reducing consumption, and recycling waste [31-32]. On the other hand, more studies are willing to measure the greenness of enterprises by discussing their greenhouse gas emissions, or carbon dioxide (CO_2) emissions [24, 33-35].

3. Basic Theoretical Framework

The basic theoretical model of this paper is the theory of ecological modernization, and the standard to measure enterprise greening is enterprises' carbon emissions. In this paper, the economic income of enterprises is selected as the objective function. The independent variable is the enterprise's carbon emissions; the regulating variable is the influence of government policy; and the control variables are the size of the enterprise and other factors. Since the main object of discussion is the impact of the carbon emissions of an enterprise on its economic income, the innovation of an enterprise is not taken into account in the model. The basic frame diagram is shown in Figure 1.

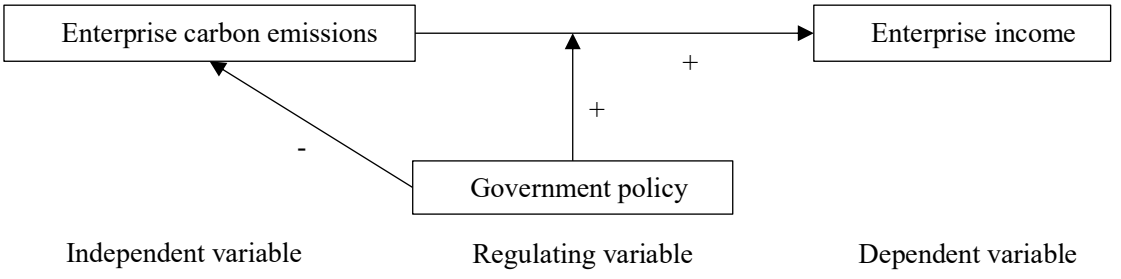

Figure 1: Basic theoretical framework diagram.

The following basic hypotheses can be obtained from the ecological modernization theory and basic theoretical framework:

- **Hypothesis 1**: Government policies will affect enterprises' carbon emission decisions.
- **Hypothesis 2**: Government policies have different effects on the carbon emission decisions made by various enterprises in the same market.

4. The Establishment of Mathematical Models

According to the basic theoretical framework mentioned above, it is assumed that government policies can be divided into positive (policy incentives) and negative (policy penalties) ways of influencing enterprise economic earnings, and it is assumed that enterprise economic earnings and enterprise carbon emissions are in a positive relationship. This paper establishes mathematical models in two cases: The enterprise income model of a single enterprise randomly producing carbon emissions and the enterprise income model of oligopolies randomly producing carbon emissions.

4.1. The Enterprise Income Model of a Single Enterprise Randomly Producing Carbon Emissions

Considering the impact of a single enterprise's carbon emissions on enterprise earnings, a basic assumption is made: under this model, the enterprise's carbon emissions will be generated randomly. Let's assume that the carbon emissions of enterprises are evenly distributed and the probability of exceeding the standard is p. According to the hypothesis, the design variables and parameters are as follows:

Q_0: Market carbon emission standards

Q_1: Enterprise carbon emissions

P: Penalty intensity for excessive policy carbon emissions (penalty coefficient)

G: Incentive intensity for policy carbon emission compliance (incentive coefficient)

p: The probability of excessive carbon emissions of enterprises

c: Rate of return of enterprise carbon emission unit

Now we assume that $Q_0 > 0, \quad Q_1 > 0, \quad 0 < p < 1.$

According to the assumption, enterprise carbon emissions compliance is rewarded for $G(Q_0 - Q_1)Q_1$, while excessive carbon emissions are penalized for $-P(Q_1 - Q_0)Q_1$. Regardless of other factors, the income model obtained by a single enterprise when carbon emissions are controlled is as follows:

$$\pi = cQ_1 + pG(Q_0 - Q_1)Q_1 - (1-p)P(Q_1 - Q_0)Q_1 \quad \text{s.t. } 0 < p < 1 \tag{3.1}$$

The first-order conditions for considering this optimization problem are as follows:

$$\frac{\partial \pi}{\partial Q_1} = c + pGQ_0 - 2pGQ_1 - 2(1-p)PQ_1 + (1-p)PQ_0 = 0 \tag{3.2}$$

The solution is:

$$Q_1^* = \frac{c + pGQ_0 + (1-p)PQ_0}{2pG + 2(1-p)P} \tag{3.3}$$

4.2. The Enterprise Income Model of Oligopolies Randomly Producing Carbon Emissions

Considering that there are several enterprises in the same market, two of which are enterprises with the carbon emission initiative, it is assumed that the carbon emissions of enterprises 1 and 2 will far exceed the market carbon emission standard. The enterprise revenue-carbon emission models of the

two enterprises are then established. According to the above conditions and basic assumptions, the design variables and parameters are as follows:

Q_0: Market carbon emission standards

Q_1: Carbon emissions of enterprise 1

Q_2: Carbon emissions of enterprise 2

P: Penalty intensity for excessive policy carbon emissions (penalty coefficient)

G: Incentive intensity for policy carbon emission compliance (incentive coefficient)

p_1: The probability of excessive carbon emissions of enterprise 1

p_2: The probability of excessive carbon emissions of enterprise 2

c_1: Rate of return of carbon emission unit of enterprise 1

c_2: Rate of return of carbon emission unit of enterprise 2

$$\pi_1 = c_1Q_1 + p_1G(Q_0 - Q_1)Q_1 - (1 - p_1)P(Q_1 - Q_0)Q_1 \tag{3.4}$$

$$\pi_2 = c_2Q_2 + p_2G(Q_0 - Q_2)Q_2 - (1 - p_2)P(Q_2 - Q_0)Q_2 \tag{3.5}$$

$$\text{s.t. } \frac{Q_1 + Q_2}{2} > Q_0, \quad 0 < p < 1$$

First, we judge whether the equation has a solution with the Jacobi determinant:

$$\boldsymbol{J} = \frac{\partial(\pi_1, \pi_2)}{\partial(Q_1, Q_2)} = \begin{vmatrix} \frac{\partial \pi_1}{\partial Q_1} & \frac{\partial \pi_1}{\partial Q_2} \\ \frac{\partial \pi_2}{\partial Q_1} & \frac{\partial \pi_2}{\partial Q_2} \end{vmatrix} = \begin{vmatrix} \frac{\partial \pi_1}{\partial Q_1} & 0 \\ 0 & \frac{\partial \pi_2}{\partial Q_2} \end{vmatrix} > 0$$

That is, the condition of the implicit function theorem holds, and its analytical solution must exist.

According to Kuhn-Tucker conditions, there are:

$$\varphi_1(Q_1, Q_2, \lambda) = c_1Q_1 + p_1G(Q_0 - Q_1)Q_1 - (1 - p_1)P(Q_1 - Q_0)Q_1 + \lambda(Q_1 + Q_2 - 2Q_0) \tag{3.6}$$

$$\varphi_2(Q_1, Q_2, \lambda) = c_2Q_2 + p_2G(Q_0 - Q_2)Q_2 - (1 - p_2)P(Q_2 - Q_0)Q_2 + \lambda(Q_1 + Q_2 - 2Q_0) \tag{3.7}$$

Considering $\varphi_1(Q_1, Q_2, \lambda)$, The first-order conditions for considering this optimization problem are as follows:

$$\frac{\partial \varphi_1}{\partial Q_1} = c_1 + p_1GQ_0 - 2p_1GQ_1 - 2(1 - p_1)PQ_1 + (1 - p_1)PQ_0 + \lambda = 0$$

$$\frac{\partial \varphi_1}{\partial Q_2} = \lambda = 0$$

$$\frac{\partial \varphi_1}{\partial \lambda} = Q_1 + Q_2 - 2Q_0 = 0$$

The solution is:

$$Q_1^* = \frac{c_1 + p_1GQ_0 + (1 - p_1)PQ_0}{2p_1G + 2(1 - p_1)P} \tag{3.8}$$

$$Q_2^* = \frac{3p_1GQ_0 + 3(1 - p_1)PQ_0 - c_1}{2p_1G + 2(1 - p_1)P} \tag{3.9}$$

5. Comparative Static Analysis and Discussion

5.1. Analysis of the Random Carbon Emission Model of a Single Enterprise

According to formula (3.3), due to $0 < p < 1$, we can get:

$$\frac{\partial Q_1^*}{\partial G} = \frac{-2pc}{(2pG+2(1-p)P)^2} < 0, \quad \frac{\partial Q_1^*}{\partial P} = \frac{-2(1-p)c}{(2pG+2(1-p)P)^2} < 0, \quad \frac{\partial Q_1^*}{\partial Q_0} = \frac{pG+(1-p)P}{2pG+2(1-p)P} > 0.$$

That is, when other conditions are given, the carbon emissions of the single enterprise will decrease with the increase in the penalty for exceeding the policy carbon emissions (negative impact). The carbon emissions will decrease with the increase of incentives for compliance with policy carbon emissions (negative impact). The carbon emissions will increase with the increase of market carbon emission standards (positive impact).

When considering the income of the single enterprise, we can find that both policy incentives and penalties can effectively restrain the carbon emissions of enterprises; that is, the introduction of relevant green policies will effectively reduce the overall carbon emission level of the market. Although the increase in an enterprise's carbon emissions will lead to growth in the enterprise's economic earnings, the enterprise's carbon emissions will still be restrained considering policy factors. For the whole market, carbon emission standards can be used as the criteria for the greening of the market, and the level of carbon emission standards in the market will directly affect the income of enterprises.

5.2. Analysis of the Random Carbon Emission Model of Oligopolies

According to formulas (3.8) and (3.9), due to $0 < p < 1$, we can get:

$$\frac{\partial Q_1^*}{\partial G} = \frac{-2p_1c_1}{(2p_1G+2(1-p_1)P)^2} < 0, \quad \frac{\partial Q_1^*}{\partial P} = \frac{-2(1-p_1)c_1}{(2p_1G+2(1-p_1)P)^2} < 0, \quad \frac{\partial Q_1^*}{\partial Q_0} = \frac{pG+(1-p)P}{2pG+2(1-p)P} = \frac{1}{2} > 0;$$

$$\frac{\partial Q_2^*}{\partial G} = \frac{2p_1c_1}{(2p_1G+2(1-p_1)P)^2} > 0, \quad \frac{\partial Q_2^*}{\partial P} = \frac{2(1-p_1)c_1}{(2p_1G+2(1-p_1)P)^2} > 0, \quad \frac{\partial Q_2^*}{\partial Q_0} = \frac{3p_1G+3(1-p_1)P}{2p_1G+2(1-p_1)P} = \frac{3}{2} > 0.$$

That is, when other conditions are given and the income of enterprise 1 is considered, the carbon emissions of enterprise 1 will decrease with the increase in the penalty for exceeding the policy carbon emissions (negative impact). The carbon emissions of enterprise 1 will decrease with the increase in incentives for compliance with policy carbon emissions (negative impact). The carbon emissions of enterprise 1 will increase with the increase in the carbon emission standard in the market (positive impact). At the same time, the carbon emissions of enterprise 2 will increase with the increase in the penalty for exceeding the policy carbon emissions (positive impact). The carbon emissions of enterprise 2 will increase with the increase in incentives for policy carbon emission compliance (positive impact). The carbon emissions of enterprise 2 will increase with the increase in the carbon emission standard in the market (positive impact). According to duality, when the income of firm 2 is considered, the revenue impact of the carbon emissions of firm 1 and firm 2 will show an opposite trend.

When multiple enterprises are considered to be in the carbon emission market, the comparative static analysis results for enterprise 1 are basically equivalent to the contents discussed in Section 5.1. It is worth noting that, when the income of enterprise 1 is considered, the carbon emission of enterprise 2 is opposite to that of enterprise 1. Oligopolies at the top of the carbon emission list will enjoy the direct benefits brought by the carbon emission initiative [36], while other enterprises at the bottom may adjust their own carbon emission strategies due to the carbon emission situation of oligopolies. When one enterprise holds the initiative of market carbon emission, other enterprises will have two choices in decision-making: 1) compete for the initiative of market carbon emission with oligopolies, so as to ignore policy restrictions and increase enterprise carbon emission; or 2) give up competing with oligopolies for the initiative of market carbon emission, instead reduce their own carbon emission, and maintain enterprise earnings by enjoying the policy carbon emission dividend. According to the comparative static analysis in this section, in the above model of random carbon emission generated by simple oligopolistic enterprises, enterprises tend to choose the latter: they

positively adjust their own carbon emission level according to the intensity of policy incentives and policy starting intensity. Therefore, according to Model 4.2, we also reversely explain that the carbon emission initiative will bring actual benefits to enterprises.

6. Summary

Based on the theory of ecological modernization, this paper discusses the impact of government policies on enterprise greening and enterprise economic benefits and selects enterprise carbon emissions as the standard for enterprise greening. This paper first introduces the basic structure of the ecological modernization theory, then establishes a mathematical model based on the assumption of comparative static analysis and discussion, and finally draws a conclusion. Firstly, for enterprises, the government's macro-control (policy incentives and penalties) can effectively inhibit the carbon emissions of enterprises, thus explaining the theory of ecological modernization. At the same time, when multiple enterprises enter the carbon emission market, enterprises with carbon emission initiatives can obtain a higher market carbon emission right. Based on the hypothesis of a positive correlation between carbon emissions and enterprise income, enterprises with carbon emission initiatives can obtain higher enterprise income. In addition, when an enterprise with the carbon emission initiative appears in the market, other enterprises will choose to reduce their carbon emissions to comply with government policy requirements and obtain higher enterprise earnings rather than compete with the enterprise with the carbon emission initiative for the market carbon emission right. Therefore, appropriate policy formulation can better realize the double benefits of enterprise benefits and enterprise greening. In this case, enterprise carbon emissions will fluctuate positively according to changes in market standards.

The main contribution of this paper is to discuss the decision-making behavior of enterprises under the topic of sustainable development and green supply chains through simple mathematical model building and comparative static analysis. The limitation of this study is that the mathematical model only considers the carbon emissions of enterprises as a factor affecting enterprise earnings, while other enterprise attributes, such as enterprise scale, enterprise type, and enterprise industry, are not taken into account. At the same time, in order to better validate the model, empirical analysis based on a certain industry is also an indispensable part of future work, including the logistics industry [37] and manufacturing industry [2, 22, 24, 38-39]. However, on the other hand, some scholars say that the theory of ecological modernization still has a long way to go. For many countries and regions, ecological modernization is not the first choice for their development mode [11].

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