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Evolutionary game analysis of vehicle procurement in the courier industry from the perspective of green supply chain

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A B S T R A C T

In the contemporary era, green development has become integral to modern industrial supply chains. Accelerating the green transformation of the supply chain in the express delivery industry poses a significant challenge in China. To address this challenge, we establish a trilateral evolutionary game model that considers the interdependent constraints involving the government, vehicle suppliers, and courier companies. This model aims to explore the optimal stable decisions for each stakeholder and the entire supply chain system. Through numerical simulations, we analyze the impact of key parameters on the stability of strategies and find that there are four Evolutionary Stable Strategies (ESS) in the system. Economic factors play a dual role: income-related factors encourage the adoption of green strategies by stakeholders, whereas cost-related factors extend the time required for stakeholders to transition to green strategies. For sustained production and utilization of new energy vehicles, the government must utilize a balanced system of rewards and penalties effectively. Vehicle suppliers and courier companies should collaborate for mutually beneficial outcomes, jointly fostering the green transformation of the supply chain with a focus on cost reduction and efficiency improvement. This study offers theoretical insights and methodological support for decision-makers in green supply chain management.

1. Introduction

1.1 Background

Amidst the backdrop of efforts to achieve peak carbon emissions and pursue carbon neutrality, China is currently confronted with numerous intricate challenges, especially about economic production, environmental conservation, and resource management. The "Outline of the 14th Five-Year Plan (2021-2025) for National Economic and Social Development and Vision 2035 of the People's Republic of China" propose an expedited transition towards green development. This plan also highlights coordinating endeavors to promote high-quality economic development and enforce the principles of a circular economy, including enhancing eco-friendly infrastructure upgrades and establishing a multi-tiered system for efficient resource recycling. The report to the 20th National Congress of the Communist Party of China (CPC) outlines a scientifically formulated plan, entitled "Accelerating the Green Transformation of Development", which unambiguously calls for the promotion of green and low-carbon production and lifestyles. These strategic initiatives and recommendations impose new requirements for reshaping the supply chain within the framework of this novel development paradigm.

In the pursuit of transforming the express industry's supply chain into an eco-friendly one, scholars primarily concentrate on green packaging, reverse logistics, smart systems, and route optimization. Behnke et al. (2017) formulated a model for minimizing carbon emissions in real-world vehicle routing problems. Their experiments highlighted the significant emissions

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reduction potential of route selection based on road network types, including urban roads and highways. Zhang et al. (2019) integrated the concept of a low-carbon economy into cold chain logistics and utilized a combination of ant colony optimization and Ribonucleic acid computing techniques to develop a cold chain logistics route optimization model. Meherish et al. (2021) investigated integrated batch size and pricing strategies for secondary product packaging to incentivize recycling in the last-mile delivery. Ding et al. (2022) developed an evolutionary game model, integrating consumer environmental awareness into the model, and explored governance mechanisms for the express packaging recycling sector. Kolasińska et al. (2022) analyzed the influence of implementing smart concepts in sustainable development on customer service changes in last-mile logistics. Mao et al. (2023) introduced a four-tier reverse logistics network for express packaging recycling, consisting of primary collection nodes, collection centers, processing facilities, and end terminals.

The courier industry confronts a growing carbon emissions challenge, which contradicts the current national priorities of achieving 'carbon peak' and 'carbon neutrality.' Addressing this challenge necessitates a comprehensive approach that encompasses not only emissions reduction through improved packaging and optimized delivery routes but also an evaluation of the environmental impact in terms of green and low-carbon aspects when selecting express delivery infrastructure and vehicles. While there have been notable advancements in research on the green supply chain of the express industry, few studies have yet focused on the significance of equipment and facility selection in advancing the industry's sustainability and environmental friendliness. García-Flores et al. (2015) introduce decision support models for selecting processing equipment based on budget constraints, equipment availability, and final product requirements to optimize the supply chain's production potential while maintaining environmental sustainability. Hodgett (2016) presents a software framework that evaluates three multi-attribute decision-making methods, including the Analytic Hierarchy Process (AHP), Multi-Attribute Range Evaluation (MARE), and ELimination Et Choix Traduisant la REalité trois (ELECTRE III) methods. Sadeghian & Sadeghian (2016) introduce a solution for establishing a decision support system (DSS) by combining Artificial Neural Network (ANN) and Fuzzy Analytic Network Process (FANP) for selecting the Flexible Manufacturing System (FMS). Chakraborty et al. (2016) employed Quality Function Deployment (QFD) specifications to incorporate customer demand and material handling equipment technology into the selection of industrial truck adaptations. Dafnomilis et al. (2018) formulated a Mixed Integer Linear Programming (MILP) model to optimize terminal equipment configuration for handling graduate materials, demonstrating cost reduction through equipment and infrastructure selection. Petroutsatou et al. (2021) applied hierarchical analysis and conducted expert interviews, resulting in the development of a decision-making model.

1.2 Objectives

This study adopts a green equipment selection perspective within the green supply chain framework to analyze the dynamic evolution of vehicle procurement decision-making in the express industry. The study employs a tripartite evolutionary game model to explore the dynamic evolutionary outcomes involving government entities, vehicle suppliers, and courier companies. Furthermore, it elucidates the constraints among these stakeholders and identifies the Evolutionary Stable Strategies (ESS) for each stakeholder and the entire system. Finally, the model is rigorously validated through numerical simulations, offering both theoretical underpinning and practical decision-making guidance for the development of a sustainable industry chain and the optimization of the extensive supply chain dynamics within express delivery.

1.3 Organization

The subsequent sections of this paper are organized as follows. Section 2 introduces a tripartite evolutionary game model for vehicle procurement in the express delivery industry. Section 3 derives the evolutionary processes and stable strategies of each stakeholder and analyzes the stable points. In Section 4, MATLAB software is utilized to simulate and assess the influence of pertinent variables on the system through parameter assignment. Finally, Section 5 presents the primary research findings, draws conclusions, and outlines managerial implications.

2. The Evolutionary Game Model

2.1 Basic Assumptions of the Model

（1）**Hypothesis 1:** The study involves three types of game players (government, vehicle supplier, and courier company), who are all assumed to be rational and maximize their interests. The vehicle supplier's strategy includes either providing new energy vehicles or not. The courier company's gaming strategy includes whether use new energy vehicles or not. The government, to promote green supply chain construction and low-carbon economic and social development, may choose to regulate or not regulate (Xu, & Lv,2014; Zi-xing & Ge, 2015; Jie et al.2021).

（2）**Hypothesis 2:** Adoption of a green strategy by the vehicle supplier and courier company will result in social and environmental benefits for the government. If either of the entities fails to adopt a green strategy, the government will incur costs for environmental remediation (Xu, & Lv, 2014). Government regulation provides subsidies for suppliers offering new energy vehicles and imposes penalties for non-compliance.

（3）**Hypothesis 3**: The government regulates with a proportion of x ($0 \le x \le 1$) and does not regulate with a proportion of (1-x). The proportion of suppliers implementing a strategy to provide new energy vehicles is y ($0 \le y \le 1$) and the proportion of not implementing such a strategy is (1-y). The proportion of courier companies using a new energy vehicle strategy is z ($0 \le z \le 1$), while the proportion not using such a strategy is (1-z).

（4）**Hypothesis 4**: The cost of vehicle suppliers providing new energy vehicles, C_1, is defined to include the cost of purchasing green materials, research and development expenses, and wages of R&D personnel. The government provides a certain subsidy, E_0, to the supplier during regulation. If the vehicle supplier does not provide new energy vehicles, the government imposes a penalty, E_1. If the courier company chooses to use new energy vehicles, the supplier will receive an income, H. It is noted that C_1, E_0, E_1, and H are all greater than zero.

（5）**Hypothesis 5**: The cost for the courier company to use new energy vehicles is denoted as C_2. When the vehicle supplier implements a green strategy by providing new energy vehicles, the courier company's generated benefit from actively participating is recorded as M_0. In the event of the supplier not offering new energy vehicles, the courier company's benefit from using new energy vehicles through alternative channels, such as rental, is recorded as M_1. It is noted that C_2, M_0, and M_1 are all greater than zero.

（6）**Hypothesis 6**: In the context of the "peak carbon, carbon neutral" target, high-consumption, and high-pollution companies will cause environmental degradation. Hence, guiding companies toward low-carbon production is necessary. Under government regulation, the environmental and social benefits gained are represented by F_0, and the regulatory cost is represented by C_0. Meanwhile, without regulation, the social and environmental benefits are represented by F_1. When courier companies do not use new energy vehicles, the government incurs an environmental management cost represented by D_0. If suppliers do not provide new energy vehicles, the government incurs an environmental management cost represented by D_1. All F_0, C_0, F_1, and D_0 are greater than 0. The symbols for the parameters in the above hypothesis can be found in Table 1.

Table 1
Model parameters and definitions

Parameter	Definition
C_0	The cost of government regulation
C_1	The cost of the supplier company providing new energy vehicles
C_2	The cost of the courier company using new energy vehicles
E_0	During government regulation, the subsidy provided by the government to the supplier of new energy vehicles
E_1	During government regulation, the fine imposed by the government on the supplier who does not provide new energy vehicles
F_0	During government regulation, both the vehicle supplier and the courier company adopt green policies, and the government gains environmental and social benefits
F_1	Without government regulation, both the vehicle supplier and the courier company adopt green policies, and the government gains environmental and social benefits
M_0	The vehicle supplier and the courier company actively participate in the use of new energy vehicles, and the courier company obtains profits
M_1	The vehicle supplier does not provide new energy vehicles, and the courier company obtains profits through other channels such as renting new energy vehicles
H	The courier company uses new energy vehicles, and the supplier of new energy vehicles gains profits
D_0	The courier company does not use new energy vehicles, and the government pays environmental management costs
D_1	The vehicle supplier does not provide new energy vehicles, and the government pays environmental management costs
x	The proportion of government regulation is x, where $0 \le x \le 1$. The proportion of non-regulation is 1-x
y	The proportion of new energy vehicles provided by the vehicle supplier is y, where $0 \le y \le 1$. The proportion of non-provision is 1-y
z	The proportion of new energy vehicles used by the courier company is z, where $0 \le z \le 1$. The proportion of non-use is 1-z.

2.2 Evolutionary game model designing

The model analysis is performed utilizing the previously mentioned parameter symbols. The initial step involves the construction of a payoff matrix. Following this, expected payoffs for the three gaming entities are computed within various decision scenarios, all stemming from the established payoff matrix. Subsequently, by amalgamating the probabilities linked to each entity's two decisions, the average payoffs for each entity are ascertained. Table 2 displays the payoff matrix for the three entities.

Table 2
Tripartite evolutionary game payoff matrix

Government	Supplier	Courier company	
		Use（z）	Non-use（1-z）
Regulation（x）	Production（y）	$(-C_0-E_0+F_0,-C_1+E_0+H,-C_2+M_0)$	$(-C_0-E_0-D_0,-C_1+E_0,0)$
	Non-production（1-y）	$(-C_0+E_1-D_1,-E_1,-C_2+M_1)$	$(-C_0+E_1-D_0-D_1,-E_1,0)$
Non-regulation（1-x）	Production（y）	$(F_1,H-C_1,-C_2+M_0)$	$(-D_0,-C_1,0)$
	Non-production（1-y）	$(-D_1,0,M_1-C_2)$	$(-D_0-D_1,0,0)$

3. Resolution of Evolutionary Stable Strategies

3.1 Constructing the Expected Return Function

U_1 Expected Value of government choice of regulation:

$$U_1 = yz(-C_0-E_0+F_0)+y(1-z)(-C_0-E_0-D_0)+z(1-y)(-C_0-E_1-D_1)+(1-y)(1-z)(-C_0+E_1-D_0-D_1) = yzF_0-E_0y-E_1z+2E_1zy+E_1-yE_1-zE_1-C_0+D_0z-D_1+D_1y-D_0 \tag{1}$$

U_2 Expected Value of government choice of non-regulation:

$$U_2 = yzF_1 - y(1-z)D_0 + z(y-1)D_1 - (1-y)(1-z)(D_0+D_1) = yzF_1 + yD_1 + zD_0 - D_0 - D_1 \tag{2}$$

U_3 Expected Value of supplier selection for production:

$$U_3 = xz(-C_1+E_0+H)+x(1-z)(-C_1+E_0)+(1-x)z(H-C_1)-(1-x)(1-z)C_1 = xE_0+zH-C_1 \tag{3}$$

U_4 Expected Value of supplier selection for non-production:

$$U_4 = -xzE_1 - x(1-z)E_1 + (1-x)z*0 + (1-x)(1-z)*0 = -xE_1 \tag{4}$$

U_5 Expected Value for courier companies choosing to use:

$$U_5 = xy(-C_2+M_0)+x(1-y)(-C_2+M_1)+(1-x)y(-C_2+M_0)+(1-x)(1-y)(M_1-C_2) = -2xC_2-2yC_2+(M_0-M_1)y+M_1-C_2 \tag{5}$$

U_6 Expected Value for courier companies choosing not to use:

$$U_6 = 0 \tag{6}$$

U_g is the government's average payoff:

$$U_g = xU_1+(1-x)U_2 \tag{7}$$

U_s is the supplier's average payoff:

$$U_s = yU_3+(1-y)U_4 \tag{8}$$

U_e is the courier company's average payoff:

$$U_e = zU_5+(1-z)U_6 \tag{9}$$

3.2 Solving the Replicated Dynamic Equation

F(x) is the replication dynamic equation corresponding to the government:

$$F(x) = \frac{dx}{dt} x(U_1-U_g) = x(1-x)(U_1-U_2) = x(1-x)(yz(F_0+2E_1-F_1)-E_0y-2zE_1+E_1-yE_1-C_0) \tag{10}$$

F(y) is the replication dynamic equation corresponding to the supplier:

$$F(y) = \frac{dy}{dt} = y(U_3-U_s) = y(1-y)(U_3-U_4) = y(1-y)(xE_0+zH-C_1+xE_1) \tag{11}$$

F(z) is the replication dynamic equation corresponding to the courier company:

$$F(z) = \frac{dz}{dt} = z(U_5-U_e) = z(1-z)(U_5-U_6) = z(1-z)(-2xC_2-2yC_2+(M_0-M_1)y+M_1-C_2) \tag{12}$$

Associating Eq. (10), Eq. (11), and Eq. (12) to obtain the set of replicated dynamic equations for the government, suppliers, and courier companies.

$$\begin{cases} F(x) = x(1-x)(yz(F_0+2E_1-F_1)-E_0y-2zE_1+E_1-yE_1-C_0) \\ F(y) = y(1-y)(U_3-U_4) = y(1-y)(xE_0+zH-C_1+xE_1) \\ F(z) = z(1-z)(-2xC_2-2yC_2+(M_0-M_1)y+M_1-C_2) \end{cases} \tag{13}$$

By applying the stability principle of differential equations, the local equilibrium point can be obtained in the system of Eqs. (13) by setting F(x)=F(y)=F(z)=0：

$A_1(0,0,0)$, $A_2(0,0,1)$, $A_3(0,1,0)$, $A_4(0,1,1)$, $A_5(1,0,0)$, $A_6(1,1,0)$, $A_7(1,0,1)$, $A_8(1,1,1)$, $A_9(x^*,y^*,z^*)$.

where A9(x*,y*,z*) satisfies the following conditions.

$$\begin{cases} yz(F_0+2E_1-F_1)-E_0y-2zE_1+E_1-yE_1-C_0=0 \\ xE_0+zH-C_1+xE_1=0 \\ -2xC_2-2yC_2+\left(M_0-M_1\right)y+M_1-C_2=0 \end{cases} \tag{14}$$

Reinhard (1980) and Ritzberger (1995) suggest that the evolutionarily stable strategy is inherently asymmetric and can only manifest as a pure strategy Nash equilibrium, rather than a mixed strategy equilibrium. To determine the evolutionarily stable strategy, we analyze the equilibria of the eight pure strategies. Two general methods are commonly employed to assess stability. As per Weibull (1998), Liu (2015), and Guo (2016), the equilibrium point is reached when both the determinant (det(J)) and trace (tr(J)) of the Jacobi matrix are less than 0. However, this method is not employed in this study due to its complexity. Alternatively, Xiao (2020) and Zhao (2020) propose using the Lyapunov discriminant (indirect method) to assess the asymptotic stability of the equilibrium point. The equilibrium point is considered stable if all eigenvalues are negative, unstable if all eigenvalues are positive, and a saddle point if there are both positive and negative eigenvalues. The Jacobi matrix is calculated as follows:

$$\begin{pmatrix} \begin{matrix}(1-2x)(yz(F0+2E1-F1)\\-E0y-2zE1+E1-yE1-C0)\end{matrix} & \begin{matrix}x(1-x)(z(F0+2E1-F1)\\-E0-E1)\end{matrix} & \begin{matrix}x(1-x)(y(F0+\\2E1-F1)-2E1)\end{matrix} \\ y(1-y)(E0+E1) & (1-2y)(xE0+zH-C1+xE1) & y(1-y)H \\ -2z(1-z)C2 & z(1-z)(-2C2+M0-M1) & \begin{matrix}(1-2z)(-2xC2-2yC2+\\(M0-M1)y+M1-C2)\end{matrix} \end{pmatrix}$$

Table 3 presents the calculated results after substituting the (x, y, z) values of A_1-A_8 into the Jacobi matrix. The system is considered in a stable state and the point is identified as a stable evolutionary equilibrium, with the corresponding strategy as an evolutionarily stable strategy when all characteristic roots are negative.

Table 3
Equilibrium Stability and Asymptotic Stability Conditions

Equilibrium point	Eigenvalue	positive/negative polarity	Stability	asymptotic stability conditions
$A_1(0,0,0)$	$R_1=E_1-C_0$ $R_2=C_1$ $R_3=M_1-C_2$	Uncertain Positive Uncertain	Unstable	/
$A_2(0,0,1)$	$R_1=-E_1-C_0$ $R_2=H-C_1$ $R_3=C_2-M_1$	Negative Uncertain Uncertain	Uncertain	$H<C_1$ $C_2<M_1$
$A_3(0,1,0)$	$R_1=-E_0-C_0$ $R_2=C_1$ $R_3=-C_2+M_0$	Negative Positive Uncertain	Saddle point and unstable	/
$A_4(0,1,1)$	$R_1=F_0-F_1-E_0-C_0$ $R_2=C_1-H$ $R_3=3C_2-M_0$	Uncertain Uncertain Uncertain	Uncertain	$F_0<F_1+E_0+C_0$ $C_1<H$ $3C_2<M_0$
$A_5(1,0,0)$	$R_1=C_0-E_1$ $R_2=E_0-C_1+E_1$ $R_3=-3C_2+M_1$	Uncertain Uncertain Uncertain	Uncertain	$C_0<E_1$ $E_0+E_1<C_1$ $M_1<3C_2$
$A_6(1,1,0)$	$R_1=E_0+C_0$ $R_2=C_1-E_0-E_1$ $R_3=M_0-5C_2$	Positive Uncertain Uncertain	Unstable	/
$A_7(1,0,1)$	$R_1=E_1+C_0$ $R_2=E_0+H-C_1+E_1$ $R_3=3C_2-M_1$	Positive Uncertain Uncertain	Unstable	/
$A_8(1,1,1)$	$R_1=C_0+F_1+E_0-F_0$ $R_2=C_1-E_0-H-E_1$ $R_3=5C_2-M_0$	Uncertain Uncertain Uncertain	Uncertain	$C_0+F_1+E_0<F_0$ $C_1<E_0+H+E_1$ $5C_2<M_0$

The stability analysis results shown in Table 3 indicate that $A_1(0,0,0)$, $A_3(0,1,0)$, $A_6(1,1,0)$, and $A_7(1,0,1)$ fail to meet the stability conditions, thus corresponding strategies are not evolutionarily stable strategies. In contrast, the evolutionary stability of $A_2(0,0,1)$, $A_4(0,1,1)$, $A_5(1,0,0)$, and $A_8(1,1,1)$ differs significantly due to their distinct evolutionary stability conditions.

3.3 Analysis of Evolutionary Stable Strategies

3.3.1 Stability analysis of the point $A_2(0,0,1)$

To establish a stable state for strategy, point $A_2(0,0,1)$, certain conditions must be met. If the supplier offers a new energy vehicle, the cost (C_1) to the supplier should be lower than the benefit (H) gained when the courier company utilizes the new energy vehicle. In the absence of the supplier providing the new energy vehicle, the courier company should derive greater benefits (M_1) from alternative sources than the cost (C_2) of using the new energy vehicle. This implies that the supplier is unlikely to offer new energy vehicles if the cost of provision exceeds the benefit, whereas the courier company will opt for new energy vehicles if the advantages of environmentally friendly choices surpass the associated costs.

3.3.2 Stability analysis of the point $A_4(0,1,1)$

To establish a stable state for strategy point $A_4(0,1,1)$, specific conditions need to be fulfilled. Firstly, the government is inclined to choose 'no regulation' when the social benefits resulting from the regulatory strategy are lower than the actual opportunity costs incurred. Secondly, the supplier is more inclined to embrace a 'green' strategy when the benefits of manufacturing new energy vehicles exceed its production costs. Finally, the courier company will choose to use the new energy vehicles produced by the supplier when the benefits of participating in the supplier's environmentally friendly decision outweigh the associated costs.

3.3.3 Stability analysis of the point $A_5(1,0,0)$

To attain a stable state for strategy point $A_5(1,0,0)$, specific conditions must be met. Namely, the penalty (E_1) imposed on the supplier for not supplying the new energy vehicle under government regulation must surpass the cost (C_0) of compliance with the regulation. Furthermore, the cost (C_1) incurred by the supplier when providing the new energy vehicle should exceed the total sum of the subsidy (E_0) and penalty (E_1) imposed by the government during regulation. Lastly, the benefits (M_1) that the courier company gains from using alternative energy vehicles should be lower than the costs (C_2) associated with using them. This implies that the benefits of government regulation outweigh its costs, motivating the government to implement such measures. Conversely, the costs of supplying new energy vehicles are usually higher than the government's subsidies, discouraging suppliers from providing them. Lastly, the benefits of using new energy vehicles through alternative channels are typically offset by their input costs, prompting courier companies to refrain from using such vehicles.

3.3.4 Stability analysis of the point $A_8(1,1,1)$

To establish a stable state for strategy point $A_8(1,1,1)$, specific conditions need to be satisfied. Firstly, the government's benefits (F_0) must surpass the combined costs of government regulation (C_0), the government subsidy to the supplier (E_0), and the social benefits to the government in the absence of government regulation when all three actors take active measures under government regulation. Secondly, the cost to the supplier (C_1) must be less than the total of the benefits to the courier company (H) when it produces a new energy vehicle, along with the subsidy (E_0) and penalty (E_1) under government regulation. Thirdly, the combined cost to the supplier and the courier company (C_1) must be lower than the total benefits to the courier company (H) when it utilizes a new energy vehicle. Fourthly, when the supplier produces new energy vehicles, the cost (C_1) must be lower than the total of the benefit (H), the subsidy (E_0), and the penalty (E_1) when the courier company employs the new energy vehicles. Furthermore, both the supplier and the courier company must embrace the 'green' strategy, and the benefit (M_0) acquired by the courier company must considerably exceed the cost (C_2) of using new energy vehicles. These conditions signify that the social and environmental benefits resulting from the government's regulatory strategy outweigh the tangible costs and opportunity costs, motivating the government to favor the regulatory strategy. Furthermore, the benefits obtained by the supplier from manufacturing new energy vehicles exceed its production costs, rendering it more inclined to embrace the 'green' strategy. Lastly, when the benefits of the courier company's involvement in the supplier's green decision significantly outweigh the costs it incurs, the courier company will opt to utilize the new energy vehicles manufactured by the supplier.

4. Numerical Simulation Analysis

To further explore the decision-making dynamics among the three players and the time required to achieve equilibrium, we employed MATLAB software to manipulate the influencing factors of each player and assign parameter values. The simulation period was set to 20 months to capture real-world dynamics. Given the imperative to establish a green supply chain, all players were required to adopt "green" measures. Therefore, the ideal scenario was set at A_8 (1,1,1).

4.1 Verify the reliability of the stability point

Point A_2 (0,0,1) represents the policy where the government does not regulate, suppliers do not provide new energy vehicles, and courier companies use new energy vehicles. In the simulation, the parameter values satisfy $H<C_1$ and $C_2<M_1$, with $C_0=1$,

C_1=5, C_2=1, E_0=4, E_1=5, F_0=4, F_1=4, M_0=5, and M_1=5. Without loss of generality, the (x,y,z) initial values for the simulation are taken as (0.1,0.2,0.3) and (0.5,0.5,0.5) respectively. As time evolves, all three game subjects evolve in the direction of (0,0,1), as shown in Fig. 1 and Fig. 2.

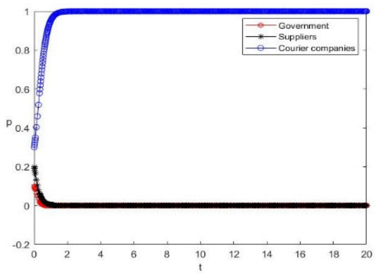

Fig. 1. The evolutionary path when (x,y,z) takes the values of (0.1, 0.2, 0.3)

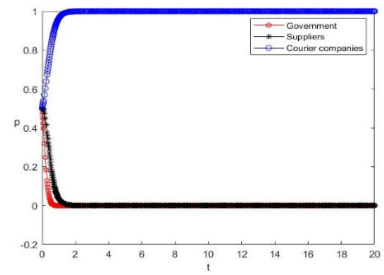

Fig. 2. The evolutionary path when (x,y,z) takes the values of (0.5, 0.5, 0.5)

The strategy of point A_4 (0,1,1) represents a scenario where the government does not regulate, suppliers provide new energy vehicles, and courier companies use new energy vehicles. To satisfy the condition F_0<F1+E0+C0 and C1<H, the values of parameters are set as C_0=1, C_1=1, C_2=1, E_0=2, E_1=5, F_0=1, F_1=2, M_0=5, M_1=5, and H=2. For the simulation, the initial values of (x,y,z) are taken as (0.2,0.3,0.4) and (0.6,0.2,0.5), respectively. The simulation results show that all three game subjects evolve in the direction of (0,1,1) (refer to Fig. 3 and Fig. 4).

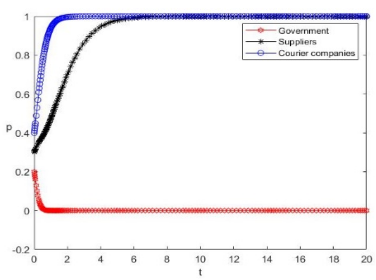

Fig. 3. The evolutionary path when (x,y,z) takes the values of (0.2, 0.3, 0.4)

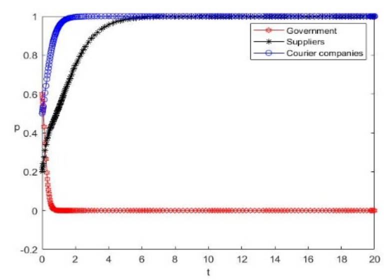

Fig. 4. The evolutionary path when (x,y,z) takes the values of (0.6, 0.2, 0.5)

The strategy of point A_5 (1,0,0) is characterized by government regulation, the absence of new energy vehicle supply from suppliers, and courier companies refraining from using new energy vehicles. The strategy is subject to the conditions $C_0 < E_1$, $E_0 + E_1 < C_1$, and $M_1 < 3C_2$, with $C_0 = 1$, $C_1 = 5$, $C_2 = 7$, $E_0 = 2$, $E_1 = 2$, $F_0 = 1$, $F_1 = 2$, $M_0 = 5$, $M_1 = 1$, and H = 2. Without loss of generality, initial values of (x, y, z) are set to (0.1, 0.6, 0.9) and (0.6, 0.4, 0.5). The simulation reveals that all three game subjects evolve towards the direction of (1,0,0) over time, as illustrated in Fig. 5 and Fig. 6.

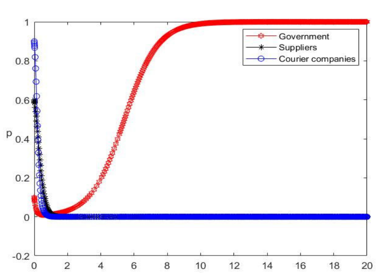

Fig. 5. The evolutionary path when (x,y,z) takes the values of (0.1, 0.6, 0.9)

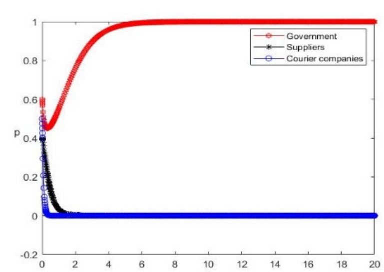

Fig. 6. The evolutionary path when (x,y,z) takes the values of (0.6, 0.4, 0.5)

The strategy at point A_8(1,1,1), comprising government regulation, supplier provision of new energy vehicles, and courier company use of new energy vehicles, must satisfy the conditions $C_0+F_1+E_0<F_0$, $C_1<E_0+H+E_1$, and $5C_2<M_0$. Setting C_0=1, C_1=1, C_2=1, E_0=1, E_1=1, F_0=6, F_1=1, M_0=7, M_1=6, and H=2 without loss of generality, the evolutionary simulation of initial values (0.3,0.6,0.3) and (0.9,0.9,0.9) shows that all three game subjects evolve towards (1,1,1) as time progresses (refer to Fig. 7 and Fig. 8).

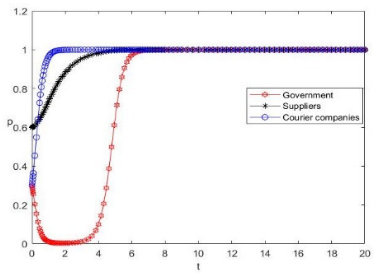

Fig. 7. The evolutionary path when (x,y,z) takes the values of (0.3, 0.6, 0.3)

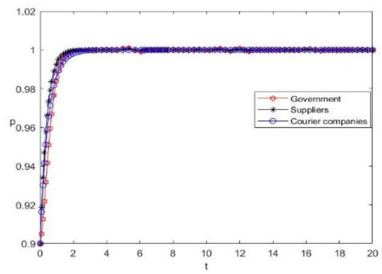

Fig. 8. The evolutionary path when (x,y,z) takes the values of (0.9, 0.9, 0.9)

The study conducted simulations based on the computed stability points and their asymptotic stability conditions. The asymptotic stability conditions of each stability point were used to determine the values of each parameter. The simulations were then conducted with varying initial points, and it was found that the results of the simulation evolution remained consistent despite changes in the initial point. This indicates the reliability of the computational analysis of the aforementioned stability points.

4.2 The influence of government-related parameters on the system

We define the initial decision-making willingness of the three participants as (0.5, 0.5, 0.5), and the parameter values are established using the idealized standard point $A_8(1,1,1)$ as a basis. In order to ensure the asymptotic stability conditions required to reach equilibrium, specific preconditions must be met for each parameter setting. The parameter values are defined as follows: C_0=1, C_1=1, C_2=1, E_0=1, E_1=1, F_0=6, F_1=1, M_0=7, M_1=6, and H=2. The initial evolutionary path diagram is obtained via simulation and is presented in Figure 9. Subsequently, the remaining parameters are held constant, while the income and expenditure parameters associated with government policies (C_0, E_0, E_1, F_0, F_1) are individually modified to observe their influence on the evolutionary path.

When C_0 is adjusted to 2 and 3, the corresponding evolutionary paths are graphed and displayed in Figure 10. The graph illustrates that as the value of C_0 increases, the time required to reach evolutionary equilibrium also increases. Consequently, the regulatory cost serves as an impediment to the government's decision to regulate, while a lower cost encourages regulatory action. Furthermore, when E_0 is adjusted to 2 and 3, the corresponding evolutionary paths are graphed and displayed in Figure 11. The graph demonstrates that as the value of E_0 increases, the time required for the government's decision to reach equilibrium also increases. This suggests that the government subsidy constitutes an additional cost, which slows down the evolutionary process.

When E_1 is set to 2 and 3, and the corresponding evolutionary path diagram is plotted (Figure 12), it becomes evident that an increase in E_1 leads to a slower government evolution toward regulation. This phenomenon arises because the penalty imposed on companies, which contributes to government utility, encourages the adoption of regulatory measures by the government. Furthermore, when F_0 is set to 7 and 8, and the corresponding evolutionary path diagram is obtained (Figure 13), it becomes evident that a higher F_0 value results in a shorter time for the government's strategy to reach equilibrium. By giving precedence to social benefits and enhancing social and environmental advantages, the government can foster green development and the harmonious coexistence of humans and nature. This aligns with the strategic goals of national development and expedites regulatory decision-making. In order to generate the evolutionary path diagram (Figure 14), we set F_1=2 and F_1=3. A higher F_1 value presents a greater challenge in reaching equilibrium. This is since, without government regulations, suppliers and courier companies can still yield social and environmental benefits through the adoption of green strategies. Nevertheless, as these benefits increase, the government's motivation and need to implement regulatory strategies diminish.

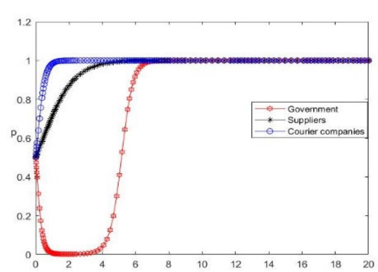

Fig. 9. Initial evolutionary path diagram

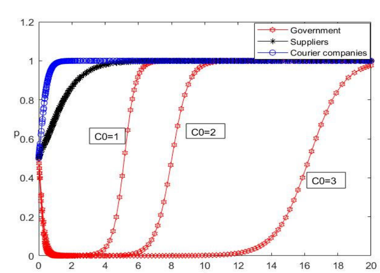

Fig. 10. Impact of Government Regulatory Costs (C_0) on ESS

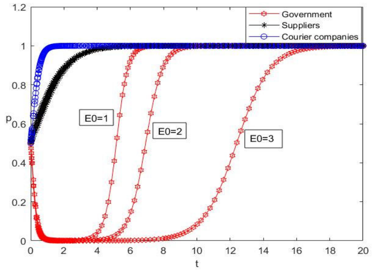

Fig. 11. Impact of subsidy (E_0) received by suppliers on ESS

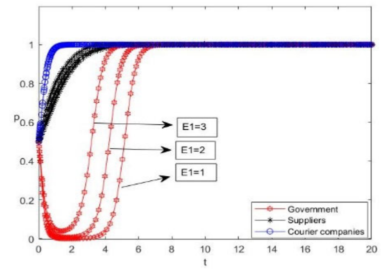

Fig. 12. Impact of the penalty imposed on suppliers (E_1) on ESS

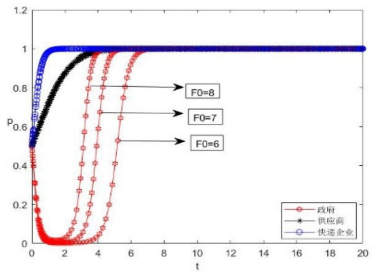

Fig. 13. Impact of benefits obtained from government regulation (F_0) on ESS

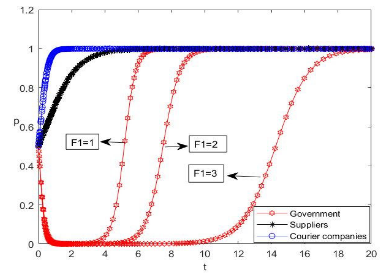

Fig. 14. Impact of benefits obtained from government non-regulation (F_1) on ESS

4.3 The influence of supplier decision parameters on the system

While keeping the remaining parameters constant, we examined the sensitivity of the system's evolution by altering the benefit and cost expenditure parameters (C_1, E_0, E_1, and H) associated with suppliers. Fig. 11 and Fig. 12 reveal that variations in the parameters E_0 and E_1 have a negligible effect on the evolutionary trajectory of supplier decisions. In contrast, the parameter H exerts a substantial influence, as illustrated by the evolutionary path diagrams when H is set to 3 and 10 in Fig. 15. A higher H value corresponds to a quicker decision-making process by suppliers regarding the provision of new energy vehicles. In practice, the development of new energy vehicles entails significant costs, and suppliers will opt to invest in them only if there is a favorable market demand. We generated the evolutionary path diagram by adjusting the parameters C_1 to 0.5 and 1.5, as depicted in Fig. 16. Notably, a higher C_1 value leads to a protracted decision-making process among suppliers regarding the production of new energy vehicles. This tendency can be ascribed to the considerable importance that companies attach to cost control and their meticulous assessment of the cost implications of their choices.

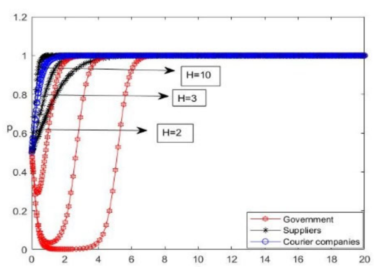

Fig. 15. Impact of vehicle supplier revenue (H) on ESS

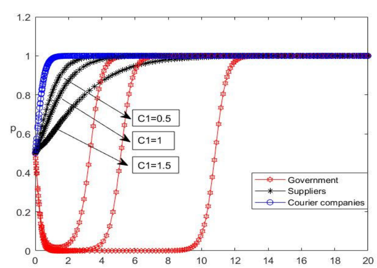

Fig. 16. Impact of vehicle supplier costs (C_1) on ESS

4.4 The influence of courier companies' decision parameters on the system

We explored the evolutionary sensitivity of the system while maintaining the other parameters constant, focusing on the benefit and cost expenditure parameters (C_2, M_0, and M_1) associated with the courier companies. We generated the evolutionary game path diagram by configuring C_2 with values of 0.5 and 1.5, as depicted in Fig. 17. A smaller C_2 results in a faster attainment of evolutionary equilibrium for the courier company. This acceleration is driven by companies' emphasis on cost reduction, which spurs investments in new energy vehicles when cost reduction is achievable. To assess the influence of two additional parameters, M_0 and M_1, on the decisions made by courier companies, we obtained the evolutionary path diagrams by configuring M_0 as 6 and 30, and M_1 as 10 and 30, as shown in Fig. 18 and Fig. 19. It is evident that higher values of both M_0 and M_1 lead to an acceleration in the courier companies' evolution toward the stability point. A comparison between Fig. 17 and Fig. 18 indicates that courier companies exhibit greater sensitivity to improvements in benefits than reductions in costs. Consequently, companies make decisions that prioritize their maximum benefit, emphasizing cost reduction and efficiency enhancement.

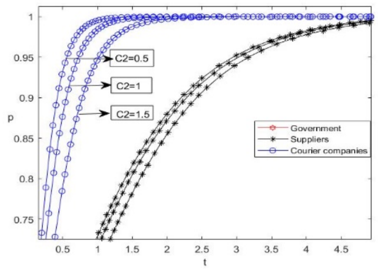

Fig. 17. Impact of courier company cost (C2) on ESS

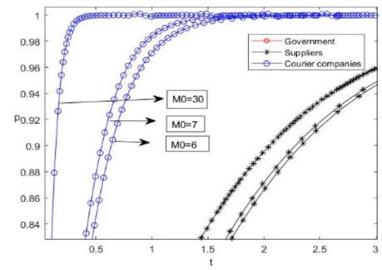

Fig. 18. Impact of the profit obtained by the express courier company (M_0) on ESS

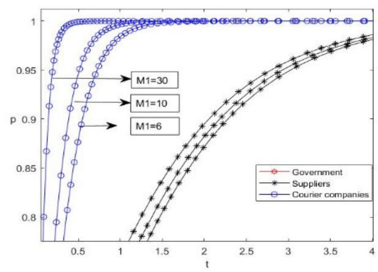

Fig. 19. Impact of the profit obtained by the express courier company (M_1) on ESS

5. Conclusion

Given that the development of a green supply chain constitutes a comprehensive endeavor, achieving the optimization of the entire system is of paramount importance. Within the framework of 'carbon peaking and carbon neutrality' in China, the overall system optimization must prioritize 'green development.' By employing evolutionary game theory, we establish a tripartite game model to analyze the dynamic evolution of the game among the government, vehicle suppliers, and courier companies. This model is utilized to identify the stable equilibrium of the system and investigate the influence of key factors on the evolutionary stable strategies of the game players. This study further demonstrates the evolutionary paths under various scenarios. More importantly, ESS analysis and numerical simulations are utilized to provide suggestions for the green transformation of supply chains. Overall, the conclusions are illustrated from three perspectives.

(1) Stakeholder decisions in the vehicle procurement process of the express industry are mutually interdependent. The government's decision-making process is influenced by its utility and the actions of suppliers and courier companies. Similarly, the government's motives and choices impact the decisions made by suppliers and courier companies. This study developed a game theory model, yielding four Evolutionary Stable Strategies (ESS).

The first strategy (0,0,1) depicts a scenario in which courier companies adopt new energy vehicles independently, without supplier involvement, in the absence of government regulation. In this scenario, upstream producers lack incentives to manufacture new energy vehicles, while courier companies can still benefit from making environmentally friendly choices. The second strategy (0,1,1) reflects a situation in which the government adopts a passive regulatory approach, while both suppliers and courier companies opt for environmentally friendly choices. In this case, the cost of government regulation exceeds the utility it provides, and both suppliers and courier companies benefit more from opting for new energy vehicles, fostering a spontaneous green transition. The third strategy (1,0,0) indicates that both suppliers and courier companies would refrain from selecting the new energy vehicle option under government regulation. This phenomenon is predominantly observed in small and medium-sized companies with limited technological capabilities. The elevated production and usage costs of new energy vehicles drive companies to embrace traditional modes instead of opting for green transformation.Finally, the fourth strategy (1,1,1) signifies that both types of companies make environmentally friendly choices under government regulation. Suppliers and courier companies will also realize substantial profits by embracing green strategies. These three entities collaborate to establish a green industry chain supply chain, progressively fostering a mutually beneficial cooperation and green development system.

(2) Numerical simulations reveal that in the entire evolutionary system where all participants engage in green actions, fines are more effective than government subsidies in triggering regulatory decisions. When comparing the benefits between the two states, one with government regulation and one without, it becomes evident that higher benefits obtained without regulation lead to greater delays in the government's regulatory decision-making. Conversely, lower benefits without regulation prompt regulatory decision-making. Notably, the government displays greater sensitivity to the benefits obtained without regulation when comparing the benefits in the two states. Suppliers are incentivized to make green decisions by profit,

but costs serve as a deterrent, and suppliers exhibit greater sensitivity to costs. Similarly to suppliers, courier companies base their decisions on the interplay of profits and costs, but they exhibit a higher sensitivity to profits. To reduce supplier costs, enhance the overall profits of courier companies, and ultimately ensure that all parties attain maximum benefits in the pursuit of green development, effective communication and information sharing among all stakeholders are imperative.

(3) To achieve the ideal state of (1,1,1), signifying the adoption of green decisions by both types of companies under government regulation, requires dynamic adjustments to key variables within both the government and the companies. The government should decrease subsidies and regulatory expenses while simultaneously raising penalties, aiming for a rapid convergence toward a stable regulatory strategy. On the corporate level, actions must be taken to curtail production costs, thereby ensuring the full realization of benefits stemming from both the company's efforts and government subsidies.

In practice, the determination of precise government incentives and penalties should be grounded in a thorough analysis of the prevailing environmental conditions, enabling the government to establish appropriate subsidy and penalty levels. Companies can implement cost-control measures and foster the transformation of their supply chains toward sustainability by engaging in activities like negotiations, collaboration, and equitable benefit sharing with their primary suppliers. Through the implementation of these measures, the green transformation of all categories of companies can be facilitated, contributing to a more sustainable and environmentally friendly future.

Previous studies have been enhanced by scholars who have explored green supply chain transformation from diverse perspectives and employed various methodologies. However, there is limited exploration of the micro-level green equipment selection problem in the existing literature. Certain scholars have assessed company equipment selection using multiple evaluation methods but without accounting for government intervention, relying primarily on static mathematical models. Building upon prior research, this paper delves into the vehicle procurement decision-making process of courier companies within the framework of green supply chain and government policy mechanisms. We propose a tripartite evolutionary game model to elucidate the cost-benefit relationships and strategic decisions involving the government, vehicle suppliers, and courier companies. This study contributes to the advancement of green supply chain transformation. The significance of this management approach lies in the government's dynamic adjustment of appropriate subsidy and penalty policies to foster mutually beneficial collaboration between vehicle suppliers and courier companies, ensuring the adoption of green and sustainable strategic decision-making within the supply chain system. Multiple stakeholders should collaborate to establish sustainable competitive advantages, create new market opportunities, leverage green operations for long-term gains, and align with the national strategy of 'carbon peaking and carbon neutrality'.

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Data Availability Statement

The data that support the findings of this study are openly available in 4TU.ResearchDataat https://doi.org/10.4121/22210771, reference number 10.4121/22210771.

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