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Computational Modeling and Numerical Simulation of a Three-Party Evolutionary Game in Drone Logistics

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Abstract
This paper proposes a computational evolutionary game model involving the government, logistics enterprises, and consumers to analyze the promotion mechanism of drone logistics.Based on replicator dynamic equations, the dynamic evolution of multi-agent strategies is formulated and solved using numerical computation methods. A simulation framework is implemented on the MATLAB platform, where multiple parameter scenarios are designed to analyze the sensitivity and convergence behavior of the system.Through computational experiments and dynamic evolution curves, the impacts of government subsidy intensity, enterprise revenue structure, and consumer perception parameters on system stability are quantitatively evaluated. The simulation results verify the theoretical stability analysis and demonstrate that appropriate subsidy policies and perception optimization can guide the system toward a stable collaborative equilibrium.The proposed model and simulation results provide a computational decision-support method for drone logistics promotion policies.

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Keywords: Computational evolutionary;Drone logistics;Dynamic equations;Multi-agent strategies

1. Introduction

With the rapid development of intelligent logistics and platform economy, drone delivery has gradually become an important technical means to enhance logistics efficiency and service coverage capabilities. However, during the actual promotion process, the development of drone logistics is not only constrained by technology, but also involves issues such as government subsidies and regulation, technological adoption by logistics enterprises, and consumer acceptance willingness, which require the collaborative decision-making of multiple stakeholders. The strategic interactions among different entities exhibit distinct dynamic evolution characteristics, resulting in a strong uncertainty in the promotion path of drone logistics. Therefore, it is necessary to depict the strategy evolution mechanism among the government, logistics enterprises, and consumers.

Pan [1] *et al*. constructed a three-party evolutionary game model from the perspective of the governance of the transportation service platform ecosystem, revealing the dynamic collaborative relationship among the government, the platform and users. Huang [2] *et al*. applied the three-party evolutionary game method to the study of subsidy-based supply chains and pointed out that the intensity of government subsidies and the revenue structure have a significant impact on the evolution of enterprise behavior. Li[3] *et al*. analyzed the problem of rumor propagation through evolutionary game analysis and further verified the applicability of this method in characterizing the dynamic adjustment process of strategies. In the field of logistics and supply chain, Wenxue [4] *et al*. studied the decision-making problem of logistics enterprise alliances based on three-party evolutionary games, and Tang[5] *et al*. explored the evolution characteristics of multi-agent strategies in emergency rescue scenarios through simulation analysis.

Although existing literature has discussed the three-party evolutionary game issues from the perspectives of platform governance, policy subsidies, and logistics collaboration, systematic research on the strategic interaction among the government, enterprises, and consumers in the promotion context of drone logistics is still relatively limited. In particular, the comprehensive analysis of subsidy incentives, technological returns, and consumer risk perception factors needs to be deepened. Based on this, this paper constructs a three-party evolutionary game model involving the participation of the government, logistics enterprises, and consumers, and through stability analysis and numerical simulation, explores the impact of key parameters on the system evolution results, providing theoretical references for the promotion of drone logistic

2. Research hypotheses and model construction

2.1. Model Symbols and Payment matrix

This article considers three main entities: the government, logistics enterprises, and consumers. The government chooses between the "subsidy" and "no subsidy" strategies, the logistics enterprises choose between the "using drone delivery" and "traditional delivery" strategies, and the consumers choose between the "accepting" and "rejecting" drone delivery strategies. The strategies of these three entities are dynamically adjusted and evolution is achieved through the replication of the dynamic mechanism.

Table 1: Symbol Assumption List

x	Probability that the government provides subsidies
y	Probability that enterprises adopt drone delivery
z	Probability that consumers accept drone delivery
Cg	government regulatory and infrastructure cost
S	Government subsidies to businesses and consumers
a	Percentage of government subsidies to enterprises
C_1	Operating cost of drone delivery
C_2	Consumer perceived safety cost
C_3	Businesses need to pay the cost of labor wages
C_4	Additional facility investment for drone delivery
R_1	Government social benefit under subsidy
R_2	Benefits of drone delivery for Businesses
R_3	Benefits for companies using traditional logistics
R_4	Government social benefit without subsidy
R_5	Benefits of consumers choosing traditional delivery methods
L_1	Reputational loss when enterprises do not adopt drone delivery
L_2	Government reputational loss under policy inaction
U	Benefits of drone delivery for consumers
W	Additional utility from supporting drone delivery
F_1	Potential loss when drone delivery is rejected by consumers
b	Proportion of government subsidies used to reduce security costs

2.2. Construction of Game Model

Based on the payoff matrix of the game among the government, logistics enterprises and consumers, a replicator dynamic equation for the three parties can be derived.

The replication dynamic equation of the government strategy is:

$$F_{(x)}=\frac{dx}{dt}=x(R_x-\bar{R}_g)=x*(x - 1)*(Cg + S - 2*L_2*z - R_1*y + R_4*y + 2*L_2*y*z)$$

The dynamic equation for the replication of logistics enterprise strategies is:

$$F_{(y)}=\frac{dy}{dt}=y(R_y-\bar{R}_e)=-y*(y - 1)*(C_3 - C_1 - C_4 - F_1 + R_2 - R_3 + C_4*x + F_1*z + L_1*z + W*z - 2*L_1*x*z)$$

The replication dynamic equation of the consumer strategy is:

$$F_{(z)}=\frac{dz}{dt}=z(R_z-\bar{R}_c)=z*(z - 1)*(- S*b*y*x\text{^}2 + R_5 + C_2*y - U*y)$$

3. Stability analysis

3.1. Analysis of Government Policy Stability

When the social benefits brought about by the use of drones for logistics delivery outweigh the total cost of subsidies and institutional construction by the government, the government strategy will evolve to provide subsidies for drone logistics; conversely, the government is inclined not to provide subsidies. Whether the government will implement the subsidy policy in the long term depends on the net social benefits created by drone logistics. When the acceptance of consumers is high, the implementation effect of the subsidy policy is more significant, thereby enhancing the government's willingness to continue providing subsidies; while in the case of low consumer acceptance, the government is more inclined to carefully assess the cost-benefit of the subsidy.

3.2. Analysis of Logistics Enterprise Strategy Stability

The net profit of enterprises adopting drones is higher than the traditional distribution costs. The benefits brought by government subsidies and consumer acceptance can cover the potential losses. Therefore, enterprises tend to adopt drone delivery in the long term. The comprehensive cost of drone delivery and government subsidies are insufficient, resulting in a net profit lower than that of the traditional model. Therefore, enterprises tend to abandon drone delivery.

3.3. Analysis of Consumer Strategy Stability

The convenience benefits of drone delivery and the reduced safety costs due to government subsidies have significantly increased. Consumers tend to accept drone delivery. The sum of the benefits and safety costs of traditional delivery exceeds the combined effect of the net profit and government subsidy of drone delivery. Therefore, consumers tend not to accept drone delivery.

3.4. Stability Analysis of System Equilibrium Point

Let $F_{(x)} = 0$, $F_{(y)}=0$, $F_{(z)} = 0$. Then, the evolutionary game system has 8 pure strategy equilibrium points: E_1 (0, 0, 0), E_2 (1, 0, 0), E_3 (0, 1, 0), E_4 (0, 0, 1), E_5 (1, 1, 0), E_6 (1, 0, 1), E_7 (0, 1, 1), and E_8 (1, 1, 1). Based on the stability analysis of the Jacobian matrix, it is shown that under general parameter conditions, most of the equilibrium points are unstable or saddle points. Under specific parameter conditions, the equilibrium points E_7 and E_8 may evolve into stable strategies. Among them, when the government subsidy cost is high or the subsidy incentive is insufficient, the system may stabilize at E_7, that is, the government does not provide subsidies, enterprises adopt drone delivery, and consumers accept drone delivery. When the government subsidy intensity is moderate, enterprises adopting drone delivery can obtain stable positive net benefits, and the government subsidy and the enterprise's behavior jointly reduce the consumer safety perception cost. In this case, the system will converge stably to the E_8 equilibrium state, that is, the government provides subsidies, the logistics enterprise adopts drone delivery, and consumers accept drone delivery, forming a coordinated stable pattern. This result indicates that the long-term stable promotion of drone logistics depends on the synergy between government incentives, the enterprise's revenue structure, and consumer perception. The behavior of the three parties can form a virtuous interaction and stable equilibrium within a reasonable parameter range.

4. Simulation experiment

To further verify the feasibility of the theoretical model and the evolutionary law of the three-party strategies, we conduct numerical simulation experiments on the Matlab platform. The simulations explore how government, enterprises, and consumers dynamically adjust their strategies under different parameter settings. Table 2 presents the baseline parameter configuration.

Table 2: baseline parameter

Cg	L_2	R_1	R_4	C_4	L_1	C_3	C_1	F_1	R_2	R_3	W	S	b	C_2	U	R_5
50	25	200	40	20	15	40	30	20	120	80	10	100	0.5	10	30	20

4.1. E_8(1,1,1) Initial Evolutionary Path Diagram

As shown in Fig. 1, the strategy evolution curves are obtained through numerical iteration of the replicator dynamic equations. All three strategies gradually converge to 1, indicating that the system reaches a stable equilibrium under the given parameter configuration.

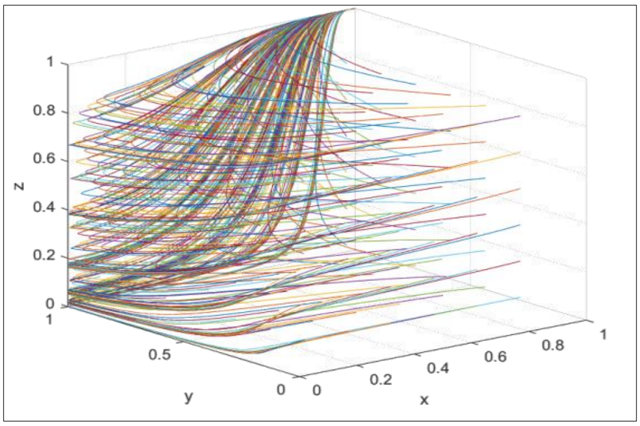

Fig 1: Initial Evolution Path Diagram of Government, Enterprises and Consumers

4.2. The influence of parameter sensitivity on x

The simulation results show that an increase in government subsidy intensity accelerates the convergence of the government's strategy toward providing subsidies. Higher consumer acceptance and enterprise adoption further enhance the effectiveness of subsidy policies, leading to faster stabilization of the government's strategy.

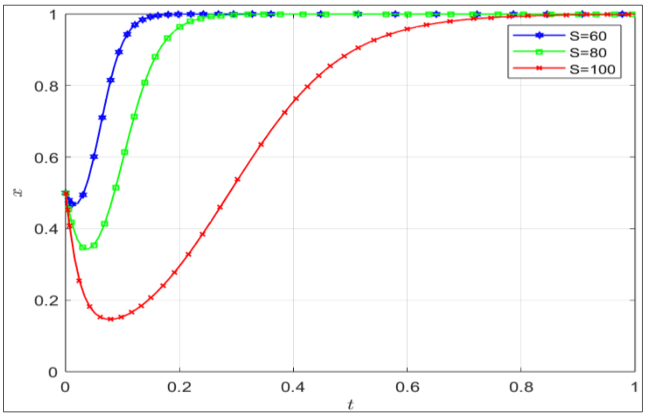

Fig 2: shows the influence of parameters S on the government's strategic behavior.

4.3. The influence of parameter sensitivity on y

With the increase in government subsidies and the revenue from drone delivery, the probability of logistics companies adopting drone delivery has significantly risen, and the convergence speed has also accelerated. This indicates that the synergy between subsidy incentives and market demand is the main driving force for enterprises to adopt drone delivery.

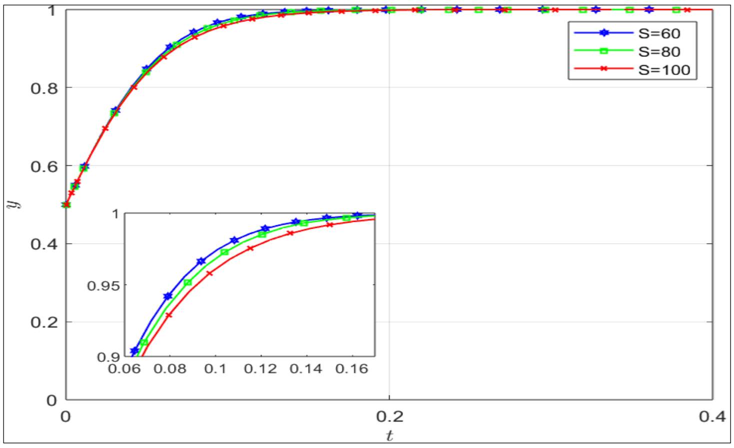

Fig 3: shows the influence of parameters S on the strategic behavior of enterprises

4.4. The influence of parameter sensitivity on z

Increasing consumers' perceived benefits and effectively reducing their safety concerns can significantly enhance consumers' willingness to accept drone delivery, thereby promoting the overall evolution of the system towards a coordinated, stable and balanced state.

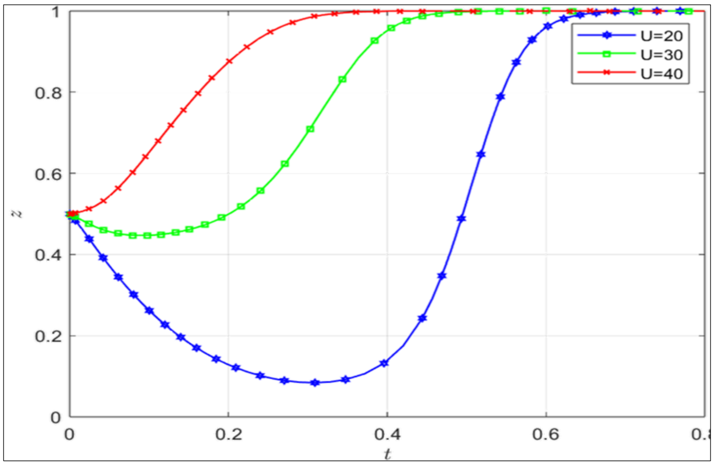

Fig 4: shows the influence of parameters U on consumers' strategic behavior.

5. Main conclusions and policy recommend actions

This article focuses on the relationship among the government, logistics enterprises, and consumers during the promotion of drone logistics, and constructs a three-party evolutionary game model. Through replicating dynamic analysis and numerical simulation, it explores the influence of key factors on the evolution results of the system.

Firstly, government subsidies play a crucial guiding role in the promotion of drone logistics. Moderate subsidies can effectively coordinate the adoption behavior of enterprises and the acceptance willingness of consumers, promoting the system to evolve from an uncoordinated state to a stable and coordinated equilibrium. However, excessive subsidies may reduce policy efficiency.

Secondly, whether logistics enterprises adopt drone delivery depends on the combined effect of government subsidy incentives and market demand. When the comprehensive benefits of drone delivery, under the influence of subsidies and consumer support, are higher than traditional delivery methods, enterprises are more likely to stabilize the adoption of drone technology.

Thirdly, consumers' decision to accept drone delivery is mainly influenced by the trade-off between perceived benefits and safety concerns. Government subsidies reduce consumers' perceived risks, and enterprises improve user experience by enhancing service quality. The synergy of these two factors helps to increase consumers' long-term acceptance of drone logistics.

Based on the above conclusions, when formulating policies for the promotion of drone logistics, the government should reasonably control the scale of subsidies and pay attention to subsidy efficiency. At the same time, it should improve relevant institutional norms to reduce the uncertainty risks for enterprises and consumers. Logistics enterprises should accelerate technology application and service optimization during the subsidy policy window period, and improve the economic efficiency of drone delivery through large-scale operation. In addition, through information disclosure and public communication mechanisms, consumers' understanding of the safety and reliability of drone logistics should be enhanced, thereby promoting the sustainable development of drone logistics.

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