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An Evolutionary Game Analysis of Digital Decision Making in Manufacturing Enterprises under Reward and Punishment Mechansim

Abstract. *This paper focuses on the evolutionary behaviour and the equilibrium strategy of the digital platform and manufacturing enterprises under the mechanism of reward and punishment. Based on the finite rationality hypothesis, the paper constructs the strategy evolution game model of government, digital platform, and manufacturing enterprise and studies the factors that affect the decision-making of the main body. The results show that: (1) Reasonable control of the amount of government subsidies to digital platforms and the amount of punishment to manufacturing enterprises is the premise of digital platforms and manufacturing enterprises to achieve the best strategy (enabling, innovation). (2) The number of products sold, the influence coefficient of manufacturing enterprises' innovation on business growth, the excess returns obtained by manufacturing enterprises and the innovation risk coefficient are important factors affecting the strategies of each main body; When the business scale of the enterprise is small or the innovation risk coefficient is low, the probability of the government choosing subsidies will be reduced, and the three parties may fall into the path of (punishment, empowerment, innovation). (3) The establishment of reward and punishment mechanisms can promote the win-win development of manufacturing enterprises and digital platforms. This study can provide a beneficial decision basis for the development of manufacturing enterprises.*

Keywords: *reward and punishment mechanism, digital platform, manufacturing enterprise, evolutionary game.*

JEL Classification: C61, C62, C70.

1. Introduction

The fourth industrial revolution with digital innovation as the core is an important development opportunity for China, and the application of digital technology to carry out digital innovation (Mohammed et al., 2023) can inject new impetus into the transformation of China's manufacturing industry to achieve high-quality development (Liu et al., 2020; Hu et al., 2022). With the continuous

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breakthrough and wide application of digital technologies such as mobile Internet, big data (Ju, 2022), cloud computing, and artificial intelligence, countries have formulated digital economy development strategies and introduced incentive policies. As a new ecology and new model, the platform economy is rapidly emerging as a new driving force for economic growth (Jiang & Jin, 2022). The wide application of digital technology can not only improve economic efficiency and promote economic development at the market level (Wang & Huang, 2022), but also help governments at all levels to form a new social governance model with multi-faceted coordination of decision-making, management, and actions (Wu & Tang, 2023). Therefore, consider how the government can change the production cost or research and development cost of enterprises through policy means such as subsidies and encourage digital platforms to empower enterprises. Ultimately, driving the digital transformation of manufacturing enterprises is very important.

In recent years, leading manufacturing enterprises at home and abroad (Taleb & PheniqiJu, 2023) have promoted the transformation of traditional production organisations to digital platform enterprises (Ruizan, 2021; Mainzer, 2022) through the implementation of digital platform transformation, which not only promotes the development of low-carbon economy and reduces energy consumption (Zhong et al., 2021; Chen et al., 2022; Guo et al., 2021), but also reconstructs the innovation advantages of enterprises in the digital era and consolidates and strengthens their competitiveness (Wang, 2023). It can be seen that the current manufacturing enterprises should seize the opportunity of digital transformation, and realise data empowerment is the key way to obtain competitive advantage. However, due to the relatively complex application scenarios of digital technologies involved in manufacturing enterprises, and the impact of technological distance and value driving force, they are easy to fall into the dilemma of "waiting for death without transformation, or facing death after transformation". Unable to continuously obtain the dividend of digital transformation (Chi et al., 2022), how to realise data empowerment for manufacturing enterprises has become the key to theoretical exploration.

This study focuses on the situation of government reward and punishment mechanism, takes digital platform and manufacturing enterprise as the research object, and uses evolutionary game theory to explore the decision-making behaviour of government, platform, and enterprise under the background of digital transformation. The innovation points lie in two aspects: (1) From the perspective of bounded rationality, evolutionary game theory is used to analyse the strategy choice and evolutionary behaviour among the government, digital platform, and manufacturing enterprises, which enriches the theoretical research on platform empowerment and enterprise innovation; (2) Considering the influence of multiple factors such as the number of products sold, the influence coefficient of manufacturing enterprises' innovation on business growth, the excess returns obtained by manufacturing enterprises and the innovation risk coefficient, the revenue model of digital platform and manufacturing enterprises under the reward and punishment mechanism is constructed, and the application scenario of platform digital empowerment is expanded through multi-factor analysis.

2. Literature survey

Studies on the digital transformation of manufacturing industry mainly include the mechanism of action (Xu & Wu, 2022), determining factors and development path, etc. Wu et al. (2023) conducted an empirical study on the enabling effect of digital economy from the dual perspectives of resource empowerment and structure empowerment, pointing out that the internal digital technology transformation of enterprises can significantly promote the improvement of green transformation and upgrading. And improving the government's digital governance ability can positively regulate the transformation of digital technology; Liu et al. (2022) took Xuzhou Construction Machinery Group and Shaanxi Automobile Group as cases to explain the generation conditions and mechanism of full digital empowerment from both the supply and demand sides. In terms of development path, although the overall level of green transformation and upgrading of China's manufacturing industry is on the rise, the main ways and means of transformation and upgrading of the manufacturing industry have not been implemented, and small and medium-sized enterprises still face implementation obstacles such as "dare not turn, unwilling to turn, will not turn" (Liu & Xu, 2023). Some scholars, based on the digital transformation experience of leading enterprises, it puts forward specific suggestions such as formulating encouraging policies, integrating manufacturing industry with related industries, and improving the resilience of industrial chain and supply chain (Shi, 2022).

Scholars mainly use case analysis, hierarchical regression analysis and evolutionary game to conduct exploratory research on platform digital empowerment. From the perspective of data empowerment, Zhou et al. (2018) discussed the impact of platform enterprise data empowerment on the process of value co-creation with the case study object, and came to the conclusion that platform enterprises effectively promote value co-creation through data empowerment. Mu et al. (2021) pointed out that the structural empowerment and resource empowerment of e-commerce platforms can provide favourable conditions for brand value creation. In addition, some scholars took Haier COSMOPlat (Sun et al., 2022) as the case study object and constructed an integrated theoretical model of "data resource action - data capability generation - ecological value realisation", which enables industrial Internet platform to promote the construction mechanism of digital business ecosystem. At the level of quantitative research, Liao et al. (2023) used hierarchical regression analysis to analyse 448 samples of effective manufacturing enterprises, and believed that digital platform capability had a significant positive effect on the service innovation performance of the manufacturing industry. Xiao et al. (2021) used game theory to build a mathematical model to discuss the optimal decision of data empowerment for retailers by e-commerce platforms, and explained the conditions for retailers to join the platform. Liu et al. (2022) discussed the impact of platform data sharing and technology empowerment on intelligent logistics ecological cooperation by constructing an evolutionary game model between platform enterprises and suppliers, and found that the relationship between agency fee, enabling cost, and service price elasticity coefficient determines the evolutionary stability strategy of both parties. Existing studies have discussed the relationship between platform empowerment and enterprise collaboration. In terms of the influence of decision-making under the government's reward and punishment mechanism, the analysis of implementation effect and the influence of determining factors are discussed, which can provide strong theoretical support for China to formulate policies to develop the digital economy and promote enterprise digital transformation.

3. Model specification

3.1 Model Description and Hypothesis

This study constructs a multi-agent game model under government subsidies and digital platform enabling manufacturing enterprise supply chain, and the logical relationship is shown in Figure 1.

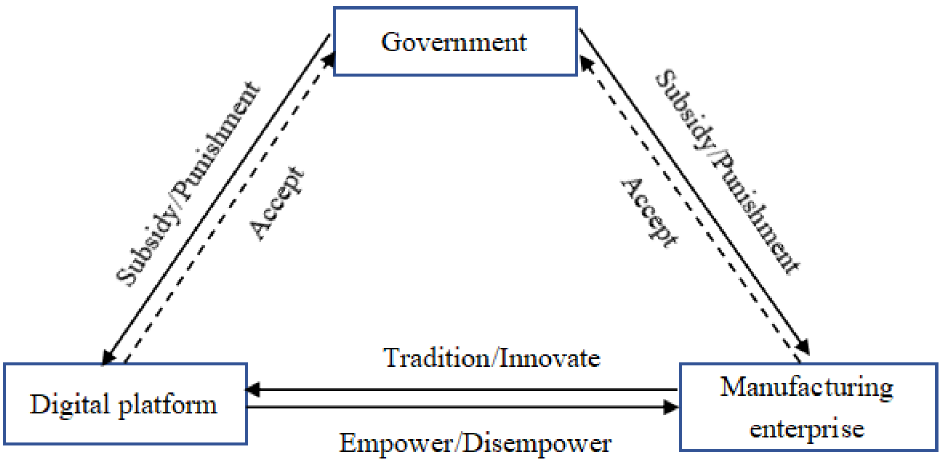


Figure 1. Multi-agent game model logical relation
Source: Authors'own creation.

In order to construct an evolutionary game model for the transformation and innovation strategies of digital platforms and manufacturing enterprises under government subsidies, the behavioural strategies of the three-party game players of the government, digital platforms, and manufacturing enterprises are studied, and the following hypotheses are proposed:

Hypothesis 1: The three players of the game are all bounded rationality, and the probabilities of the government choosing to supervise and not to supervise are respectively x, 1-x; The probability of the digital platform choosing to enable and not enable is respectively y, 1-y ; The probability of manufacturing enterprises choosing innovation and tradition is respectively z, 1-z。

Hypothesis 2: When the government subsidises or penalises the enabling behaviour of the digital platform and the innovative behaviour of the manufacturing enterprise, the digital platform and the manufacturing enterprise should choose to accept the subsidy, and the subsidy issued by the government is proportional to the efforts of the platform and the enterprise.

Hypothesis 3: The digital platform can obtain basic income when it chooses not to enable, and basic income and investment income when it chooses to enable. The basic income depends on commission income and is directly related to the transaction amount of the enterprise. Investment income is derived from enabling decisions, including the digital enabling service fees charged by the platform to enterprises and the long-term income obtained by investing in intelligent technologies or hardware facilities; when digital platforms choose to empower and manufacturers choose to innovate, spillover effects occur, and digital platforms can reap excess returns.

Hypothesis 4: Manufacturing enterprises can obtain basic benefits when they choose traditional operation mode, and basic benefits and innovation benefits when they choose innovative operation mode. When enterprises obtain digital support from the platform, they can avoid risks; otherwise, enterprises will face higher basic benefits of innovation risks. When digital platforms choose to empower and manufacturers choose to innovate, spillover effects occur, and manufacturers can reap excess returns.

Hypothesis 5: Both digital platforms and manufacturing companies face potential opportunity losses. When the platform chooses to enable and the enterprise chooses not to innovate, the enterprise will face the loss of missing the innovation opportunity. Similarly, when platforms choose not to empower but companies choose to innovate, platforms face lost opportunities to enter new areas. The main symbols of this study are described in Table 1.

Table 1. Description of main symbols

Code	Implication
E_S	Government subsidies for digital platforms
E_Q	Government subsidies for manufacturing enterprises
L_S	The amount of government penalties for digital platforms
L_Q	The amount of government penalties for manufacturing enterprises
e	Value-added tax benefits from digital platforms and manufacturing enterprises
α	Digital platform commission percentage
R_S	Basic cost of digital platform
T	A digital enabling service fee charged by a digital platform to an enterprise
θ_{SQ}	Excess returns from digital platforms
D_S	Potential lost opportunities for digital platforms
C_S	Digital enabling costs for digital platforms
$\ln(1+C_S)$	Forward investment returns on digital platforms, $\ln(1+C_S)>0$

Code	Implication
R_Q	Marginal return on a product
I_Q	The number of products sold indicates the business scale of the enterprise
k	The influence coefficient of manufacturing enterprise innovation on business growth, $0<k<1$
Δ	Digital enabling cost factor
β	The innovation risk coefficient of manufacturing enterprises, $0 \le \beta < 1$
D_Q	The potential opportunity loss faced by manufacturing enterprises
θ_{QS}	Excess earnings obtained by manufacturing enterprises

Source: Authors' own creation.

Based on the above analysis, the mixed strategy game matrix of the three game players of government, digital platform, and manufacturing enterprise is shown in Table 2.

Table 2. Tripartite game model payoff matrix

Strategy selection		Digital platform	Manufacturing enterprise: Innovate(z)	Manufacturing enterprise: Tradition(1-z)
Government	Subsidy (x)	Empower (y)	$e-E_S-E_Q,$ $E_S+\alpha(1+k)R_QI_Q+ln(1+C_S)+\theta_{SQ}+T-C_S,$ $E_Q+(1+k)R_QI_Q+\theta_{QS}-T$	$e-E_S,$ $E_S+\alpha R_QI_Q+ln(1+C_S)-C_S,$ $R_QI_Q-D_Q$
		Disempower (1-y)	$e-E_Q,$ $\alpha(1+k-\beta)R_QI_Q-\theta_{SQ}-R_S,$ $E_Q+(1+k-\beta)R_QI_Q$	$e,$ $\alpha R_QI_Q-R_S,$ R_QI_Q
	Punishment (1-x)	Empower (y)	$e,$ $\alpha(1+k)R_QI_Q+ln(1+C_S)+\theta_{SQ}+T-C_S,$ $(1+k)R_QI_Q+\theta_{QS}-T$	$e+L_Q,$ $\alpha R_QI_Q+ln(1+C_S)-C_S,$ $R_QI_Q-D_Q-L_Q$
		Disempower (1-y)	$e+L_S$ $\alpha(1+k-\beta)R_QI_Q-\theta_{SQ}-R_S-L_S$ $(1+k-\beta)R_QI_Q$	$e+L_Q+L_S,$ $\alpha R_QI_Q-R_S-L_S,$ $R_QI_Q-L_Q$

Source: Authors' own creation.

3.2 The model analyses

The stability and evolutionary path of the strategies of the three game players by using the stability theorem of differential equations. The stable point of the replicated dynamic equation should meet two conditions: $F(x)=0$ and $dF(x)/dx<0$.

（1）Analysis of strategic stability of manufacturing enterprises

In the supply chain system of the equipment manufacturing platform, the expected return of "subsidy" and "punishment" chosen by the government are U_{11} and U_{12} respectively, the average expected return is $\overline{U_1}$;

$$U_{11}=yz(e-E_S-E_Q)+y(1-z)(e-E_S)+(1-y)z(e-E_Q)+(1-y)(1-z)e \tag{1}$$

$$U_{12} = yze + y(1-z)(e+L_Q) + (1-y)z(e+L_S) + (1-y)(1-z)(e+L_Q+L_S) \quad (2)$$

$$\overline{U_1} = xU_{11} + (1-x)U_{12} \quad (3)$$

Replication dynamic equation:

$$H(x) = dx/dt = x(U_{11} - \overline{U_1}) = x(1-x)\left[y(E_S+L_S) - z(E_Q+L_Q) - L_S - L_Q\right] \quad (4)$$

$$H'(x) = dH(x)/dx = (1-2x)\left[y(E_S+L_S) - z(E_Q+L_Q) - L_S - L_Q\right] \quad (5)$$

When $W(z) = y(E_S+L_S) - z(E_Q+L_Q) - L_S - L_Q$, $z_0 = \left[y(E_S+L_S) - L_S - L_Q\right]/(E_Q+L_Q)$, proposition 1 is true.

Proposition 1: $z_0 = \left[y(E_S+L_S) - L_S - L_Q\right]/(E_Q+L_Q)$, When $0<z<z_0<1$, x=1 is the evolutionary stability point, and the stabilization strategy of the government is subsidy; When $0<z_0<z<1$, x=0 is the evolutionarily stable point, the government tends to adopt punitive strategies.

Proof: W(z) is a decreasing function, when $z=z_0$, W(z) =0, that is H(x)=0 and $H_x'(x) = 0$, therefore, $x \in [0,1]$ is a stable state, the manufacturing enterprise strategy will not change with time. When $0<z<z_0<1$, W(z)>0, $H(x)|_{x=1} = 0$ and $H_x'(x)|_{x=1} < 0$, so x=1 is the stable point; When $0<z_0<z<1$, W(z)<0, $H(x)|_{x=0} = 0$ and $H_x'(x)|_{x=0} < 0$, x=0 is the stable point.

According to proposition 1, the phase diagram of government strategy selection is shown in Figure 2.

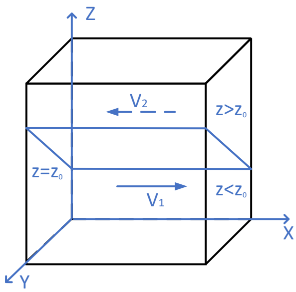


Figure 2. Phase diagram of government strategy selection
Source: Authors' own creation.

Corollary 1. When other parameters remain unchanged, with the decrease of E_S and E_Q, the government is more inclined to choose the subsidy strategy; with the increase of L_S and L_Q, the government is more inclined to choose the punishment strategy.

Proof: Because $z_0 = \left[y(E_S+L_S) - L_S - L_Q\right]/(E_Q+L_Q)$, when E_S *and* E_Q decrease, z_0 will increase, resulting in a continuous decrease in the volume of V_2 and an increase in the probability of choosing a subsidy strategy; similarly, when L_S and L_Q increase,

z_0 will decrease, resulting in a continuous decrease in the volume of V_1 and an increase in the probability of choosing a penalty strategy.

(2) Digital platform strategy stability analysis

The expected returns of digital platforms choosing "enable" and "not enable" are U_{21} and U_{22} respectively, and the average expected returns is $\overline{U_2}$;

$$U_{21} = xz[E_S + \alpha(1+k)R_Q I_Q + \ln(1+C_S) + \theta_{SQ} + T - C_S] + x(1-z)[E_S + \alpha R_Q I_Q + \ln(1+C_S) - C_S] \\ + (1-x)z[\alpha(1+k)R_Q I_Q + \ln(1+C_S) + \theta_{SQ} + T - C_S] + (1-x)(1-z)[\alpha R_Q I_Q + \ln(1+C_S) - C_S] \quad (6)$$

$$U_{21} = xz[\alpha(1+k-\beta)R_Q I_Q - \theta_{SQ} - R_S] + x(1-z)(\alpha R_Q I_Q - R_S) \\ + (1-x)z[\alpha(1+k-\beta)R_Q I_Q - \theta_{SQ} - R_S - L_S] + (1-x)(1-z)(\alpha R_Q I_Q - R_S - L_S) \quad (7)$$

$$\overline{U_2} = yU_{21} + (1-y)U_{22} \quad (8)$$

Replication dynamic equation:

$$H(y) = dy/dt = y(U_{21} - \overline{U_2}) = y(1-y)\begin{bmatrix} xz(C_S - R_S - L_S - \ln(1+C_S)) + x(E_S - L_S) + z(\alpha\beta R_Q I_Q + 2\theta_{SQ} + T) \\ + \ln(1+C_S) + R_S + L_S - C_S \end{bmatrix} \quad (9)$$

$$H'(y) = dH(y)/dy = (1-2y)\begin{bmatrix} xz(C_S - R_S - L_S - \ln(1+C_S)) + x(E_S - L_S) + z(\alpha\beta R_Q I_Q + 2\theta_{SQ} + T) \\ + \ln(1+C_S) + R_S + L_S - C_S \end{bmatrix} \quad (10)$$

when $W(x) = xz(C_S - R_S - L_S - \ln(1+C_S)) + x(E_S - L_S) + z(\alpha\beta R_Q I_Q + 2\theta_{SQ} + T) + \ln(1+C_S) + R_S + L_S - C_S$,

$$x_0 = \frac{\ln(1+C_S) + R_S + L_S - C_S + z(\alpha\beta R_Q I_Q + 2\theta_{SQ} + T)}{(L_S - E_S) + z[\ln(1+C_S) + R_S + L_S - C_S]} \\ = \frac{\alpha\beta R_Q I_Q + 2\theta_{SQ} + T}{\ln(1+C_S) + R_S + L_S - C_S} + \frac{[\ln(1+C_S) + R_S + L_S - C_S]^2 - (L_S - E_S)(\alpha\beta R_Q I_Q + 2\theta_{SQ} + T)}{z[\ln(1+C_S) + R_S + L_S - C_S]^2 + (L_S - E_S)[\ln(1+C_S) + R_S + L_S - C_S]},$$

proposition 2 is true.

Proposition 2: When $0<x<x_0<1$ and $y=0$ is the evolution-stable point, the digital platform tends to adopt the non-enabling strategy. When $0<x_0<x<1$ and $y=1$ is the evolutionary stable point, the digital platform tends to adopt the enabling strategy.

Proof: W(x) is an increasing function, when $x=x_0$, $W(x)=0$, $H(y) = 0$ and $H'_y(y) = 0$, so $y \in [0,1]$ steady state, the digital platform strategy does not change over time. When $0<x<x_0<1$, $W(x)<0$, $H(y)|_{y=0} = 0$ and $H'_y(y)|_{y=0} < 0$, so $y=0$ is the stable point; When $0<x_0<x<1$, $W(x)>0$, $H(y)|_{y=1} = 0$ and $H'_y(y)|_{y=1} < 0$, and so $y=1$ is the stable point.

According to proposition 2, the phase diagram of government strategy selection is shown in Figure 3.

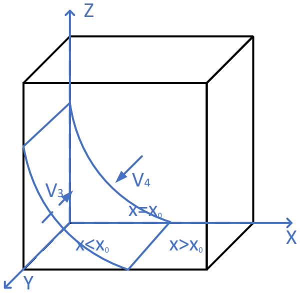


Figure 3. Phase diagram of digital platform strategy selection
Source: Authors' own creation.

Corollary 2: When other parameters remain unchanged, the digital platform is more inclined to choose the enabling strategy with the increase of R_S and L_S, while the digital platform is more inclined to choose the non-enabling strategy with the increase of C_S and E_S.

Proof: Because

$$x_0 = \left[\ln(1+C_S) + R_S + L_S - C_S + z(\alpha\beta R_Q I_Q + 2\theta_{SQ} + T)\right] / \left\{(L_S - E_S) + z\left[\ln(1+C_S) + R_S + L_S - C_S\right]\right\}$$,

when R_S and L_S increase, x_0 will decrease, resulting in the continuous increase of V_4's volume and the increase of the probability of selecting an enabling strategy; similarly, when C_S and E_S increase, x_0 will increase accordingly, resulting in the continuous increase of V_3's volume and the increase of the probability of selecting a non-enabling strategy.

（3） Analysis of strategic stability of manufacturing enterprises

The expected returns of manufacturing enterprises choosing "innovation" and "tradition" are U_{31} and U_{32} respectively, and the average expected returns is $\overline{U_3}$.

$$U_{31} = xy\left[E_Q + (1+k)R_Q I_Q + \theta_{QS} - T\right] + x(1-y)\left[E_Q + (1+k-\beta)R_Q I_Q\right] + (1-x)y\left[(1+k)R_Q I_Q + \theta_{QS} - T\right] + (1-x)(1-y)\left[(1+k-\beta)R_Q I_Q\right] \quad (11)$$

$$U_{32} = xy(R_Q I_Q - D_Q) + x(1-y)R_Q I_Q + (1-x)y\left[R_Q I_Q - D_Q - L_Q\right] + (1-x)(1-y)\left[R_Q I_Q - L_Q\right] \quad (12)$$

$$\overline{U_3} = zU_{31} + (1-z)U_{32} \quad (13)$$

Replication dynamic equation:

$$H(z) = dz/dt = z(U31 - \overline{U3}) = z(1-z)\begin{bmatrix} x(E_Q - L_Q - \beta R_Q I_Q) + y(\beta R_Q I_Q + \theta_{QS} - T + D_Q) \\ -xy\theta_{QS} + (k-\beta)R_Q I_Q + L_Q \end{bmatrix} \quad (14)$$

$$H'(z) = dH(z)/dz = (1-2z)\begin{bmatrix} x(E_Q - L_Q - \beta R_Q I_Q) + y(\beta R_Q I_Q + \theta_{QS} - T + D_Q) \\ -xy\theta_{QS} + (k-\beta)R_Q I_Q + L_Q \end{bmatrix} \quad (15)$$

When $W(y) = x(E_Q - L_Q - \beta R_Q I_Q) + y(\beta R_Q I_Q + \theta_{QS} - T + D_Q) - xy\theta_{QS} + (k-\beta)R_Q I_Q + L_Q$ and

$$y_0 = [(k-\beta)R_Q I_Q + L_Q + x(E_Q - L_Q - \beta R_Q I_Q)]/[x\theta_{QS} - (\beta R_Q I_Q + \theta_{QS} - T + D_Q)] = \frac{E_Q - L_Q - \beta R_Q I_Q}{\theta_{QS}} + \frac{(k-\beta)R_Q I_Q \theta_{QS} + (E_Q - L_Q - \beta R_Q I_Q)(\beta R_Q I_Q + \theta_{QS} - T + D_Q)}{x\theta_{QS}\hat{}2 - (\beta R_Q I_Q + \theta_{QS} - T + D_Q)\theta_{QS}}$$

, proposition 3 is true.

Proposition 3: When $0<y<y_0<1$ and $z=0$ is the evolutionarily stable point, manufacturers tend to adopt the non-enabling strategy. When $0<y_0<y<1$, $z=1$ is the evolutionarily stable point, manufacturing enterprises tend to adopt the enabling strategy.

Proof: W(y) is an increasing function, when $y=y_0$, $W(y)=0$, $H(z) = 0$ and $H_z'(z) = 0$, so $z \in [0,1]$ the steady state, the demand firm strategy does not change over time. When $0<y<y_0<1$, $W(x)<0$, $H(z)|_{z=0} = 0$ and $H_z'(z)|_{z=0} < 0$, so $z=0$ is the stable point; When $0<y_0<y<1$, $W(x)>0$, $H(z)|_{z=1} = 0$ and $H_z'(z)|_{z=1} < 0$, so $z=1$ is the stable point.

According to proposition 3, the phase diagram of cloud platform strategy selection is shown in Figure 4.

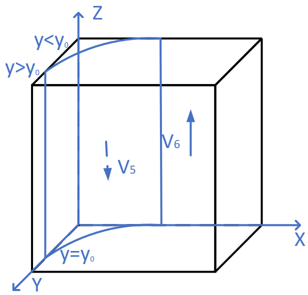


Figure 4. Phase diagram of strategy selection for manufacturing enterprises
Source: Authors' own creation.

Corollary 3: Under the condition that other parameters remain unchanged, with the increase of k、R_Q、I_Q、D_Q and θ_{QS}, manufacturing enterprises are more inclined to choose traditional strategies; with the increase of β and T, manufacturing enterprises are more inclined to choose innovative strategies.

Proof: Because

$$y_0 = [(k-\beta)R_Q I_Q + L_Q + x(E_Q - L_Q - \beta R_Q I_Q)]/[x\theta_{QS} - (\beta R_Q I_Q + \theta_{QS} - T + D_Q)]$$

when k、R_Q、I_Q、D_Q and θ_{QS} increase, y_0 will increase, will lead to the V_5 volume continues to increase, manufacturing enterprises choose traditional strategy to increase, similarly, when β and T increase, y_0 will decrease, V_6 volume increases, manufacturing enterprises choose innovation strategy probability increases.

4. Results and discussion

4.1 Strategy stability analysis of evolutionary game

The local stability of these equilibrium points is analysed according to the Jacobian matrix.

$$J=\begin{bmatrix} H'_x(x) & H'_y(x) & H'_z(x) \\ H'_x(y) & H'_y(y) & H'_z(y) \\ H'_x(z) & H'_y(z) & H'_z(z) \end{bmatrix}$$

$$=\begin{bmatrix} (1-2x)[y(E_S+L_S)-z(E_Q+L_Q)-L_S-L_Q] \\ x(1-x)(E_S+L_S) \\ x(x-1)(E_Q+L_Q) \\ y(1-y)[z(C_S-R_S-L_S-\ln(1+C_S))+(E_S-L_S)] \\ (1-2y)[xz(C_S-R_S-L_S-\ln(1+C_S))+x(E_S-L_S)+z(\alpha\beta R_Q Z_Q+2\theta_{SQ}+T)+\ln(1+C_S)+R_S+L_S-C_S] \\ y(1-y)[x(C_S-R_S-L_S-\ln(1+C_S))+(\alpha\beta R_Q Z_Q+2\theta_{SQ}+T)] \\ z(1-z)(E_Q-L_Q-\beta R_Q I_Q-y\theta_{QS}) \\ z(1-z)(\beta R_Q I_Q+\theta_{QS}-T+D_Q-x\theta_{QS}) \\ (1-2z)[x(E_Q-L_Q-\beta R_Q I_Q)+y(\beta R_Q I_Q+\theta_{QS}-T+D_Q)-xy\theta_{QS}+(k-\beta)R_Q I_Q+L_Q] \end{bmatrix}$$

The characteristic values and stability of each equilibrium point are shown in Table 3.

Table 3. Stability analysis of tripartite evolutionary game

Equilibrium	Eigenvalue	Symbol	Stability
E1(0,0,0)	$-L_S-L_Q$, $\ln(1+C_S)+R_S+L_S-C_S$, $(k-\beta)R_Q I_Q+L_Q$	(-,X,+)	Instability
E2(0,0,1)	$-E_Q-2L_Q-L_S$, $\alpha\beta R_Q I_Q+2\theta_{SQ}+T+\ln(1+C_S)+R_S+L_S-C_S$, $-(k-\beta)R_Q I_Q-L_Q$	(-,X,-)	Instability
E3(0,1,0)	E_S-L_Q, $-\ln(1+C_S)-R_S-L_S+C_S$, $kR_Q I_Q+\theta_{QS}+D_Q-T+L_Q$	(X,X,+)	Instability
E4(1,0,0)	L_S+L_Q, $\ln(1+C_S)+R_S+E_S-C_S$, $(k-2\beta)R_Q I_Q+E_Q$	(+,X,X)	Instability
E5(0,1,1)	$E_S-E_Q-2L_Q$, $-(\alpha\beta R_Q I_Q+2\theta_{SQ}+T+\ln(1+C_S)+R_S+L_S-C_S$, $-(kR_Q I_Q+\theta_{QS}+D_Q-T+L_Q)$	(X,X,-)	Condition I is met to achieve ESS

Equilibrium	Eigenvalue	Symbol	Stability
E6(1,0,1)	$E_S + E_Q + 2L_Q$, $\alpha\beta R_Q I_Q + 2\theta_{SQ} + T + \ln(1+C_S) + E_S - L_S$, $-kR_Q I_Q - E_Q$	(+,X,X)	Instability
E7(1,1,0)	$L_Q - E_S$, $-\ln(1+C_S) - R_S - E_S + C_S$, $(k-\beta)R_Q I_Q + D_Q + E_Q - T$	(X,X,X)	Condition II is met to achieve ESS
E8(1,1,1)	$-E_S + E_Q + 2L_Q$, $-(\alpha\beta R_Q I_Q + 2\theta_{SQ} + T - L_S + E_S)$, $-((k-\beta)R_Q I_Q + D_Q + E_Q - T)$	(X,-,X)	Condition III is met to achieve ESS
Note: X denotes symbolic uncertainty and ESS denotes evolutionary stability strategy Condition I: $E_S < E_Q + 2L_Q, C_S < \alpha\beta R_Q I_Q + 2\theta_{QS} + T + \ln(1+C_S) + L_S + R_S$ Condition II: $E_S > L_Q, C_S < \ln(1+C_S) + L_S + R_S, T > (k-\beta)R_Q I_Q + D_Q + E_Q$ Condition III: $E_S > E_Q + 2L_Q, T < (k-\beta)R_Q I_Q + E_Q + D_Q$			

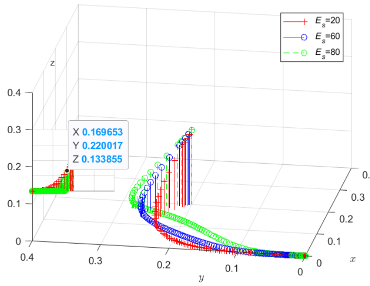
Source: Authors' own creation.

4.2 Numerical Simulation Analysis

(1) The stable equilibrium state of the model

In order to verify the effectiveness of the evolutionary stability analysis, the model was assigned numerical values combined with the actual situation, and Matlab 2021b was used for the numerical simulation. Array 1: E_S=25, E_Q=25, R_Q=1.4, I_Q=200, L_S=10, L_Q=15, C_S=120, R_S=100, T=5, θ_{QS}=200, α=0.05, β=0.6, D_Q=100, k=0.16. On the basis of array 1, the effects of E_S、L_Q、I_Q、k、θ_{QS} and β on the process and outcome of evolutionary game are analysed.

First, in order to analyse the influence of ES changes on the process and results of evolutionary game, E_S is assigned as E_S= 20,60,80 respectively, and the simulation results of the evolution of dynamic equations over time for 50 times are replicated, as shown in Figure 5. In order to analyse the influence of L_Q changes on the process and results of evolutionary games, L_Q was assigned L_Q= 5,15,25 respectively, and the simulation results were shown in Figure 6.



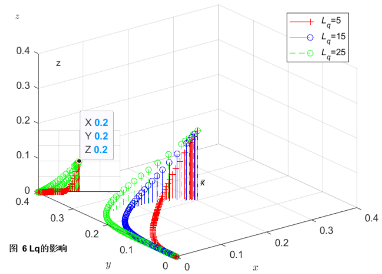
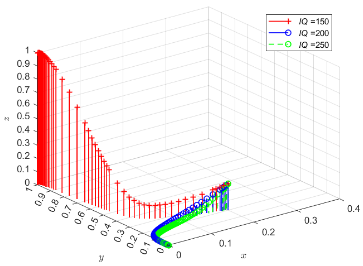


Figure 5. The influence of E_S **Figure 6. The influence of L_Q**

Source: Authors' own creation.

As can be seen in Figure 5, in the process of system evolution to a stable point, the increase of government subsidies to digital platforms can promote the evolution of digital platform enabling. With the increase of E_S, the probability of a digital platform enabling enterprises is on the rise, and the probability of manufacturing enterprises choosing innovation is on the rise. Therefore, the government's increase in the amount of subsidies for digital platforms can help digital platforms better empower enterprises, and also improve the speed of digital transformation of small and medium-sized manufacturing enterprises. Figure 6 shows that in the evolution process, with the increase of L_Q, the probability of enabling digital platforms increases, and the probability of innovation of manufacturing enterprises increases. The government can increase the punishment amount of manufacturing enterprises by improving the punishment mechanism and reasonably strengthening the penalty intensity, so as to improve the probability of digital platform empowerment and manufacturing enterprises' innovation.

Next, I_Q=150, 200, 250 were assigned, respectively, and the simulation results were shown in Figure 7; k=0.08, 0.16, 0.24, respectively. The simulation results are shown in Figure 8.



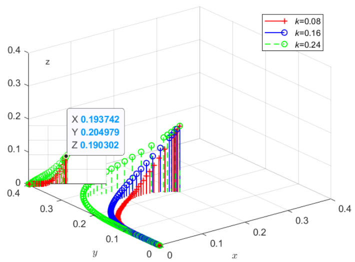


Figure 7. The influence of I_Q **Figure 8. The influence of k**

Source: Authors' own creation.

Figure 7 shows that when the enterprise business scale I_Q is 150, the system stable state is E(0,1,1), that is, when the enterprise scale is small, the enabling of the digital platform and the innovation of the manufacturing enterprise present an ideal stable state under the punishment of the government. As I_Q continues to increase, the probability of government subsidies increases and the probability of digital platform empowerment falls. Figure 8 shows that in the evolution process, the increase of k will decrease the probability of government subsidies. Therefore, manufacturing enterprises should reasonably plan policy subsidies according to their own business scale and business growth ability under the innovation strategy, which can drive the efficient empowerment of digital platforms through technology introduction, docking professional projects, and other programs.

Moreover, θ_{QS}=100, 150, 200 were assigned respectively to replicate the simulation results of the evolution of dynamic equations over time for 50 times, as shown in Figure 9. β is assigned β =0.3, 0.6, 0.9 respectively, and the simulation results are shown in Figure 10.

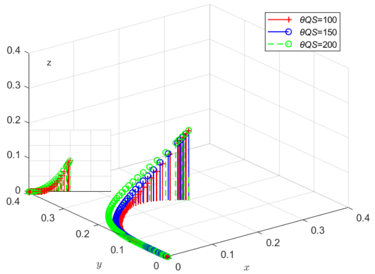


Figure 9. The influence of θ_{QS}

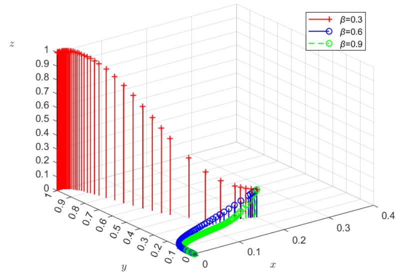


Figure 10. The influence of β

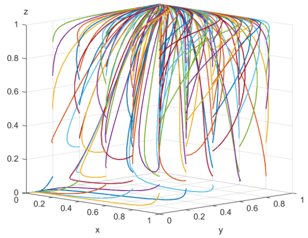
Source: Authors' own creation.

Figure 9 shows that in the process of evolutionary stabilisation, the probability of government subsidies will decrease with the increase of excess earnings θ_{QS} obtained by manufacturing enterprises, and the probability of digital platform selection enabling will increase. Figure 10 shows that when the innovation risk coefficient β is low, the system stable state is E(0,1,1), and the increase of β will increase the probability of government punishment and decrease the probability of digital platform empowerment. It can be seen that the innovation risk coefficient of manufacturing enterprises is too high and too low and will cause different degrees of impact on the digital transformation of enterprises. Manufacturing enterprises should pay attention to the change of innovation risk coefficient and timely adjust innovation strategies to further increase the robustness of enterprise development.

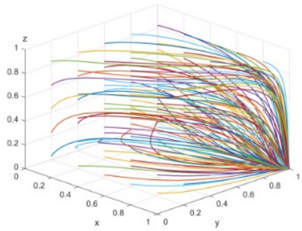
(2) Numerical simulation

The evolution trajectory of each game party is numerically simulated. Corrected array 1: E_S=25, E_Q=25, R_Q=1.4, I_Q=200, L_S=10, L_Q=15, C_S=120, R_S=100, T=5, θ_{QS}=150, α=0.05, β=0.5, D_Q=100, k=0.3 meets Condition I, assign array 2: E_S=30, E_Q=25, R_Q=1.4, I_Q=200, L_S=10, L_Q=15, C_S=100, R_S=100, T=5, θ_{QS}=150, α=0.1, β=0.6, D_Q=80, k=0.3 meets Condition II, array 3: E_S=60, E_Q=25, R_Q=1.4, I_Q=200,

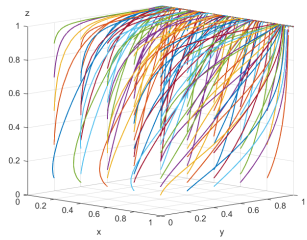
L_S=10, L_Q=15, C_S=120, R_S=100, T=5, θ_{QS}=150, α=0.05, β=0.16, D_Q=100, k=0.16 meets Condition *III*, Starting from different initial strategy combinations, the three sets of values evolved 50 times over time, and their evolution results were shown in a, b, and c in Figure 11.



a. E5(0,1,1)



b. E7(1,1,0)



c. E8(1,1,1)

Figure 11. System evolutionary stability
Source: Authors' own creation.

The simulation results can be obtained from Figure 11: In the early stage of the establishment of the government reward and punishment mechanism, the enabled benefit of the digital platform is less than the net benefit under the non-enabled strategy, and the digital platform will stabilise in the non-enabled mode. When the digital platform chooses to empower the enterprise, if the subsidy amount of the manufacturing enterprise is greater than the possible loss caused by its innovation risk, the manufacturing enterprise will tend to choose the innovation strategy, and the penalty income of the government will be greater than the subsidy input, the government will stabilise at the penalty, and the evolutionary game system will stabilise at E5(0,1,1). When the government's reward and punishment mechanism is gradually established, with the increase of government subsidies, manufacturing enterprises will stabilise the traditional operation mode, so the system is stable at E7(1,1,0). In the mature stage of the development of the government reward and punishment mechanism, with the increase of the subsidy amount of the digital platform, the production capacity of the manufacturing enterprises increases, and the income obtained under the innovation mode is greater than that under the traditional mode. Therefore, the manufacturing enterprises tend to the innovation mode, and the system is stable at E8(1,1,1). This means that as long as both digital platforms and manufacturers have a long-term development concept and recognise the benefits of empowerment and innovation, the road to digital transformation with government subsidies will be smoother. It can be seen that the simulation analysis is consistent and effective with the conclusion of the strategic stability analysis of all parties, and has practical guiding significance for the reward and punishment mechanism of manufacturing enterprises and digital platforms.

5. Conclusions

Considering the relationship and influencing factors of digital platform enabling manufacturing enterprises under the government's reward and punishment mechanism, this paper constructs a tripartite evolutionary game model among the government, digital platform and manufacturing enterprises, analyses the stability of each party's strategy choice, the stability of the game system's equilibrium strategy combination and the influence relationship of each element, and verifies the validity of the analysis conclusion through simulation analysis. The conditions of enabling the digital platform as a stable strategy combination are obtained, and relevant countermeasures and suggestions are put forward for the government reward and punishment mechanism according to the influence relationship and the stable conditions of each factor.

The main conclusions are as follows:

(1) The amount of government subsidies and penalties under the reward and punishment mechanism is an important factor affecting the development of manufacturing enterprises' platformisation. The enhancement of rewards and punishments by the government is conducive to promoting the digital empowerment of platforms and the innovative behaviour of digital transformation of manufacturing enterprises. A reasonable formulation of the amount of government subsidies for digital platforms and the amount of punishment for manufacturing enterprises is the premise for digital platforms and manufacturing enterprises to achieve the best strategy (empowerment, innovation).

(2) The influence coefficient of manufacturing enterprises' innovation on business growth and the excess earnings obtained by manufacturing enterprises are important factors affecting the government's reward and punishment strategy, and the number of products sold and the innovation risk coefficient of manufacturing enterprises are important factors affecting the digital platform empowerment strategy. With the increase of enterprise scale, the empowerment of digital platforms and innovation of manufacturing enterprises under government punishment show an ideal stable state. With the increase of innovation risk coefficient, the probability of government punishment increases, and the probability of digital platform empowerment decreases. Enterprises should choose the appropriate operation mode according to their own business scale and innovation risk coefficient.

(3) The establishment of government reward and punishment mechanisms can

promote the win-win development of manufacturing enterprises and digital platforms. When the efforts of digital platforms and manufacturing enterprises are low, increasing the amount of government punishment can improve the innovation efficiency of enterprises and stabilise the innovation strategy. With the improvement of the efforts of digital platforms and manufacturing enterprises, the amount of government subsidies to digital platforms will increase, and the production capacity of manufacturing enterprises will increase, and the system will eventually stabilise (subsidies, empowerment, innovation) to achieve win-win development of all subjects.

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