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Research article

An evolutionary game analysis of digital currency innovation and regulatory coordination

Bo Lan[1,*], Lei Zhuang[2] and Qin Zhou[1]

[1] School of Economics and Management, Southeast University, Nanjing 211189, China
[2] School of Economics and Management, Nanjing Tech University, Nanjing 211816, China

* **Correspondence:** Email: lanbo_seu@163.com.

Abstract: The innovation and regulatory coordination of digital currency is an important proposition in the new era of Fintech. There is increasing competition between traditional currencies and new digital currencies, so a spontaneous game model of currencies is analyzed. By introducing the role of financial coordination, this paper revises the evolutionary game model of digital currency innovation, and analyzes their competition strategies through case and simulation. The results show that: first, the dominant result of digital currency spontaneous game is that both parties tend to digital cooperation strategy. Second, with the introduction of financial regulation, the dominant result of digital currency tripartite evolutionary game is that financial institutions tend to participate in coordination and both currency parties tend to cooperate. Third, the choice strategy of currency is more sensitive to the changes of willingness to participate in cooperation, cooperation costs and cooperation benefits of financial coordination. The selection strategy of financial coordination institutions for digital currency is more influenced by changes in cooperation costs and incentive return in the process of participating in cooperation.

Keywords: digital currency; Fintech; currencies competition; financial regulatory coordination; evolutionary game

1. Introduction

The digitization of currency changes the form of money and intensifies market competition. Digital currency is increasingly playing an important role in the economic development of financial services, economic life and international exchanges. In the digital era, various types of currency competition are intensifying from a deeper level and a wider dimension. With the innovative application of digital technology, various forms of digital currency and payment have emerged in an endless stream, from the initial electronic ticket, to electronic card, to mobile payment, and various forms of virtual currency. The digital currency based on blockchain technology has triggered a new upsurge in currency innovation competition and cooperation among countries. At present, there are more than thousands of digital currencies which are in different financial ecosystems, such as Bitcoin, Litecoin, Ethereum, etc. Digitalization has changed the pattern of currency competition, including the competition between digital currency and traditional currency, private digital currency and central bank digital currency, as well as the competition between legal digital currency of various countries. The development of central bank digital currencies in many countries further highlights the importance of research on competition and cooperation in the international digital currency system. Therefore, the innovation competition and regulatory coordination of digital currency is a problem worthy of further study.

Digital currency is a new form of currency driven by fintech innovation, including electronic money, virtual money and legal digital money in a broad sense [1,2]. In the Internet era, the extensive use of information technology in the financial field has promoted a new round of fintech upsurge, and the innovation and application of blockchain technology is currently a hot spot [3,4]. At present, the digital currency based on blockchain technology is different from the electronic form of legal currency, the virtual currency provided by network operators and applied in the virtual space of the network [5-6]. The current electronic currency refers to the digitalization of cash or deposits representing certain wealth through electronic means, and the direct settlement of claims and debts through data trading system, which is essentially the digitalization of legal notes [7–9]. The virtual currency mainly refers to the exchange symbol of service value related to real wealth provided by the network virtual space, which can be roughly divided into three categories: game currency, special currency issued by network service providers (such as Tencent Q Coin), and virtual currency used for Internet financial investment (such as Bitcoin and Litecoin) [10,11]. Therefore, the current research on digital currency mainly focuses on the evolution and assumption of specific forms [12,13], mostly using the form of electronic money or virtual money for comparative analysis [14,15].

Digitalization is changing the pattern of currency competition. From the perspective of monetary innovation, the extensive use of science and technology in the financial field has promoted a new round of fintech climax, especially the innovation and application of blockchain technology. In the era of credit money, money itself has no value, but a problem of money credit [16,17]. Under different currency issuing systems, there are great differences in credit guarantee [18–20]. At present, from the perspective of attributes, it is mainly divided into public and private issuance, which is essentially the difference between fiat money (national credit) and private money (private credit) [21,22]. Therefore, the competition of digital currency mainly includes: the competition between digital currency and traditional currency, the competition between private digital currencies and central bank digital currencies, and the game of fiat digital currency will become a new focus of international currency competition, and the game around sovereign digital currencies is in full bloom [23–25]. It is an inevitable process for currency competition to evolve from private currency to national sovereign currency to super-sovereign currency, or to monopolize with a few sovereign currencies as international currency [26–28]. Digital currency competition has reached a consensus. First, competition among virtual currencies. Market results of virtual sales strategy different from traditional real sales strategy (players can only use real currency to purchase payment modules) are analyzed, and users are guided to use more virtual currency [29–31]. Second, competition among central bank digital currencies (CBDC). Various competitions have arisen due to central bank digital currencies or synthetic central bank digital currencies, including the competition between global stable currency (GSC) and fiat currency [32,33]. Competition between global stable currencies as well as competition between different central bank digital currencies [34,35].

There is a lot of literature on the analysis of currency competition methods. Based on the method of game theory, the international currency competition is deeply studied. From the interest game relationship between the issuing countries and the using countries of international currency, it is necessary to establish a fair international financial order, balance the interest risks between the issuing countries and the using countries of international currency, analyze the win-win model of currency internationalization and study the quantitative impact [36,37]. It constructs a game theory model in the open economy and analyzes the game process in which the central bank changes agents' expectations by changing exchange rate and monetary policy signals [38]. It analyzed the evolutionary equilibrium of euro and US dollar in a single population network [39]. Then, it extended the evolution of international currency in a single population environment to a multi-population environment, analyzing enterprises' preference for currency, the international usage of currency and the degree of currency internationalization in a multi-population environment [40]. Based on the revenue function of currency issuance and circulation, a two-country currency network model is established and extended to the multi-country model by evolutionary network game simulation [41,42].

At present, most research results and practices on digital currency are based on the evolution of digital currency, and they try to guide the development of digital currency and the design of future sovereign digital currency through technological innovation, promotion and use and financial regulation [43–45], while it ignored the competition and cooperation among digital currencies in the multi-currency network. This paper establishes an evolutionary game model among digital currencies without considering external factors to discuss the strategy adopted among different currencies. On this basis, financial supervision coordination is introduced. Under the condition that financial institutions participate in cooperation and provide incentive mechanism, the cooperative evolutionary game process of three-party game model is established and simulated, the countermeasures for the development of digital currency are put forward with the results of mathematical simulation. The remainder of this paper proceeds as follows. Section 2 spontaneous model of digital currency competition. Section 3 evolutionary model of digital currency competition under the financial coordination. Section 4 illustrates and simulates the digital currency competition. Finally, the conclusions and suggestions are given in Section 5.

2. Spontaneous model of digital currency competition

Digital currency takes technological innovation and use preference as their core competitiveness. The competition among currencies is a game based on currency dominance, which is essentially a series of game processes such as competing for currency market share among digital currencies to build a currency system with the dominant currency as the core. By establishing the digital currency game model, the digital currency participant spontaneous competitive game is carried out. Combined with the dominant and persistent problems in digital currency competition, a competitive game model is constructed to analyze the competition and cooperation strategies of participants, and the optimal behavior in the process of digital currency competition is obtained. Based on the above analysis, the following hypothesis is proposed.

Hypothesis 1: There are traditional electronic currency A (issued by institution A) and new digital currency B (issued by enterprise B), which players of the game are bounded rationality regardless of the external environmental friction. In the multi-currency market, currency A and B have two strategies that they can choose to cooperate or not to cooperate. Cooperation strategies of currencies include information sharing, system compatibility, application channel interaction, etc., while non-cooperation strategies include market barriers, system incompatibility, etc.

Hypothesis 2: The initial income of currency A and B is A_1 and A_2 respectively. If currency A and B have cooperative intention to become partners, the additional revenue of the cooperation between the two parties is ΔV, where the additional revenue of currency A is $\theta\Delta V$ and that of currency B is$(1-\theta)\Delta V$, $\theta(0<\theta<1)$ is the additional distribution coefficient of income. If the cooperation breaks down, the revenue of currency A and B are respectively T_1 and T_2. Due to the continuity of business development and the asymmetry of countermeasures, the benefits of both parties in the process of termination of cooperation are inconsistent, which the party that actively chooses to withdraw from the cooperation in advance will gain more speculative gains. If both parties have no intention to cooperate, the income of both parties shall be the initial operating income.

Hypothesis 3: Currency A and currency B need to pay certain operating costs in the operation process, and if the two parties cooperate, they also need to pay cooperation costs. The total cooperation cost paid by currency A and B is c, where the cost paid by currency A is tc, the cost paid by currency B is $(1-t)c$, $t(0<t<1)$ is the ratio coefficient of cost-sharing. If the partnership breaks down, the cost of currency A and B are respectively L_1 and L_2. While part of the business is still in contact, the exiting party needs to bear default costs W as a certain penalty, and the party who chooses to continue needs to undertake additional loss costs.

The probability of cooperation strategy adopted by currency A is x ($0\leq x\leq 1$), then the probability of non-cooperative strategy is (1-x). The probability of cooperation strategy adopted currency B is y($0\leq y\leq 1$), then the probability of non-cooperative strategy is (1-y).

The payoff matrix of the game between currency A and B is shown in Table 1 below:

Table 1. Payoff matrix for currency A and B game.

		Currency B	
		Cooperation	Non-cooperation
Currency A	Cooperation	$A_1+\theta\Delta V-tc$, $A_2+(1-\theta)\Delta V-(1-t)c$	$A_1+W-tc-L_1$, A_2+T_2-W
	Non-cooperation	A_1+T_1-W, $A_2+W-(1-t)c-L_2$	A_1, A_2

In the competitive process, the phased game strategy chosen by currency A and B may not be stationary and optimal, because the influence of the environment and cognition factors of the monetary institution. They will constantly adjust their strategies according to the growth of currency innovation, and through the adjustment of strategies to obtain a stable strategy for both sides. According to the above assumptions and payoff matrix (Table 1), then the income of cooperation strategy adopted by currency A is U_A^1, the income of the non-cooperation strategy is U_A^2 and the average income of comprehensive strategy selection is $\overline{U}_A$.

The income of cooperation strategy adopted by currency A:

$$U_A^1=y(A_1+\theta\Delta V-tc)+(1-y)(A_1+W-tc-L_1) \tag{2.1}$$

Benefits of non-cooperative strategy of currency *A*:

$$U_A^2 = y(A_1 + T_1 - W) + (1-y)A_1 \tag{2.2}$$

The average income of combined possible strategies adopted by currency *A*:

$$\overline{U}_A = xU_A^1 + (1-x)U_A^2 \tag{2.3}$$

Then, the replication dynamic equation for currency *A*:

$$\frac{dx}{dt} = x(1-x)[y(\theta\Delta V - T_1 + L_1) + W - tc - L_1] \tag{2.4}$$

In the same way, the replication dynamic equation for of currency *B*:

$$\frac{dy}{dt} = y(1-y)\{x[(1-\theta)\Delta V - T_2 + L_2] + W - (1-t)c - L_2\} \tag{2.5}$$

According to Eqs (2.4) and (2.5), the two-dimensional dynamical system model of currency *A* and *B* is:

$$\begin{cases} F_x = x(1-x)[y(\theta\Delta V - T_1 + L_1) + W - tc - L_1] \\ F_y = y(1-y)\{x[(1-\theta)\Delta V - T_2 + L_2] + W - (1-t)c - L_2\} \end{cases} \tag{2.6}$$

The local stable equilibrium points of the model are:

$$(0, 0), (0, 1), (1, 0), (1, 1), \left(\frac{(1-t)c + L_2 - W}{(1-\theta)\Delta V - T_2 + L_2}, \frac{tc + L_1 - W}{\theta\Delta V - T_1 + L_1}\right)$$

The first-order partial derivatives of *x* and *y* of the replication dynamic equation are obtained respectively. The Jacobian matrix is as follows:

$$J = \begin{bmatrix} (1-2x)[y(\theta\Delta V - T_1 + L_1) + W - tc - L_1] & x(1-x)(\theta\Delta V - T_1 + L_1) \\ y(1-y)[(1-\theta)\Delta V - T_2 + L_2] & (1-2y)\{x[(1-\theta)\Delta V - T_2 + L_2] + W - (1-t)c - L_2\} \end{bmatrix} \tag{2.7}$$

We can judge the local stability in various situations by the eigenvalues of the Jacobian matrix and the signs of the trace, and obtain the evolutionary stability strategy. It can be seen from Table 2 that the equilibrium points (0, 0) and (1, 1) is the local stable point, and $\left(\frac{(1-t)c+L_2-W}{(1-\theta)\Delta V-T_2+L_2}, \frac{tc+L_1-W}{\theta\Delta V-T_1+L_1}\right)$ is the saddle point. So, the evolutionary stable strategy of spontaneous currencies competition is {cooperation, cooperation} or {no cooperation, no cooperation}.

Table 2. Evolutionary stability analysis of spontaneous currencies competition equilibrium.

Equilibrium point	det*J*	tr*J*	Stability
(0, 0)	+	–	ESS
(1, 1)	+	–	ESS
(0, 1)	+	+	Unstable
(1, 0)	+	+	Unstable
$\left(\frac{(1-t)c+L_2-W}{(1-\theta)\Delta V-T_2+L_2}, \frac{tc+L_1-W}{\theta\Delta V-T_1+L_1}\right)$	–		Saddle point

According to the evolutionary stability analysis and dynamic replication equation phase diagram of currencies game, the connection between points (0,0), (1,0) and saddle point determines each part of the region, which the final strategy of currency A and currency B in the game is affected by the saddle point. When the coordinate value corresponding to the saddle point converges to (0,0), the area of the upper region is larger, indicating that currency A and B are more likely to choose cooperation strategy. On the contrary, when the coordinate value corresponding to the saddle point converges to (1,1), the area of the lower region is larger, indicating that currency A and B are more inclined to choose the non-cooperative strategy. In the currency evolutionary game model, the position of saddle point is affected by cooperation income and distribution coefficient, cooperation cost and sharing coefficient, loss cost, liquidated damages and speculative income. When the initial parameters reach a stable state, the cycle of collaborative strategies among digital currencies will become longer, which is conducive to promoting the common development of digital currencies. Therefore, cooperation strategies such as information technology sharing and market opening can promote collaborative innovation among currencies.

3. Evolutionary model of digital currency competition under the financial coordination

Financial regulation coordination is an important external force affecting the innovation and development of digital currencies. The innovative development of digital currency needs not only internal technical support, but also external financial policies and norms. In the innovation and cooperation of digital currency, on the one hand, faced with the upgrade of fintech, emerging currencies at a disadvantage may make traditional currencies fall into difficulties through innovation, and the new mode of one side makes the original operation of the other side difficult to continue. On the other hand, in the face of sudden policies such as financial regulation, both parties may face the risk of failure of the original business. In the wave of fintech innovation, many financial institutions cooperate with third-party payment companies to use new technological tools and products to improve currency business development and realize the interaction of different currencies through technological cooperation. From the perspective of financial regulation, financial coordination and regulation can solve the problem of market participation of digital currency in different growth stages. Based on the above content, financial coordination institution C as a third party is added into the game model of currency A and B for analysis, and the following assumptions are put forward.

Hypothesis 4: Financial regulatory coordination bodies mainly meet the practical needs, financial efficiency and policy security of digital currencies at various stages of regional development. The selection coordination strategy set of financial regulators is {strong participation, weak participation}. Therefore, the three parties involved in the game are bounded rationality and choose the optimal strategy through multiple games.

Hypothesis 5: When the financial coordination institution participates in the development of digital currency, the policies made by financial regulatory coordination can reduce the total cost of currency A and B in the collaborative innovation cooperation process by s, and the distribution coefficient of participation cost remains unchanged. Currency A and B can use their own technology to help financial coordination institutions complete the digital transformation and form a good credit reputation for currencies, and obtain cooperation benefits as R， where the distribution coefficient of cooperation income is $a(0 < a < 1)$. Then, the income of currency A and B are aR、$(1-a)R$ respectively. If financial coordination institutions Cchoose the strategy of ‘strong participation’ in the development of digital currencies, their gains are A_3. If financial coordination institution C chooses the strategy of "weak participation" which means little or no participation in currency competition regulation, and their gains are bA_3, Where b $(0 < b < 1)$ is the ratio between the income obtained by the financial coordinating institution by choosing the "weak participation" strategy and the income obtained by choosing the "stronger participation" strategy.

Hypothesis 6: When financial regulators participate in the coordination of digital currency innovation and development, they need to supervise the commercial activities of digital currency, and they need to invest corresponding human, material and financial resources. Thus, the total cost incurred by financial regulators is K_1. In addition, financial regulators also need to give certain incentives to digital currencies that actively participate in cooperation as K_2.

There is a chance that financial regulators will move into co-ordination. The probability that financial regulator *C* chooses to participate in the coordination strategy is z $(0 \le z \le 1)$, then the proportion of non-cooperative strategy is (1–*z*). According to the above six assumptions, the payment matrix of the game between financial coordinating institution and currencies is shown in Tables 3 and 4.

Table 3. Payment matrix of tripartite game under the stronger participation of financial coordinating institution.

Financial Coordination *C*		Currency *B* Cooperation	Non-cooperation
Currency *A*	Cooperation	$A_1 + \theta\Delta V - t(c-s) + K_2 + aR$, $A_2 + (1-\theta)\Delta V - (1-t)(c-s) + K_2 + (1-a)R$, $A_3 - K_1 - 2K_2$	$A_1 - t(c-s) - L_1 + K_2 + aR + W$, $A_2 + T_2 - W$, $A_3 - K_1 - K_2$
	Non-cooperation	$A_1 + T_1 - W$, $A_2 - (1-t)(c-s) - L_2 + K_2 + (1-a)R + W$, $A_3 - K_1 - K_2$	A_1, A_2, $A_3 - K_1$

Table 4. Payment matrix of tripartite game under the weak participation of financial coordinating institution.

Financial Coordination *C*		Currency *B* Cooperation	Non-cooperation
Currency *A*	Cooperation	$A_1 + \theta\Delta V - tc$, $A_2 + (1-\theta)\Delta V - (1-t)c$, bA_3	$A_1 + W - tc - L_1$, $A_2 + T_2 - W$, bA_3
	Non-cooperation	$A_1 + T_1 - W$, $A_2 + W - (1-t)c - L_2$, bA_3	A_1, A_2, bA_3

According to Table 3 and Table 4, the expected benefits of currency *A* when adopting the strategy of "cooperation" is U_A, the expected benefits of currency *A* when adopting the strategy "non-cooperation" is U_{1-A}, the average income of an integrated situation is $\overline{U}_A$.

$$U_A = yz[A_1 + \theta\Delta V - t(c-s) + K_2 + aR] + (1-y)z[A_1 - t(c-s) + K_2 + aR + W - L_1]$$
$$+y(1-z)(A_1 + \theta\Delta V - tc) + (1-y)(1-z)(A_1 + W - tc - L_1) \tag{3.1}$$

$$U_{1-A} = yz(A_1 + T_1 - W) + (1-y)z\ A_1 + y(1-z)(A_1 + T_1 - W) + (1-y)(1-z)A_1 \tag{3.2}$$

$$\overline{U}_A = x\ U_A + (1-x)U_{1-A} \tag{3.3}$$

The expected benefits of currency *B* when adopting the strategy of "cooperation" is U_B, and the expected return when adopting the strategy of "non-cooperation" is U_{1-B}, and the comprehensive average expected return is $\overline{U}_B$.

$$U_B = xz[A_2 + (1-\theta)\Delta V - (1-t)(c-s) + K_2 + (1-a)R] +$$
$$(1-x)z[A_2 - (1-t)(c-s) + K_2 + (1-a)R + W - L_2] + x(1-z)[A_2 + (1-\theta)\Delta V$$
$$-(1-t)c] + (1-x)(1-z)[A_2 + W - (1-t)c - L_2] \tag{3.4}$$

$$U_{1-B} = xz(A_2 + T_2 - W) + (1-x)z\ A_2 + x(1-z)(A_2 + T_2 - W) + (1-x)(1-z)\ A_2 \tag{3.5}$$

$$\overline{U}_B = yU_B + (1-y)U_{1-B} \tag{3.6}$$

The expected return of financial coordination institution *C* when adopting the strategy of "stronger participation" is U_C, and the expected return when adopting the strategy of "weak participation" is U_{1-C}, the comprehensive average return is $\overline{U}_C$.

$$U_C = xy(A_3 - K_1 - 2K_2) + x(1-y)(A_3 - K_1 - K_2) +$$
$$x(1-y)(A_3 - K_1 - K_2)(1-x)(1-y)(A_3 - K_1) \tag{3.7}$$

$$U_{1-C} = xybA_3 + x(1-y)bA_3 + x(1-y)bA_3 + (1-x)(1-y)bA_3 \tag{3.8}$$

$$\overline{U}_C = zU_C + (1-z)U_{1-C} \tag{3.9}$$

Thus, the replication dynamic equation of currency *A* can be written as:

$$F_{(x)} = \frac{dx}{dt} = x(1-x)[z(aR + K_2 + ts)y(\theta\Delta V - T_1 + L_1) + W - tc - L_1] \tag{3.10}$$

The replication dynamic equation of currency *B* is:

$$F_{(y)} = \frac{dy}{dt} = y(1-y)\{z[(1-a)R + K_2 + (1-t)s] +$$
$$x[(1-\theta)\Delta V - T_2 + L_2] + W - (1-t)c - L_2\} \tag{3.11}$$

The replication dynamic equation of financial coordination institution *C* is:

$$F_{(z)} = \frac{dz}{dt} = z(1-z)[(1-b)A_3 - K_1 - (x+y)K_2] \tag{3.12}$$

Therefore, the replication dynamic equations of currency *A*, currency *B* and financial coordination institution *C* are established as:

$$\begin{cases} F_{(x)} = x(1-\mathrm{x})[z(\mathrm{aR}+K_2+ts)+y(\theta\Delta\mathrm{V}-T_1+\mathrm{L}_1)+W-tc-\mathrm{L}_1] \\ F_{(y)} = y(1-y)\{z[(1-a)R+K_2+(1-t)s]+x[(1-\theta)\Delta V-T_2+L_2]+W-(1-t)c-L_2\} \\ F_{(z)} = z(1-z)[(1-b)A_3-K_1-(x+y)K_2] \end{cases} \quad (3.13)$$

Proposition 1: The equilibrium points of the dynamic evolutionary game of currency A, B and financial coordination institution C in the same equilibrium state are respectively: $E_1=(0,0,0)$, $E_2=(0,0,0)$, $E_3=(0,0,1)$, $E_4=(0,1,0)$, $E_5=(0,1,1)$, $E_6=(1,0,0)$, $E_7=(1,1,0)$, $E_8=(1,1,1)$.

Proof: Partial derivatives are obtained for the replication dynamic equations of currency A, currency B and financial coordination institution C, namely, $\frac{dx}{dt}=0$, $\frac{dy}{dt}=0$, $\frac{dz}{dt}=0$. It can be concluded that $E_1=(0,0,0)$, $E_2=(0,0,1)$, $E_3=(0,1,0)$, $E_4=(0,1,1)$, $E_5=(1,0,0)$, $E_6=(1,0,1)$, $E_7=(1,1,0)$, $E_8=(1,1,1)$ are the balance points of the system. So, the proof is completed.

Therefore, the first-order partial derivatives of x, y, and z of the replication dynamic equation are respectively calculated to determine the evolution and stability strategy of the system. The corresponding Jacobian matrix is as follows:

$$J=\begin{bmatrix} a_1 & x(1-x)(L_1+\theta\Delta V-T_1) & x(1-x)(R_1+K_2+ts) \\ y(1-y)[L_2+(1-\theta)\Delta V-T_2] & a_2 & y(1-y)[K_2+R_2+(1-t)s] \\ -z(1-z)K_2 & -z(1-z)K_2 & a_3 \end{bmatrix} \quad (3.14)$$

Where, $a_1=(1-2x)[z(aR+K_2+ts)y(\theta\Delta V-T_1+L_1)+W-tc-L_1]$, $a_2=(1-2y)\{z[(1-a)R+K_2+(1-t)s]+x[(1-\theta)\Delta V-T_2+L_2]+W-(1-t)c-L_2\}$, $a_3=(1-2z)[(1-b)A_3-K_1-(x+y)K_2]$.

The above eight equilibrium points are put into the Jacobian matrix, and the eigenvalues obtained are shown in Table 5.

Table 5. Eigenvalues of Jacobian matrix in three-party game.

Equilibrium point	λ_1	λ_2	λ_3
$E_1(0,0,0)$	$W-tc-\mathrm{L}_1$	$W-(1-t)c-\mathrm{L}_2$	$(1-b)A_3-K_1$
$E_2(0,0,1)$	$K_2+aR+W-t(c-s)-L_1$	$K_2+(1-a)R+W-(1-t)(c-s)-L_2$	$-[(1-b)A_3-K_1]$
$E_3(0,1,0)$	$\theta\Delta V+W-T_1-tc$	$-[W-(1-t)c-\mathrm{L}_2]$	$(1-b)A_3-K_1-K_2$
$E_4(0,1,1)$	$K_2+aR+\theta\Delta V+W-t(c-s)-T_1$	$-[K_2+(1-a)R+W-(1-t)(c-s)-L_2]$	$-[(1-b)A_3-K_1-K_2]$
$E_5(1,0,0)$	$-(W-tc-\mathrm{L}_1)$	$(1-\theta)\Delta V-T_2+W-(1-t)c$	$(1-b)A_3-K_1-K_2$
$E_6(1,0,1)$	$-[K_2+aR+W-t(c-s)-L_1]$	$K_2+(1-a)R+W-(1-t)(c-s)+(1-\theta)\Delta V-T_2$	$-[(1-b)A_3-K_1-K_2]$
$E_7(1,1,0)$	$-[\theta\Delta V-T_1+W-tc]$	$-[(1-\theta)\Delta V-T_2+-(1-t)c]$	$(1-b)A_3-K_1-2K_2$
$E_8(1,1,1)$	$-[K_2+aR+W]-t(c-s)+\theta\Delta V-T_1$	$-[K_2+(1-a)R+W-(1-t)(c-s)+(1-\theta)\Delta V-T_2]$	$-[(1-b)A_3-K_1-2K_2]$

The symbols of eigenvalues corresponding to each equilibrium point are analyzed to judge the results of three-party game strategies. According to the realistic feasibility, assuming the participation of financial institutions, the net income of three partner currency A, B and financial coordination institution C is greater than the net income of the three parties without cooperation. That is $W - tc - T_1 > 0$, $W - (1-t)c - T_2 > 0$, $(1-b)A_3 - K_1 - 2K_2 > 0$. It is necessary to consider the changes in parameters such as costs, cooperation benefits, and incentives paid by various participating entities when financial coordination institutions services digital currencies. The following three propositions is proposed for discussion.

Proposition 2: When $K_2 + aR + W - t(c-s) - L_1 < 0$ and $K_2 + (1-a)R + W - (1-t)(c-s) - L_2 < 0$, the sum of the rewards and cooperation benefits obtained from the financial institution that the currency *A* adopts a cooperation strategy is less than the cooperation cost paid by currency *A* with the participation of financial coordination institution *C* and the additional payment paid by the counterparty's midway exit. The sum of the loss cost of currency B adopting the cooperation strategy and the return and cooperation income obtained from the financial coordination institution is less than the cooperation cost paid by currency B and the additional loss cost paid by currency B withdrawing from the cooperation strategy when the financial coordination institution participates. In this case, the equilibrium point of the system is $E_2(0,0,1)$ and $E_8(1,1,1)$, then the evolutionary equilibrium strategy of the system is {no cooperation, no cooperation, participation} or {cooperation, cooperation, participation}.

Proof: According to Lyapunov stability theory, the asymptotic stability at the equilibrium point is judged by analyzing the eigenvalues of Jacobian matrix. When all the eigenvalues are not positive, the equilibrium point is the stable point of the evolutionary game. Therefore, the equilibrium points of proposition 2 is determined, as shown in Table 6.

Table 6. Local stability of game equilibrium point (Proposition 2).

Equilibrium point	Proposition 2			Stability
	λ_1	λ_2	λ_3	
$E_1(0,0,0)$	–	–	+	Unstable
$E_2(0,0,1)$	–	–	–	ESS
$E_3(0,1,0)$	+	+	+	Saddle point
$E_4(0,1,1)$	+	+	–	Unstable
$E_5(1,0,0)$	+	+	+	Saddle point
$E_6(1,0,1)$	–	+	–	Unstable
$E_7(1,1,0)$	–	–	+	Unstable
$E_8(1,1,1)$	–	–	–	ESS

Proposition 3: When $W - tc - L_1 > 0$ or $W - (1-t)c - L_2 > 0$, the return obtained by currency *A* by adopting cooperation strategy from financial coordination institution is greater than the sum of the cost paid by currency *A* when the financial coordination institution *C* does not participate and the additional loss cost paid by the counterparty's midway exit. Or the return obtained by currency *B* adopts a cooperative strategy from financial coordinating institution is greater than the sum of the cost paid by currency B when financial coordinating institution *C* does not participate and the additional loss cost paid by the counterparty's midway exit. At this point, the system game equilibrium point is $E_8(1,1,1)$, then the evolution strategy is {cooperation, cooperation, participation}.

Proof: The process as above. The equilibrium points of proposition 3 is determined, as shown in Table 7.

Table 7. Local stability of game equilibrium point (Proposition 3).

Equilibrium point	Proposition 3			Stability
	λ_1	λ_2	λ_3	
$E_1(0,0,0)$	+	+	+	Saddle point
$E_2(0,0,1)$	+	+	–	Unstable
$E_3(0,1,0)$	+	–	+	Unstable
$E_4(0,1,1)$	+	–	–	Unstable
$E_5(1,0,0)$	–	+	+	Unstable
$E_6(1,0,1)$	–	+	–	Unstable
$E_7(1,1,0)$	–	–	+	Unstable
$E_8(1,1,1)$	–	–	–	ESS

Proposition 4: When $K_2 + aR + W - t(c - s) - L_1 > 0$ and $W - tc - L_1 < 0$ or $K_2 + (1 - a)R + W - (1 - t)(c - s) - L_2 > 0$ and $W - (1 - t)c - L_2 < 0$, the sum of the return from the financial coordination institution and cooperation income obtained by currency *A* which adopts a cooperation strategy is greater than the cooperation cost paid by currency *A* with the participation of financial coordination and the payment of counterparty's exit. The sum of the additional loss cost and the rewards from financial coordination obtained by currency *A* adopts a cooperative strategy is less than the sum of the cost paid by currency *A* when the financial coordination institution *C* does not participate and the additional loss cost paid by the counterparty's exit. Or the sum of cooperation benefits and rewards from financial coordination obtained by currency *B* adopts a cooperation strategy is greater than the sum of the cooperation cost paid by currency *B* with the participation of financial coordination and the additional loss cost paid by the other party's company withdrawing midway. The return from financial coordination obtained by currency *B* adopts a cooperative strategy is less than the sum of the cost paid by currency *B* when the financial coordination institution does not participate and the additional loss cost paid by the counterparty's currency withdrawing midway. In this case, the system equilibrium point is $E_8(1,1,1)$, then the evolution strategy is {cooperation, cooperation, participation}.

Proof: The process as above. The equilibrium points of proposition 4 is determined, as shown in Table 8.

Table 8. The local stability of the equilibrium point of the system (Proposition 4).

Equilibrium point	Proposition 4			
	λ_1	λ_2	λ_3	Stability
$E_1(0,0,0)$	-	-	+	Unstable
$E_2(0,0,1)$	+	+	-	Unstable
$E_3(0,1,0)$	+	+	+	Saddle point
$E_4(0,1,1)$	+	-	-	Unstable
$E_5(1,0,0)$	+	+	+	Saddle point
$E_6(1,0,1)$	-	+	-	Unstable
$E_7(1,1,0)$	-	-	+	Unstable
$E_8(1,1,1)$	-	-	-	ESS

4. Case and simulation analysis of digital currency competition

Many governments have paid more attention to digital currencies and adopted a series of policies and actions to support the development of digital currency, especially those based on blockchain technology. In response to the innovation and coordination of digital currency, more regions centered on the themes of fintech and legal digital currency, and encouraged banks to increase the research and development of payment through diversified fintech policies. Some digital currency competition cases or scenarios are more in-depth and intuitive discussion. The survey selects two types of currency, that is the traditional electronic currency A and a new blockchain digital currency B in the innovation incubator. Financial coordination institution C chooses the right strategy according to the competitive gains of currency A and B. In order to more intuitively determine the evolutionary path of each participant, numerical experiments are used to analyze the influence of currencies and financial coordinating institution's selection strategy and the influence of parameter changes on the evolutionary path. According to the hypothesis and analysis of the previous model, the parameters in the payment matrix should meet $W - tc - T_1 > 0$, $W - (1-t)c - T_2 > 0$, $(1-b)A_3 - K_1 - 2K_2 > 0$. According to literature and practical experience, assume that the initial value of some parameter in the three-party game is: ΔV = 20, $\theta = t = a = b$ =0.5, A_1= 25, A_2 = 30, A_3= 60, $W = 30, R = 16, s = 16, c = 50$, T_1=5, T_2=10, L_1=40, L_2=45, K_1=10, K_2=8. In addition, the initial willingness of currencies A and B and financial coordination institution C to participate is $x = y = z = 0.5$.

According to the above parameter settings, the selection strategy dynamic change and the dynamic equilibrium result of the intention change of financial coordination institution C and currency A and B in the game are simulated. On this basis, it further explores the influence of the distribution coefficient of cooperation income, the reduction in cooperation cost of currencies, the cooperation cost of financial institutions and the changes in incentive parameters on the evolution path of currencies innovation game when financial coordination institutions participate in cooperation.

4.1. Scenario analysis of initial willingness change of game players

During the development of digital currencies, the willingness of currency issuing institutions and financial regulatory coordination bodies to participate in cooperation affects the choice of currency competition strategies. With other initial parameters unchanged, the influence of the change of the initial willingness coefficient of financial coordination institution C and currency A and B on the outcome of the game strategy is simulated and analyzed (Figure 1). It is assumed that the initial willingness of the three parties in the game is the same, that is, the initial willingness thresholds of the currency A and B and financial coordinating institution C is between 0.4 and 0.5. When the initial willingness of the three parties to participate in cooperation is less than the critical value 0.4, x and y tend to converge to 0, and z tends to converge to 1, so the final game equilibrium point tends to (0,0,1). Meanwhile, it is found that the willingness of well-developed currency B to participate converges faster than that of currency A. When the initial willingness of the three parties to participate in cooperation is greater than the critical value 0.5, x, y, z tends to converge to 1. Therefore, the final game equilibrium point tends to (1,1,1). In this case, the larger the initial willingness parameter value of currency A is, the faster its convergence speed will be. When the initial willingness of the three parties to participate in cooperation is at the medium level, as the willingness of financial coordination institutions to participate in cooperation slowly increases, so does the willingness of currency A to participate in cooperation, while that of currency *B* slowly declines. With the increasing willingness of financial coordination institution *C* and currency *A* to participate in cooperation, and the increasing willingness of currency *B*, both of them finally choose to participate. When the willingness of the three parties to participate in cooperation is high, the willingness of financial coordination institutions and currencies to participate in cooperation will directly increase and eventually converge to the equilibrium point (1,1,1). The results show that with the increasing initial willingness of the three parties to participate in cooperation, x and y converge to 1 more quickly, and z converges to 1 more slowly. Finally, the three parties tend to participate in cooperation. In this process, when financial coordination institutions have strong willingness to cooperate and participate, currencies will eventually choose cooperation and reach long-term cooperation with financial coordination institutions, so as to obtain the support of financial authorities and achieve their own stable development.

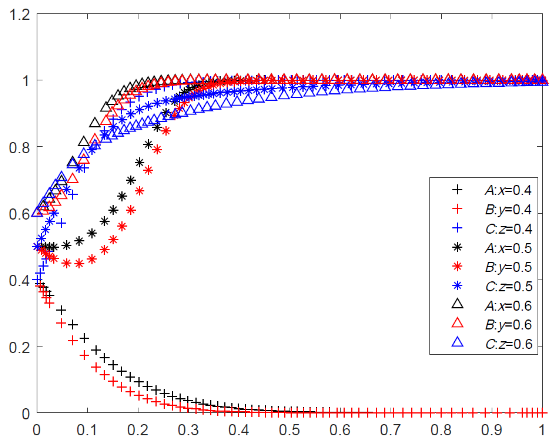

Figure 1. Simulation of simultaneous change of initial cooperation willingness x, y and z.

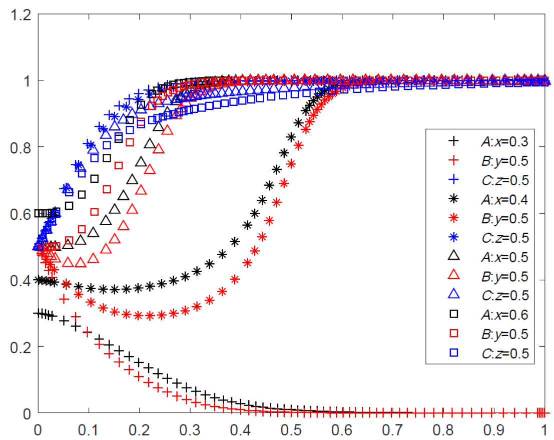

Figure 2. Simulation of change of initial cooperation willingness x in the currency.

Whether a currency participates in the cooperation of financial coordination institutions is affected by similar currencies. When other parameters remain unchanged, the influence of the change of the initial willingness of currency *A* on the strategy of the three-way game is simulated and analyzed (Figure 2). When the initial cooperation willingness of currency *B* and financial coordination institution *C* is neutral, the initial cooperation willingness of currency *A* is between 0.3 and 0.4. When the initial willing value of currency *A* is less than 0.3, *x* and *y* converge to 0 and *z* converges to 1, and the final game equilibrium point tends to (0,0,1). At this time, currency *B* with higher initial participation willingness is affected by currency *A*'s participation willingness, and its convergence speed is faster. When the initial willing value of currency *A* is greater than 0.4, *x*, *y* and *z* all converge to 1, and the final game equilibrium tends to (1,1,1). In this case, currency *A,* which has a higher initial willingness value, converges to 1 faster than currency *B*. When the initial willingness of currency *A* is less than that of currency *B*, as the initial willingness of currency *A* continues to decline, the initial willingness of currency *B* declines faster, and the willingness to cooperate with financial coordinating institutions slowly rises. When the initial value of the willingness to cooperate with currency *A* is greater than that of currency *B*, the willingness to cooperate with currency *A* continues to increase, while the willingness to cooperate with currency *B* slowly declines first and then continues to rise. The willingness to cooperate with financial coordinating institutions still rises slowly and finally converges to the equilibrium point (1,1,1). The results show that the willingness of currencies to participate in cooperation continues to rise, and the willingness to participate in the same type of currency *B* and financial coordination will gradually increase. This is because financial coordination provides monetary participants with certain policies and market norms, and whether monetary participants adopt cooperative strategies is largely affected by the participation willingness of peer enterprises. When one party is less willing to participate in cooperation, it will eventually choose non-cooperative strategy.

Whether currency participates in the cooperation of financial coordination institutions is affected by the cooperation willingness of financial coordination institutions. When other parameters remain unchanged, the three parties' willingness to participate in cooperation is simulated and analyzed (Figure 3). Both currency *A* and currency *B* are in a neutral state, and the willingness of financial coordination institutions to participate in cooperation is between 0.3 and 0.4. When the cooperation willingness of financial coordination institutions is less than the critical value 0.3, *x* and *y* converge to 0, *z* converges to 1, and the final game equilibrium point tends to (0,0,1). At this time, the willingness of currency *A* and currency *B* to participate in cooperation is greatly reduced. When the willingness of financial coordination institutions to participate in cooperation is greater than the critical value 0.4, *x*, *y* and *z* all converge to 1, and the final game equilibrium point tends to (1,1,1). At this time, the willingness of currency *A* and currency *B* to participate in cooperation increases sharply with the increase of the willingness of financial coordination institutions to cooperate, and finally converges to 1. When the willingness of financial coordination institutions to participate in cooperation continued to increase, the willingness of currency to participate in cooperation first dropped sharply, and then rose sharply, and finally reached cooperation with financial coordination. The results show that when the willingness of financial coordination institutions to cooperate is low, the currency is still in a wait-and-see state, and its willingness to cooperate declines sharply over time. The greater the willingness of financial coordinators to cooperate, the greater the willingness of currencies to participate in cooperation. This is because cooperation with currencies can bring the development of fintech and additional cooperation benefits to themselves, and financial institutions will change from low willingness to participate in cooperation to high willingness to cooperate.

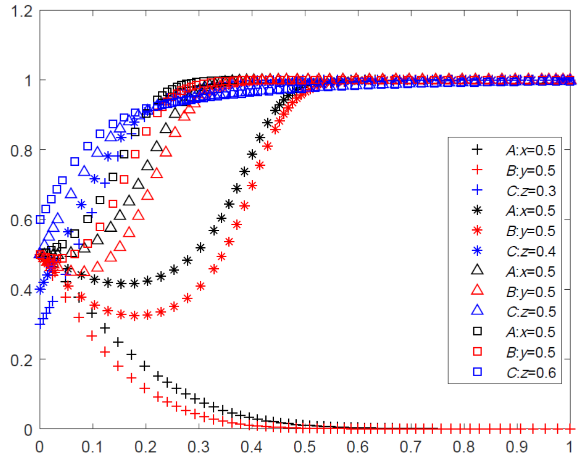

Figure 3. Simulation of the change of initial cooperation willingness *z* in financial coordination institution.

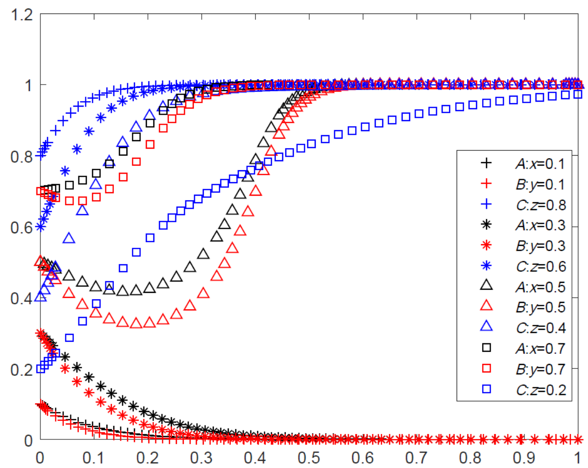

Figure 4. Simulation of the simultaneous change of cooperative willingness *x* and *y* in currencies.

When other parameters remain unchanged, the final cooperation strategy of the three parties is simulated and analyzed while the willingness to participate in cooperation changes (Figure 4). When the willingness of currency *A* and currency *B* to participate in cooperation is very low, even if the willingness of financial coordination institutions to participate in cooperation is very high, *x* and *y* converge to 0, and *z* converges to 1, currency *A* and currency *B* will not adopt cooperation strategy. When the willingness of currency *A* and currency *B* to participate in cooperation is high, *x* and *y* will converge to 1 and *z* will converge to 1 even if the willingness of the financial coordination institution to participate in cooperation is low. That is, both currency *A* and currency *B* are willing to cooperate with financial coordinator *C*, and weaker currency *A*'s willingness to cooperate converges faster than currency *B*.

4.2. Scenario analysis of cooperation cost changes

The change in cost reduction resulting from the cooperation between currencies under the financial coordination will affect the competitive strategies adopted by the currency A and the currency B in their development. When other parameters remain unchanged, a simulation analysis is conducted on the reduction of cooperation cost brought by currencies under the financial regulation coordination (Figure 5). As can be seen from Figure 5, the critical value of cooperation cost reduction S is between 8 and 12. When the cooperation cost reduction S is less than the critical value, x and y tend to converge to 0, and the final game equilibrium point converges to (0, 0, 1). With the continuous increase of S, the convergence speed of x and y slows down, and the cost reduction of currency A is obvious. When the cooperation cost reduction S is greater than the critical value, x and y tend to converge to 1, and the final game equilibrium point converges to (1, 1, 1). With the continuous increase of S, the convergence speed of x and y accelerates, and the convergence speed of currency A is also faster than that of currency B. The results show that when the cooperation cost reduction is not enough to bring more benefits to the cooperation between currencies, it is difficult for monetary parties to reach cooperation under the financial coordination institution. The cost reduction brought about by cooperation under the financial coordination affects whether currencies adopt cooperation strategies, which has a greater impact on the weaker currency A.

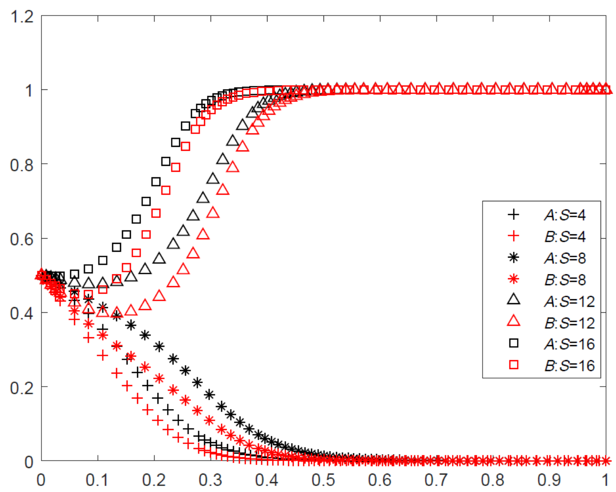

Figure 5. Simulation analysis of cooperation costs S changes.

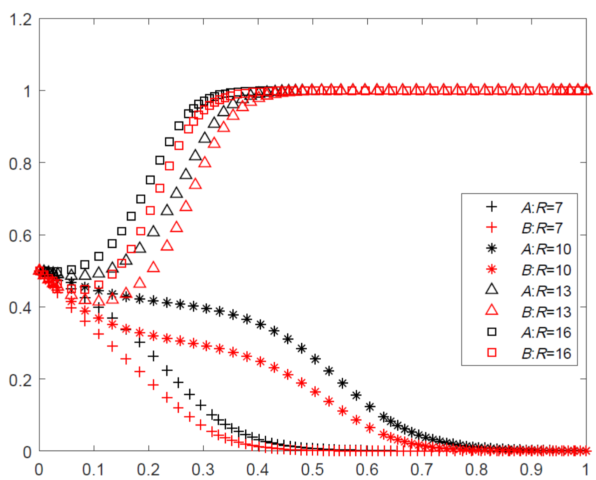

Figure 6. Simulation analysis of cooperative revenue R changes.

4.3. Scenario analysis of cooperation revenue changes

The cooperation benefits brought by the coordination of currencies under the financial coordination affect the competitive strategies adopted by currency A and B in the development process. When other parameters remain unchanged, a simulation analysis is carried out on the change of cooperation revenue R brought by monetary parties under the financial regulation coordination (Figure 6). As can be seen from Figure 6, the critical value of cooperation revenue R under the financial coordination in the currency game ranges from 10 to 13. When the cooperation income is lower than the critical value, both x and y converge to 0, and the final game equilibrium point converges to (0, 0, 1). As R increases, the converge of x and y slows down. When the cooperative gain is higher than the critical value, both x and y tend to converge to 1, and the final game equilibrium point converges to (1, 1, 1). As R increases, x and y converge faster, which currencies are more willing to adopt cooperative strategies. The results show that the higher the cooperation benefits brought by the cooperation between currencies under the financial coordination institution, the greater the willingness of currencies to participate in cooperation. This is because currencies cooperation under the financial regulation coordination may introduce positive externalities that are better positioned to grow and develop in the market.

4.4. Scenario analysis of cooperation cost change in financial coordination

The cooperative cost of financial coordination institutions affects the competitive strategies adopted by currency A, B and financial coordination institution C. With other parameters unchanged, the impact of financial institutions' participation in coordination and cooperation cost changes is simulated and analyzed (Figure 7). As can be seen from Figure 7, the critical value of the cost K_1 paid by financial institutions to participate in coordinating cooperation ranges from 10 to 22. When the cost of financial coordination institutions participating in cooperation K_1 is less than the critical value, x, y, and z tend to converge to 1, and the final game equilibrium point is (1, 1, 1), which the financial coordination institution is more willing to cooperate with currency A and B. When the cost of financial coordination institution participation in cooperation K_1 is greater than the critical value, x, y, and z tend to converge to 0, and the final game equilibrium point is (0, 0, 0), which financial coordination institution and currency A and B are unwilling to cooperate, and the convergence rate of financial coordinating institutions' participation intention is faster than that of currencies A and B. The results show that when the cost of cooperation in financial coordination is high, the cooperation income of financial coordination institution is lower than that of non-cooperative strategies, financial coordination institution will not be willing to cooperate and coordinate, and currencies will not seek help from financial coordination.

4.5. Scenario analysis of incentive changes in financial coordination

The incentive income of financial coordination institution's participation in cooperation affects the competitive strategy adopted by currency A, B and financial coordination institution C. With other parameters unchanged, a simulation analysis is conducted on the influence of change on the incentive income K_2 of financial coordination institutions participating in cooperation (Figure 8). It can be seen from figure 8 that the critical value of cooperation incentive K_2 given by the financial institution's coordination participation is between 8 and 14. When the incentive income of financial coordination participation is less than the critical value, x and y tend to converge to 0, z converges to 1, And the final game equilibrium point is (0,0,1), which currencies are unwilling to adopt the cooperation strategy. When the incentive income of financial coordinating institutions is greater than the critical value, x and y tend to converge to 1, z converges to 0, and the final game equilibrium point converges to (1,1,0), which financial coordinating institutions are unwilling to adopt cooperative strategies in this case. When the financial coordination incentive income is between critical values, x, y and z all converge to 1, and the final game equilibrium point is (1,1,1). At this point, the three parties are willing to cooperate, and with the continuous increase of K_2, the willingness of currency to participate in cooperation converges faster than that of financial coordination institutions. The results show that when the incentive returns of currencies from participating financial coordination is low, the subjective willingness of currencies to participate in cooperation is less, which influenced by the selection of peer firms and market behavior. When the incentive returns reach a certain standard, the currencies will reach a cooperation agreement with the financial coordinating institution. However, once the incentives beyond the financial institutions to bear, the willingness of financial coordination institutions to participate in cooperation will slowly rise, then sharply decline, and finally choose non-cooperation strategy.

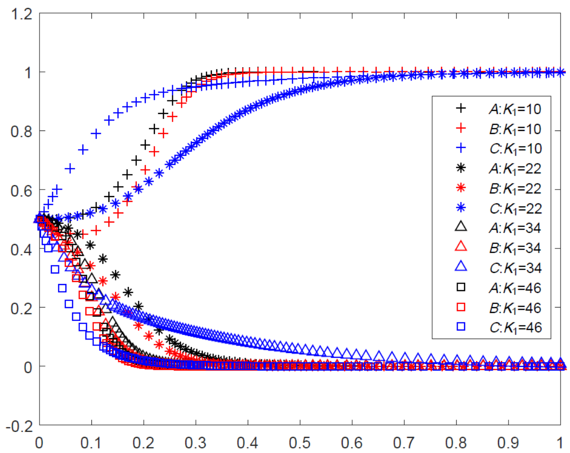

Figure 7. Simulation of cooperation cost change in financial coordination K_1.

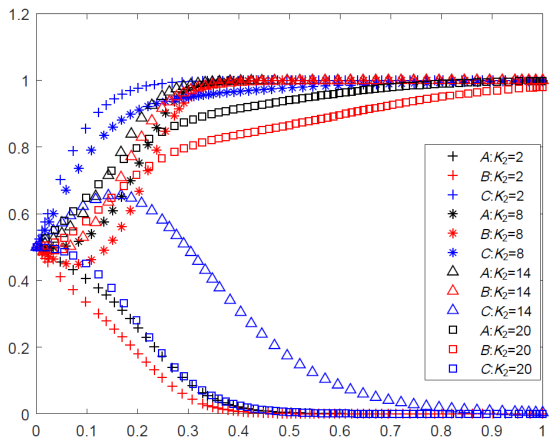

Figure 8. Scenario of incentive changes in financial coordination K_2.

5. Conclusions

The application of digital currencies based on fintech has intensified the competition among currencies. New digital currencies with advanced technology will exert a great influence on the field of currency payment with the increase of application and recognition, thus promoting the improvement of financial efficiency. The technical cooperation and market sharing among digital currencies cannot meet the needs of the late growth of currencies, and will also generate a lot of competition risks. The healthy development of digital currencies needs to seek coordination and legal norms of financial regulatory authorities. Under the coordination of financial regulators, technical standards and legal norms can be formed among digital currencies to promote the orderly development of currencies. Meanwhile, the coordination of financial supervision can break through the technical and market barriers of currency interaction to improve financial efficiency. This paper systematically analyzes the two-party competitive game strategy of currency *A*, *B* and the three-party game strategy introduced by financial coordinating institution *C* by establishing the evolutionary game model between currency *A*, *B* and financial coordinating institution *C*, and analyzes the influence relationship of the changes of main variables by numerical simulation.

The following conclusions can be drawn: first，the willingness of currency *A*, *B* and financial coordination institution *C* to participate in cooperation has different influence on each other's choice of competitive strategy and influence relationship. The strategy adopted by the currency is greatly affected by the willingness of the peer unit to participate in cooperation. The strategies adopted by currencies are also significantly affected by the willingness of financial coordinator to participate in cooperation. Second, the change of monetary cooperation costs and benefits will have a great impact on the strategies adopted by the three parties with the participation of financial coordination institutions. The reduction of the cost of monetary cooperation is greater than the range it can bear, and the willingness of financial coordination institutions to participate in cooperation decreases. The monetary cooperation income with the participation of financial coordination institutions is lower than the expected range, and the willingness of monetary and financial coordination institutions to establish cooperation is reduced. Third, the costs and incentive benefits of financial coordination institutions are more sensitive than those between currencies. Financial coordination institutions are willing to provide support for monetary cooperation when the cost and incentive benefits of participating in cooperation are within a certain range. Once beyond a certain range, the establishment of cooperative relations between financial coordinators may be greatly reduced.

During the growth of digital currency, it learns from the development experience and practice path of technology-leading currency, actively cooperates with technology enterprises to carry out fintech innovation, accelerates the application scenarios of new currency, and learns to seek help from financial regulators. In light of the development needs and characteristics of digital currencies, financial regulators have launched new currency access standards in a timely manner to promote the digital transformation of traditional currencies and improve the level of financial services. In digital currency innovation, in addition to the influence of financial institutions on the development of digital currency, government regulatory policies also have a significant impact on it. At present, governments around the world are actively introducing policies and regulations related to digital currencies, promoting the connection between traditional currencies and new currencies, and realizing cooperation and application coordination among digital currencies. The tripartite dialogue mechanism and docking platform of digital currency provide an effective way for regional financial development. At the same time, it is necessary to strengthen the coordination of financial regulation, avoid mainstream currencies from abusing their dominant market position and harming the rights and interests of consumers, and better realize the healthy development of the digital economy.

Currency digitization and effective supervision are the future trend of financial development. The competition between global legal digital currency and non-legal digital currency is worth further study. Due to the short development history of the new digital currency based on blockchain technology and the fact that the legal digital currency in many countries is still in the research and development and testing stage, there is a lack of complete digital currency operation data and evaluation indicators, and there are certain difficulties in the empirical test of competition. In this paper, the competitive situation of digital currency is analyzed by numerical simulation, and there is a lack of actual data effect support. In the future, we will continue to track the research on digital currency competition, systematically collect various data indicators of digital currency, and better measure the trend of digital currency competition and market efficiency.

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Conflict of interest

The authors declare there is no conflict of interest.

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