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Research on the Collaborative Innovation Mechanism of Multiple Entities in the Integrated Circuit Industry Chain of Zhuhai City under the 'Chain Leader System'

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Abstract: The innovation and development of the integrated circuit industry is an important support carrier of the new quality productivity, which is of great significance for promoting the high-quality development of Zhuhai's economy. In order to further reveal the intrinsic mechanism of multi-body collaborative innovation in the integrated circuit industry chain of Zhuhai under the 'chain leader system', this paper analyses the stability and influencing factors of the selection of collaborative innovation strategies of each body by constructing a tripartite evolutionary game model between the government, the main enterprises of the chain and the enterprises on the chain. It is found that factors such as collaborative innovation benefits, costs, risks and government incentives have a significant impact on the collaborative innovation behaviour of the industrial chain. High co-innovation benefits and reasonable benefit distribution can promote industry chain co-innovation; when co-innovation costs are lower than enterprises' expectations and cost sharing is reasonable, enterprises are more inclined to choose co-innovation strategies; when co-innovation benefits are higher than costs, government financial subsidies can effectively promote enterprises' participation. Therefore, it is recommended that chain master enterprises design a fair benefit distribution mechanism and pay attention to risk management, and the government formulate differentiated incentives to enhance the overall competitiveness and innovation capacity of the industry chain.

1. Introduction

In today's world of rapid globalization and informatization, the integrated circuit industry, as a core area of information technology, plays a vital role in national economic development and social progress. As an important high-tech industrial base in southern China, the development of Zhuhai's integrated circuit industry chain is particularly noteworthy [1]. However, faced with fierce market competition at home and abroad and the ever-changing industrial environment, how to improve the efficiency of multi-subject collaborative innovation in Zhuhai's integrated circuit industry chain has become an urgent problem to be solved. In this context, the “chain leader system” came into being as an innovative industrial chain management model, which aims to promote close cooperation between upstream and downstream enterprises through a combination of government guidance and market mechanisms, and jointly promote industrial innovation and development [2]. How to achieve efficient collaboration among various entities under this framework has become a focus of common concern in academia and industry.

In response to this situation, this paper aims to deeply explore the multi-subject collaborative innovation mechanism of Zhuhai's integrated circuit industry chain under the "chain leader system", in order to provide a useful reference for theoretical research and practical operations in this field. This paper analyzes in detail the collaborative innovation practices of Zhuhai's integrated circuit industry chain driven by the "chain leader system" to reveal its internal mechanisms and influencing factors. In this paper, we firstly sort out the research progress on collaborative innovation of industrial chain at home and abroad through literature review, and clarify the theoretical foundation and background of the research. On this basis, a three-party evolutionary game model is constructed to simulate the co-innovation behaviors of the government, chain master enterprises and chain enterprises under the ‘chain leader system’ and a series of basic assumptions are put forward. Matlab software is used to simulate and analyses the impact of co-innovation benefits and distribution coefficients, co-innovation cost and sharing coefficients, co-innovation risks and government subsidies on the selection of co-innovation strategies. Finally, based on the simulation results, corresponding policy recommendations are put forward, aiming to promote the collaborative innovation and enhance the overall competitiveness of the integrated circuit industry chain in Zhuhai City by optimizing the distribution of benefits, reducing the cost of collaborative innovation, strengthening the risk management and optimizing the government incentive mechanism.

2. Related Works

Many scientists have explored how to promote sustainable progress and improvement in the innovation capabilities of the integrated circuit industry, providing different perspectives and levels from different angles and levels to industrial modeling changes and modernization. Wang et al. proposed a strategy to enhance the modernization of the industrial chain against the delay of the technology and the external dependence of core technology in Japan[3]. In addition, Chen and Wang's research revealed the significant impact of government support on the coupling and coordination degree between the enterprise innovation chain and capital chain. When the number of talents reaches a certain scale, government support can further promote this coupling, thus emphasizing the indispensability of government support and talent resources in industrial development[4]. Through three-party evolutionary game and numerical simulation analysis, Li and Ma found that factors such as cost subsidies, corporate default benefits, rewards and penalties affect the stability of the integrated circuit industry alliance, providing a method for improving industry competitiveness [5]. Vivona et al. proposed a new cost theory to evaluate innovative cooperation arrangements, identifying four primary factors: governance, closeness, reliability, and institutionalization, providing a basis for determining the optimal governance structure to reduce costs and promote reciprocity and fairness[6].

Research related to the high-quality development of the integrated circuit industry. The current research is mainly carried out from the perspectives of technological innovation, policy support, international division of labour, risk and security, and cross-regional synergy and cooperation [7]. Under the perspective of technological innovation, the impact of knowledge width, knowledge depth, social value, cohesion, cooperation intensity, industry fund investment, etc. on innovation performance is analysed, and the subversive innovation model of IC industry in the context of digital technology is constructed, proposing that industrial synergy can effectively break through the key core technology research. Under the perspective of policy support, it is proposed that there is a significant positive impact of planning and guidance measures on the development of key core technologies, and that the synergy between financial support and guidance measures, and the synergy between financial support and R&D innovation are of great significance to the development of the IC industry. Under the perspective of international division of labour, the mechanism of the number of international research cooperation on the quality of scientific and technological innovation is clarified, and the position of IC industry in the international division of labour and the upgrading path are studied. Under the perspective of risk and security, it reveals the security risks of China's IC industry, such as monopoly of oligopolistic enterprises, excessive geographic concentration, and low resilience of short-term adjustment of the industry.

Research related to the evolution and development of IC industry chain. Academic research mainly focuses on analysing the layout of the industrial chain, the influence mechanism of construction, risk and security, and resilience enhancement [8]. China's integrated circuit industry chain links are not well connected, structural hierarchy is not high, the risk of chain breakage and supply breakage still exists, empowering government behaviour can effectively drive the construction of a complete industry chain, the need to play the state's ability to take the initiative to act to strengthen the supply of policies, to enhance the autonomy of the key areas of technology, to promote the collaborative development of the industry chain across the region, and to put forward a strategy for the integration of the industrial chain, the innovation chain and the capital chain.

Specialised research on the development of integrated circuit industry in Zhuhai. The research on related topics in Zhuhai City mainly focuses on studying the evolution path of the innovation network, the financial policy of industrial development, the development mode and the upgrade path [9].

The above studies have achieved fruitful results in the study of related fields of the integrated circuit industry, mainly discussing the development path of the industry and the industrial chain from a macro perspective. There has been little attention to the collaborative innovation among micro-subjects in the industrial chain. The theoretical logic, internal mechanisms, and implementation paths of multi-subject collaborative innovation in the integrated circuit industry chain under the "chain leader system" lack systematic research, and studies based in Zhuhai City are still relatively weak. Through this research, we can reveal how Zhuhai's integrated circuit industry chain can achieve efficient collaboration under the "chain leader system", thereby enhancing the overall competitiveness and innovation capabilities of the industry chain[10].

3. Problem Description and Evolutionary Game Model Construction

3.1 Problem Description and Basic Assumptions

Under the guidance of the “Chain Leader System”, The operation mode of multi-body collaborative innovation in Zhuhai's IC industry is led by core enterprises (i.e. chain master enterprises), which organize collaborative research on key technologies and common technology R&D to enhance their own technological strength and at the same time drive other enterprises in the industry chain to form synergistic advantages. The government plays a guiding and coordinating role in this process, and promotes the co-operation between key suppliers and core enterprises in the industry chain through policy support and resource integration. Other enterprises in the chain respond positively, provide technical support and solutions, and jointly promote technology R&D and innovation. After successful R&D, core enterprises are responsible for industrializing the results and promoting technology iteration and upgrading, forming an efficient closed-loop innovation ecosystem.

Based on this mode of operation, this paper constructs an IC industry chain collaborative innovation evolution game model with the chain leader (i.e., the government), the chain master enterprise and the enterprises on the chain as the main body. The following hypotheses are proposed:

(1) Selection strategy. Government, chain owners and chain enterprises choose the set of strategies as respectively. Among them, the government's 'regulation' strategy is mainly to adopt effective reward and punishment mechanisms to promote collaborative innovation among the relevant enterprises in the IC industry chain; the chain master's 'leading' strategy is mainly to provide conditions for collaborative innovation for the enterprises in the chain, such as providing technical support and training, etc.; the chain enterprises' "leading" strategy is mainly to provide conditions for collaborative innovation for the enterprises in the chain. The 'leading' strategy of the main enterprise in the chain is to provide the conditions for the enterprises in the chain to carry out co-innovation, such as providing technical support and training, etc. The 'participation' strategy of the enterprises in the chain refers to actively fulfilling the co-innovation mechanism of the main enterprise in the chain, and collaborating with the relevant enterprises to carry out technical innovation.

(2) Collaborative innovation gain. Assuming thatR_i(i=2,3) is the normal gain of the chain master enterprise and the chain enterprise, the total gain due to collaborative innovation is A, and its co-innovation gain distribution coefficient is β, respectively, and $\beta \in[0,1]$, the two sides of the collaborative innovation gain distribution amount is Aβ and 1-β)A. If the chain master enterprise and the chain enterprise both choose collaborative innovation, it will bring short-term financial income to the government, and the enterprise's continuous innovation will have an effect of influence. Attracting more enterprises in the chain to join the IC industry chain system innovation system will bring long-term financial income to the government as μR_1, where μ is the coefficient of increase of government financial income and $\mu>1$[11].

(3) Collaborative innovation cost. The government chooses the 'regulation' strategy, will produce regulatory costs for C_1; chain master enterprise and the chain of enterprises as the main participants in collaborative innovation, need to invest in manpower, material resources and technology development costs for C, cost sharing coefficient for t, where$t \in[0,1]$, the cost of collaborative innovation of the chain of master enterprises for tC, the cost of collaborative innovation of the chain of enterprises for$(1-t)$C.

(4) Collaborative innovation risk. It is assumed that when the industry chain enterprises are in collaborative innovation, the costs jointly triggered by the chain master enterprise and the chain enterprise due to strategic risk, technological risk and human factor risk are D_2 and D_3[12].

(5) Reward and punishment mechanism. Under the 'chain leader system', the government will actively adopt the reward and punishment mechanism to regulate the industry chain enterprises to carry out collaborative innovation, and give financial subsidies to the chain master enterprises and chain enterprises that actively participate in collaborative innovation, respectivelyM_2 and M_3. Under the government regulation, when the chain master enterprise carries out co-innovation and the chain enterprises do not actively participate in co-innovation, the chain enterprises need to pay a penalty amount to the chain master enterprise N_3; when the chain enterprises actively participate in co-innovation and the chain master enterprise does not actively lead the enterprises to participate in co-innovation, the chain master enterprise needs to pay a liquidated damages amount to the chain enterprises N_2.

3.2 Construction of the Evolutionary Game Model

Assuming the probability of the government choosing "regulation" is x and the probability of choosing "non regulation" is 1-x; The probability of the chain owner enterprise choosing "lead" is y, and the probability of choosing "not lead" is 1-y; The probability for on chain enterprises to choose "participate" is, and the probability for choosing "not participate" is 1-z. Among them,x,y,z ∈ [0,1]. Based on the above assumptions and parameter settings, a multi-party behavior game profit matrix for the integrated circuit industry chain based on the "chain length system" is constructed, as shown in Table 1.

Table 1: Game benefit matrix of IC industry chain multi-party behaviour based on 'chain leader system

Chain company	Government regulation(x)		Failure of the government to regulate(1-x)	
	Chain owners lead(y)	Chain owners do not lead(1-y)	Chain owners lead(y)	Chain owners do not lead(1-y)
Participate (z)	MR_1-C_1-m_2-m_3	-C_1-m_3	R_1	0
	R_2+aβ-tc-D_2+m_2	R_2-n_2	R_2+aβ-tc-D_2	R_2
	R_3+a(1-β)-$(1-t)$c-D_3+m_3	R_3-$(1-t)$c-D_3+m_3+n_2	R_3+a(1-β)-$(1-t)$c-D_3	R_3-$(1-t)$c-D_3
Non-participation(1-z)	-C_1-m_2	-C_1	0	0
	R_2-tc-D_2+m_2+n_3	R_2	R_2-tc-D_2	R_2
	R_3-n_3	R_3	R_3	R_3

Set U_{ij} as the expected return when the i-th participant adopts the strategy, where $i = \mathrm{g, z, s}$,are the government, the chain owner enterprise, and the on chain enterprise, respectively; j=1,2. The expected return when the government chooses to 'regulate', the expected return when it chooses to 'not regulate' and the average expected return are:

$$U_{g1}=yz(\mu R_1-C_1-M_2-M_3)+z(1-y)(-C_1-M_3)+y(1-z)(-C_1-M_2)-C_1(1-y)(1-z)$$

$$U_{g2}=yzR_1$$

$$U_g=xU_{g1}+(1-x)U_{g2}$$

Similarly, the expected returns of chain-owning firms that choose to 'lead', the expected returns of those that choose not to lead, and the average expected returns are, respectively:

$$U_{z1}=xz(R_2+A\beta-tC-D_2+M_2)+x(1-z)(R_2-tC-D_2+M_2+N_3)+z(1-x)(R_2+A\beta-tC-D_2)+(1-x)(1-z)(R_2-tC-D_2)$$

$$U_{z2}=xz(R_2-N_2)+x(1-z)R_2+z(1-x)R_2+(1-x)(1-z)R_2$$

$$U_z=yU_{z1}+(1-y)U_{z2}$$

Similarly, the expected returns of the chain firms that choose to 'participate', the expected returns of those that choose not to participate, and the average expected returns are, respectively:

$$U_{s1}=xy[R_3+A(1-\beta)-(1-t)C-D_3+M_3]+x(1-y)[R_3-(1-t)C-D_3+M_3+N_2]+y(1-x)[R_3+A(1-\beta)-(1-t)C-D_3]+(1-x)(1-y)[R_3-(1-t)C-D_3]$$

$$U_{s2}=xy(R_3-N_3)+x(1-y)R_3+y(1-x)R_3+(1-x)(1-y)R_3$$

$$U_s = zU_{s1} + (1\text{-}z)U_{s2}$$

From the principle of evolutionary game, the replication dynamic equations of the government, chain master enterprises and chain enterprises in the IC industry chain are respectively:

$$F(X) = \frac{d_x}{d_t} = x(1\text{-}x)(U_{g1}\text{-}U_{g2}) = x(x\text{-}1)(C_1 + M_2 y + M_3 z + yzR_1(1\text{-}\mu))$$

$$F(y) = \frac{d_y}{d_t} = y(1\text{-}y)(U_{z1}\text{-}U_{z2}) = y(y\text{-}1)[D_2 + tC\text{-}x(M_2 + N_3)\text{-}A\beta z + xz(N_3\text{-}N_2)]$$

$$F(z) = \frac{d_z}{d_t} = z(1\text{-}z)(U_{s1}\text{-}U_{s2}) = z(1\text{-}z)[x(M_3 + N_2) + xy(N_3\text{-}N_2) + yA(1\text{-}\beta) + (t\text{-}1)C\text{-}D_3$$

4. Simulation Analysis of Multi-Subject Collaborative Innovation in the Integrated Circuit Industry Chain of Zhuhai City

The city of Zhuhai has formed an integrated circuit industry cluster with the High-Tech Industrial Development Zone in Xiangzhou District as its core. In order to promote industrial innovation and enhance the stability and competitiveness of the industrial chain supply chain, the government has issued a series of policies and measures, including the ‘Opinions of Zhuhai on Strongly Supporting the Development of the Integrated Circuit Industry’ and the ‘Certain Policies and Measures on Promoting the Development of the Integrated Circuit Industry in Zhuhai’, which provide ex ante financial assistance and complementary support for breakthroughs in key technologies and innovative projects, with financial support for a single project up to a maximum of 5 million yuan. The amount of financial support for a single project can be up to 5 million yuan. In order to further analyse the impact of different factors and the ‘chain leader system’ on the collaborative innovation behaviour of multiple actors in the IC industry chain of Zhuhai, the course team conducted a field survey in the upstream and downstream enterprises of the city of Zhuhai, collected relevant data, and invited senior administrators to conduct interviews. In order to simplify the calculation, the initial values of the parameters are as follows: R_2=100, R_3=60, A=40, β=0.6, R_1=60, μ=2.8, C_1=20, C=30, t=0.6, D_2=10, D_3=5, M_2=10, M_3=8, N_2=N_3=10, In this chapter, the evolutionary game process of the multi-body collaborative innovation strategy of the integrated circuit industry chain in Zhuhai will be simulated by Matlab software.

4.1 Evolutionary Behavioural Paths for the Three Parties of the Game

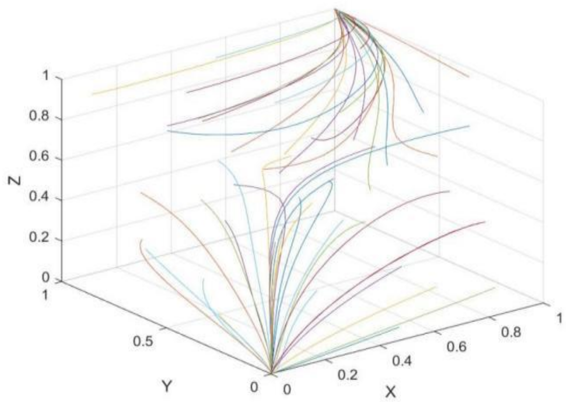

Figure 1: Behavioural path of multi-subject evolutionary game of integrated circuit industry chain

Set the initial values of x, y, and z to 0.5, and substitute the above parameters into the three-dimensional dynamic system to simulate the tripartite evolution behavior path of the integrated circuit industry chain collaborative innovation system in Zhuhai. The simulation results shown in Figure 1 are obtained. As shown in Figure 1, the equilibrium stable points for the strategic choices of the government, chain owner enterprises, and on chain enterprises are (1,1,1) and (0,0,0), which means that all parties in the integrated circuit industry chain either actively participate in the collaborative innovation of the industry or abandon the strategy of collaborative innovation.

4.2 Impact of Co-Innovation Benefits and Allocation Coefficients on Evolutionary Outcomes

The co-innovation gain A takes different values, and the simulation of the evolution path of the behavioural strategy of the IC industry chain multi-subjects is obtained in Figure 2. As shown in Figure 2, with the increase of the co-innovation gain, the stable point evolves from (0,0,0) to (1,1,1), and ultimately stays stable; when the co-innovation gain of the chain enterprises is higher than the cost of co-innovation, the willingness to co-innovate of the chain enterprises will be enhanced, and shows the trend of convergence to 1. The results show that: co-innovation gain affects the choice of co-innovation strategy of multiple subjects in IC industry chain, and the higher the gain, the stronger the willingness of enterprises to co-innovate; the co-innovation gain of any one party affects the behaviours of other subjects in the whole system.

Figure 3 is a simulation diagram of the evolution path of collaborative innovation strategies among multiple entities in the integrated circuit industry chain when the profit distribution coefficient β takes different values. As shown in Figure 3, when the profit distribution coefficient is lower than 0.3, z first shows a trend of rapid convergence to 1, but eventually is forced to decrease due to x and y rapidly converging to 0; Under the average profit distribution, x, y, and z tend to 1 at the fastest speed, indicating that when the cost input difference is not significant, the average profit distribution can promote collaborative innovation among multiple entities in the integrated circuit industry chain; When the profit distribution coefficient is higher than 0.7, y first shows a trend of rapidly converging to 1, but eventually is forced to decline due to x and z rapidly converging to 0; In addition, the chain owner enterprise is more sensitive to the profit distribution coefficient, and when the profit distribution is unreasonable, the chain owner enterprise converges to 0 faster.

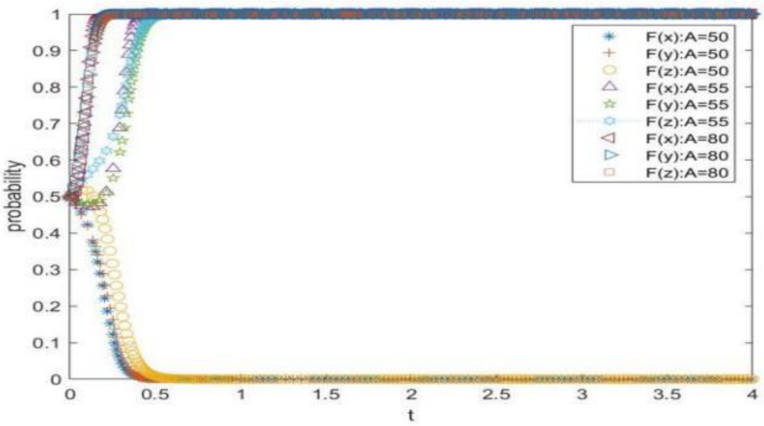

Figure 2: Impact of co-innovation benefits on evolutionary outcomes

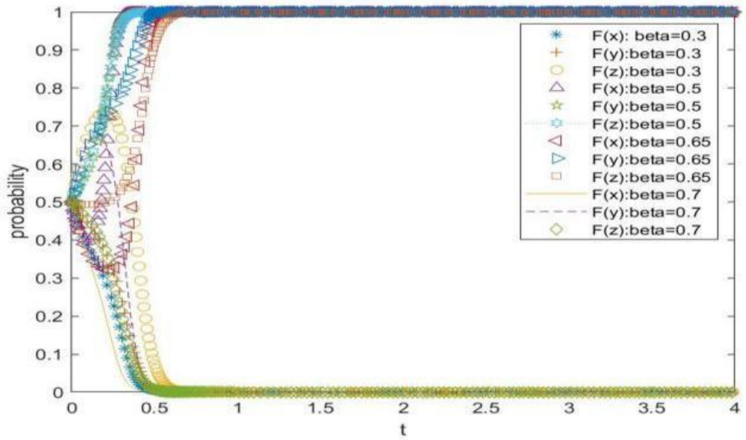

Figure 3: Impact of yield distribution coefficients on evolutionary outcomes

4.3 The impact of co-innovation costs and sharing coefficients on evolutionary outcomes

The cost of co-innovation C takes different values, and the evolution path of the behavioural strategy of multiple subjects in the IC industry chain is simulated, and Figure 4 is obtained. as shown in Figure 4, when the cost of co-innovation exceeds the expectation of enterprises, the multiple subjects in the IC industry chain will give up the co-innovation strategy due to the excessively high cost; as the cost of co-innovation increases, the equilibrium point gradually converges to (0, 0,0), and vice versa, the equilibrium point gradually tends to (1, 1,1).

The cost sharing coefficient t for collaborative innovation takes different values to simulate the evolution path of multi-agent behavior strategies in the integrated circuit industry chain, and Figure 5 is obtained. As shown in Figure 5, when the cost allocation coefficient t is higher than 0.85, it means that the chain owner enterprise bears the vast majority of the costs. At this point, z first shows a trend of rapidly converging to 1, but ultimately is forced to converge to 0 due to x and y converging quickly to 0; When the cost sharing coefficient $t \in [0.4,0.85)$ is used, the equilibrium point of the multi-agent evolutionary game in the integrated circuit industry chain tends towards (1,1,1), otherwise it tends towards (0,0,0).

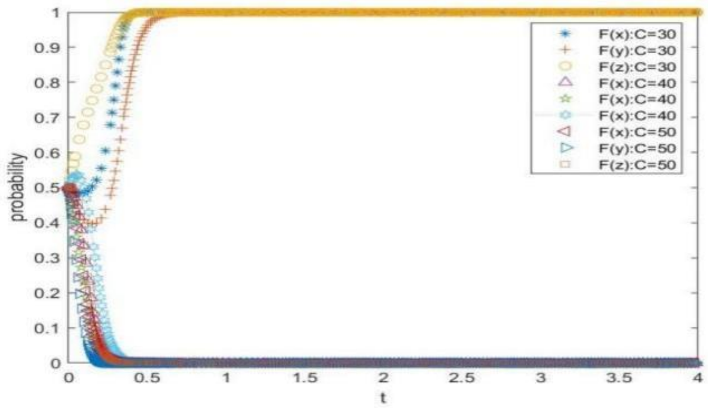

Figure 4: Impact of co-innovation costs on evolutionary outcomes

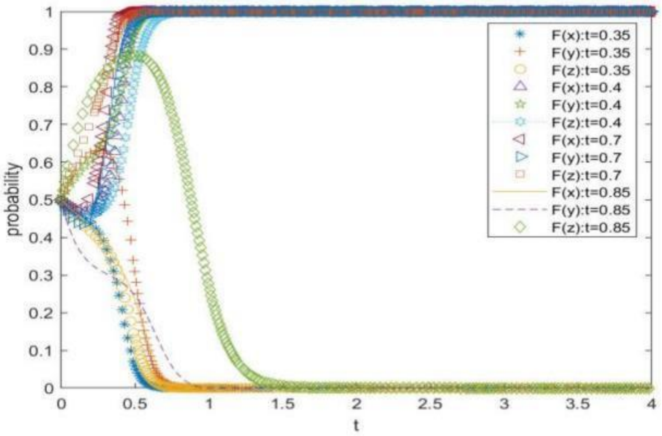

Figure 5: Impact of cost-sharing coefficients on evolutionary results

4.4 Impact of government funding subsidies on evolutionary outcomes

Figure 6 shows the simulation diagram of the effect of government financial subsidies on the behavioural strategies of multiple subjects in the integrated circuit industry chain at time C. Figure 7 shows the simulation diagram of the effect of government financial subsidies on the evolutionary results at time C. From Figure 6 and Figure 7, it can be seen that when the cost of IC industry chain multi-body collaborative innovation is higher than the gain, the government's incentive mechanism is not effective in stimulating enterprises to participate in collaborative innovation, and the probability of enterprises choosing collaborative innovation strategy is 0 when the financial subsidy fails to make up for the cost of their inputs; when the gain of IC industry chain multi-body collaborative innovation is higher than the cost, the government's incentive mechanism can effectively promote enterprises to participate in collaborative innovation, the higher the government financial subsidy, the higher the willingness of enterprises to choose collaborative innovation.

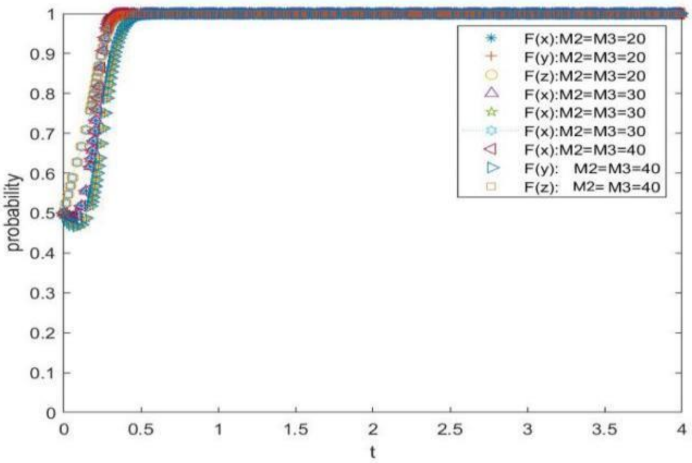

Figure 6: The impact of government funding subsidies on the evolutionary results during C<A

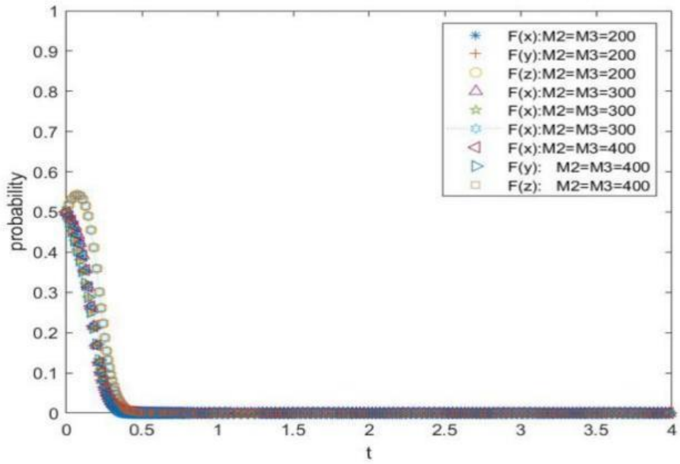

Figure 7: The effect of government funding subsidies on evolutionary outcomes when C > A

4.5 The Influence of Collaborative Innovation Risk on Evolutionary Outcome

The cost of collaborative innovation risk D takes different values, and the simulation of the evolution path of the behavioural strategy of multi-subjects in the IC industry chain is obtained in Figure 8. As shown in Figure 8, when D is higher than the critical value, the equilibrium point of the collaborative innovation strategy of the multi-subjects in the IC industry chain evolves from (1,1,1) to (0,0,0) as the risk of collaborative innovation increases, and ultimately stays stable.

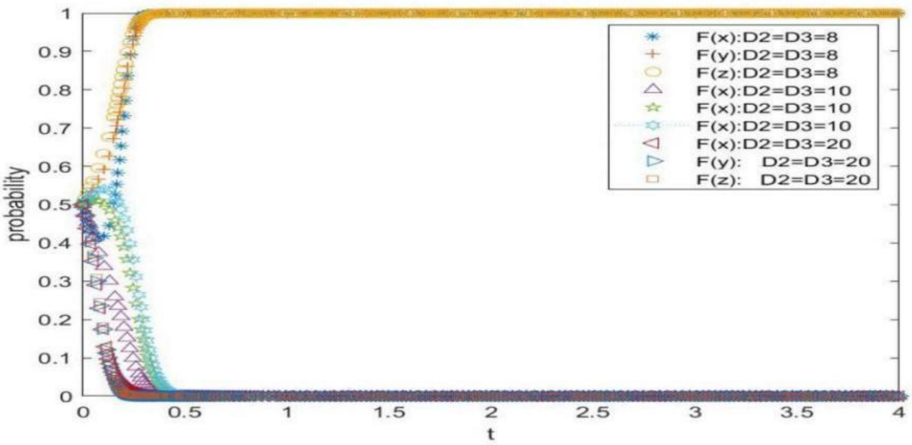

Figure 8: Impact of co-innovation risk on evolutionary outcomes

5. Conclusions and Policy Recommendations

Taking the integrated circuit industry in Zhuhai as an example, this paper further clarifies the internal mechanism of collaborative innovation in the integrated circuit industry chain of Zhuhai under the 'chain leader system' by constructing a tripartite evolutionary game model of collaborative innovation between the government, the chain master enterprise and the enterprises in the chain, and analysing the stability of the selection of collaborative innovation strategies and the influencing factors of each subject. The following conclusions are drawn:

(1)Co-innovation gain affects the selection of co-innovation strategy of IC industry chain, and the higher the gain, the stronger the willingness of enterprises to co-innovate, meanwhile, when the difference of co-innovation cost is not significant, the average distribution of gain can promote the co-innovation of IC industry chain. Therefore, the chain master enterprise should design a fair and reasonable gain distribution mechanism to ensure that each participant can obtain reasonable returns from co-innovation, so as to stimulate the innovation vitality of the whole industry chain.

(2) When the cost of collaborative innovation is lower than the expected cost of the enterprise and the cost sharing coefficient $t \in [0.4, 0.85)$, the equilibrium stable point for the enterprise to choose collaborative innovation strategy is (1, 1, 1). Therefore, as a technologically strong chain owner enterprise, it should reduce the cost of on chain enterprises participating in collaborative innovation through technical support, resource sharing, and other means. At the same time, it should improve the cost sharing mechanism to ensure that all participants achieve fairness and equality in cost sharing, thereby promoting the widespread participation and in-depth development of collaborative innovation within the industrial chain.

(3)Incentive mechanisms implemented by the government may not be effective in stimulating the participation of enterprises in the industry chain in collaborative innovation in all situations, especially when the cost of collaborative innovation exceeds the expected gain, the financial subsidies provided by the government may not be able to play the expected role of incentives. Therefore, when designing incentive policies, the government needs to comprehensively consider the net benefits and cost structure of collaborative innovation. At the same time, taking into account the differences in costs and benefits faced by different enterprises in collaborative innovation, it should design differentiated incentives to adapt to the needs of different enterprises to ensure the effectiveness and adaptability of the policies.

(4) The risk of collaborative innovation is also a major factor affecting the collaborative innovation of multiple subjects in the IC industry chain. Therefore, enterprises in the industry chain should pay attention to the risk management in the process of collaborative innovation, firstly, establish a comprehensive risk assessment system, systematically identify all kinds of risks in the process of collaborative innovation, including technology risk, market risk, organisational and management risk as well as policy making risk, and carry out an in-depth risk assessment; secondly, establish a ‘Trinity Secondly, establish a ‘three-in-one’ risk prevention and control system to strengthen risk management around R&D, supply guarantee and other business levels; and thirdly, establish a risk-sharing mechanism to strengthen the cooperation between the upstream and downstream of the industrial chain and enhance the resilience and safety of the industrial chain.

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