Multi-agent-based simulation on technology innovation-diffusion in China*

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Abstract. An innovation-diffusion model was developed with agent-based modelling (ABM); the model is used to study technical innovation and its diffusion process in China. The results are as follows: only a small fraction of firms conduct independent product-innovation, and most firms prefer imitation and/or purchases; most of the innovative firms are located in the East; approximately three or four technology generation products can exist in the market simultaneously; preferential policies can speed the process of innovation diffusion and improve economies of less developed areas, especially in Middle China; lastly, preferential policies can also improve the labour attractiveness of the Middle, West and Northeast and reduce emigration to the East.

JEL classification: L11, O31, O33, R23

Key words: Innovation, diffusion, agent-based simulation (ABS), technology generation, China

1 Introduction

The innovation and spatial diffusion of knowledge is an entity that we refer to as innovation-diffusion. Innovation diffusion is always defined as the communication process of innovation through special channels among members of a social system in a given period of time (Rogers 1995, 2003). As far back as 1934, Schumpeter discussed innovation diffusion. He considered the diffusion process as a time-based process. However, the regional diffusion after innovation has a more direct meaning in terms of economic growth. There were several research papers on this topic before the 1990s (Hagerstrand 1966; Darwent 1969; Richardson 1978; Malecki 1983; Malecki and Varaiya 1986; Nelson 1991), and these works form, for example, spatial reacting diffusion theory and hierarchical diffusion theory. In spatial reaction-diffusion theory, innovations diffuse to neighbouring regions and continue to spread following this regulation. In

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hierarchical diffusion theory, innovations diffuse from their original place to another centre because large cities always have advantages in their technology level and social structure, and furthermore, the decision centres of large enterprises are always located in large cities. Thus, in hierarchical diffusion theory, the main factor of diffusion is not the spatial distance but the size of a region (Brown 1981; Malecki and Varaiya 1986). This theory concluded that innovations first diffuse to regions that have large sizes and populations, after which they diffuse to secondary regions. This diffusion mode always occurs in developing countries. However, there is no strict spatial reacting diffusion model or hierarchical diffusion model that is always followed in the real world. Actually, diffusion processes always follow a hierarchical diffusion model at the beginning, after which they turn to a spatial reaction-diffusion model.

From the 1990s, knowledge diffusion and spillover have drawn the attention of economists and developed into a research hotspot in the field of regional economic development (Grossman and Helpman 1991; van de Klunder and Smulders 1996; Choi 1997; Caniëls and Verspagen 2001). Beckmann (1995) presented the knowledge network framework to discuss the regional diffusion of innovation. In his theory, what the nodes form is not a continuous spatial region but a node-network system where the diffusion and spillover processes of knowledge occur. The theory of Beckmann solves the relation problem between spatial reaction-diffusion theory and hierarchical diffusion theory and presents new innovation-diffusion problems. Because of high non-linearity, progress toward solving this network diffusion problem had not been made before the 2000s. Bretschger (1999) had researched the astringency and catching-up issues of regional growth, which are caused by knowledge diffusion in a regional network system. In addition, Cowan and Jonard (2004) performed simulation-based dynamics research on the complexity of knowledge diffusion in a regional network.

However, most of the researches use exploratory spatial data and spatial econometrical methods to research the spatial trace and model as well as the influence of such spatial trace and model on the regional economic growth and revenue (Anselin et al. 1997, 2000a, 2000b; Keilbach 2000; Costa and Iezzi 2004; Funke and Niebuhr 2005; Zhao and Bai 2009). Static methods include description, measure, classification, and indicator analysis. In those methods, results are obtained by analysing quantitative statistical data. However, those methods can neither analyse and explain the geodynamic mechanism of innovation diffusion nor analyse the behaviours of innovative individuals and dynamic diffusion’s progress under a complex spatial structure.

In this study, we try to trace the innovation process back to individual firms, and to understand the dynamic behaviours of innovation diffusion through the emergence of firms’ behaviours. Agent-based simulation (ABS) is the main research method in this study. There are two obvious advantages of ABS in the research of regional science analysis: first, ABS can reflect a spatial heterogeneity that is ubiquitous in a regional background. Ignoring such a spatial heterogeneity will lead to obvious mistakes. Second, it can be helpful to depict the behaviours of agents that participate in technology innovation and diffusion.

Agent-based simulation is an important approach in the field of complex system analysis and simulation; its key idea is the complex adaptive system theory (Holland 1995, 1998; Wang et al. 2005). A significant assumption is that social phenomena emerge from local interactions of agents (Jennings and Campos 1997). Therefore, macro phenomena can be generated by the behaviours of individual agents (Schilhoa et al. 2000). Together, individual agents and the simulation environment constitute a ‘bottom-up’ complex system (Gu et al. 2011).

From the 1980s, ABS has become a powerful method and has been widely discussed and used in the fields of social science, regional science and economic simulation (Wooldridge and Jennings 1995a, 1995b; Bonabeau 2002; Ostrom 1988). In the field of innovation diffusion and spillover, Gilbert et al. (2001) applied multi-agent simulation to their research of innovation networks and relative policy-effect problems. Derioan (2002) used ABS to build a social
network and applied heuristic methods to the simulation of innovation diffusion and its evolutionary process. In addition, Zhang (2003) analysed high-technology industrial agglomeration in Silicon Valley using the ABS method. Furthermore, Marz et al. (2006) simulated the process of knowledge diffusion and spatial agglomerations’ formation by firms’ innovation and imitation behaviours. Their work concluded that imitating firms obtain technologies in a less expensive and more successful way. Wang et al. (2010) built an ABS model that they combined with the models of Nelson and Winter (1982) and Zhang (2003) to examine the effect of several factors on high-tech industrial development. Our work is the continuation of the works of Zhang (2003) and Wang et al. (2010).

In summary, in this study ABS is adopted to simulate the innovation process and the real economic data of China are used for approximations. As additional products, some innovation diffusion regulations of China are obtained.

2 An agent-based model

2.1 The basic assumptions of the model

The basic thought of innovation diffusion modelling is that the mainstays of innovation and its diffusion are the micro individuals (firms) that innovate for higher profit and survive in the market. The innovation behaviours of firms are affected by both geographic conditions and market environments. In detail, a market is the external environment of the technical innovation and diffusion, and firm agents start their businesses and produce to obtain profits in the market. The geographic conditions, which include the natural conditions and locations, are the basic attributes of regions.

According to their profits, firm agents will invest one part of their profits in another place to obtain higher profits (labourers also migrate across regions to maximize their utilities). Another part of firms’ profits will be input into R&D activities for gaining new technologies. Through technology upgrades, firms will earn more profits and then invest more in R&D activities. Accordingly, the main assumptions of the market and the firm agents are as follows:

1. There are hierarchical relationships among the regions in space. Regional associations are formed by regions, and there are potential firm agents in every region. To depict regional growth and innovation diffusion on the prefecture level, it is assumed that every region is a potential firm in China’s mainland. Thus, every city is defined as an agent in this model, every province is defined as a region group and the whole country is divided into four areas according to the National Development and Reform Commission of China: the East, the Middle, the West and the Northeast. The major cities of China’s mainland are marked on Figure B1 in Appendix B.

2. In the initial step, the municipalities, provincial capitals and some more developed cities are defined as group leaders and start their businesses first. Thus, the innovation diffusion mode’s initial steps have some characteristics of hierarchical diffusion.

3. A sequence-innovation-generation mode is used to represent the technology levels in this study: in one step, one firm agent can only produce one generation of products.

4. There is no trade barrier among regions, and therefore, the market is totally free. Whereas products in the same generation have the same price in the market, products in different generations have different prices.

5. The initial capital stocks and labour forces of firms are the capital stock and labour force data of cities, which are cited from the Chinese Statistics Yearbooks. It is assumed that capital only moves to one region in one step.
6. The innovation behaviours of the capital agents are affected by the local geographic conditions, which include the natural conditions, the regional economy’s conditions, the communal facility and service conditions and the human capital conditions.

7. The human capital conditions include a regional college index and the average education level. A higher college index means higher R&D capability in that city, and a higher education level represents stronger adsorption ability with respect to external technologies.

The computing methods of the natural conditions, regional economic conditions, communal facility and service conditions and human capital conditions can be accessed from the works of Wang et al. (2012).

2.2 The economic behaviours of firm agents

The innovation and researching behaviours of firm agents are based on their economic behaviours. The premise of these economic behaviours is that firm agents must succeed in starting their own businesses. In this study, it is assumed that firm agent j’s probability of successfully starting a business in region i is as follows:

$$Prs_{i,j,t} = \frac{\sum_{j=1}^{C} K_{i,j,t-1}}{\sum_{i=1}^{R} \sum_{j=1}^{C} K_{i,j,t-1}} + \sigma_{0}RI + a\tau,$$

where $K_{i,j,t-1}$ represents the capital stock of agent j in area i in step $t - 1$ and $RI$ represents the geographical condition index, which is composed of the roughness of the geographic environment and location. Furthermore, $\tau_0$ represents the preferential part of the normal tax rates, i.e., $\tau$ will be defined as follows:

$$\tau = t_{ast}(1 - \tau_0),$$

where $t_{ast}$ means the normal case tax rate and $a$ represents the impact of the preferential tax rate on the entrepreneurial possibility.

The above equation indicates that if a market area has a larger capital proportion, its success probability of starting a business among the agents in this group is higher. In addition, superior regional conditions and preferential tax rates also play positive roles in the success probability of starting a business. It is worth noting that $\sum_{i=1}^{R} \sum_{j=1}^{C} Prs_{i,j,t}$ is greater than 1. Thus, the success possibility of entrepreneurship is influenced by external driving forces: it depends not only on the amount of the firm’s capital stock, but on the roughness of the geographic conditions and preferential tax rates. The neighbouring economic conditions can also have an influence on the possibility of a successful start of a business.

The producing behaviour is the major behaviour after a firm agent has started its business successfully. We adopt the Cobb-Douglas production function to simulate the producing behaviour of firm agent i as follows:

$$Y_{i,t} = h_{i,t}^{\alpha_{i}} L_{i,t}^{\beta_{i}} K_{i,t}^{1-\beta_{i}},$$

where $Y_{i,t}$ represents the output of firm agent i, $K_{i,t}$ represents this agent’s capital stock, $L_{i,t}$ represents this agent’s amount of labour force, $h_{i,t}$ represents its technology level, $\alpha_{i}$ is its
technical elasticity coefficient and $\beta_i$ is its labour elasticity coefficient. Due to the differences among the entrepreneurial conditions in different regions, the marginal outputs of the labour force are different in distinct regions.

The profit $\pi_{i,t}$ of firm agent $i$ in the current step can be obtained by following Equation 4:

$$\pi_{i,t} = (P_g - c)Y_{i,t}(1 - \tau),$$

where $\pi_{i,t}$ represents the agent’s profit in step $t$, $P_g$ means the price of generation $g$ products in the market, and $c$ is the fixed cost in the process of producing.

In the real world, labourers and capital will be transferred in space. This process is controlled by the spatial interaction that is determined by Wilson’s model (1967). From the viewpoint of statistical mechanics, Wang (2000) proved that the flows of capital and population (or labour) can be modelled by the following equation.

$$T_{ij} = AO_iD_j \exp(-\eta r_{ij}),$$

where $O_i$ means the capital stock or labourers in region $i$, $D_j$ represents the actual demand for capital or labour force in region $j$, $A$ is a normalization parameter, $r_{ij}$ represents the distance between these two regions, and $\eta$ represents the spatial damping coefficient. This equation is a basic form of the Wilson spatial interaction model. Similarly, we obtain the labour attractiveness as the following equation:

$$TP_{ij} = A \cdot \text{Pop}_i \cdot w_{ij} \cdot \exp(-\eta L r_{ij}),$$

where $TP_{ij}$ represents the labour attraction of region $j$ that acts on labourers in region $i$, $w_{ij}$ represents the wage rate in region $j$, $\eta L$ represents the spatial damping coefficient of labourer migration, $\text{Pop}_i$ is the population in region $i$, and $A$ is the normalization parameter. Thus, the migration of labourers from region $i$ to region $j$ can be given by

$$m_{ij} = \text{Pop}_i \frac{T_{ij}}{\sum_i \sum_j T_{ij}}, \quad i \neq j.$$  

This model indicates that the migrations of labourers are ubiquitous.

In the process of capital flow, the firm agents prefer to select regions that have higher returns-on-capital as their investment destinations. In this study, we regard the capital return rate and the market demand of a region as the thrust of the capital flow, and we regard the spatial distance as an obstruction. In addition, during the capital-transfer process, a part of the capital may be lost, and if the investing destination’s geographic conditions are too unfavourable, the investment may not have the expected effect. The situation that many agents select the same investment destination may lead the capital return rate to be lower or negative. Hence, the capital organization agent will depend on its actual situation to make decisions and invest only a part of its capital in its investment destination. In the model, the capital return rate is defined as the marginal benefit of capital. Based on Equation 3, the capital return rate can be derived as follows:

$$\nu_i = \frac{\partial Y}{\partial K_i} (P_g - c_i)(1 - \tau_i) = (P_g - c_i) \cdot (1 - \beta)h_i^\alpha L_i^\beta K_i^{-\beta} (1 - \tau_i).$$
The market demand of one region represents the total product demand from other regions to this region. The shorter the spatial distance is, the larger the market demand is. At the same time, if people in these regions are richer, they will have a stronger desire for consumption and their demand for products will be greater. In this study, the product demand of region $i$ is defined as follows:

$$D_i = \sum_j w_j P_j \exp(-\eta K_{ij}),$$

(9)

where $\eta K$ is the spatial damping coefficient of the goods supply. Using the above equation, we can obtain the investment destination $p$, which has the maximum capital efficiency:

$$u_{\text{max}} = u_p = \max(D_i u_i),$$

(10)

where $u_p$ represents the value of the maximum capital efficiency obtained at region $p$. The meaning of this model is that the movements of capital have concentricity.

$$K^c_f(t) = -k_{pj}, \quad p \neq j.$$  

(11)

The investing destination $p$ can be obtained according to $u_{\text{max}}$. Thus, the capital that is moving into region $p$ can be given by

$$K^c_f(t) = \sum_{k \neq p} \omega(R_p) k_{pk} (1 - \phi),$$

(12)

where $\phi$ represents the loss rate of capital, $\omega$ represents the transfer success probability and $k_{pk}$ represents the capital that is moving from region $k$ to region $p$. The success probability is only related to the geographic condition $R_p$. Thus, the better the geographic conditions of a region are, the higher the probability of investment success is. The geographic conditions are used to indicate the size of the success probability; they are cited from Wang et al. (2012).

2.3 The R&D behaviour of a firm agent

After the capital and labour have begun to flow, the firm agents begin to choose their R&D behaviours. To obtain a monopoly position in the market and high profits, firm agents improve their equipment and productivities. Whereas some firms develop new products to obtain higher profits, others choose to purchase or imitate the popular technologies to follow the external technology’s progress. Such purchase and imitation behaviours make the technology diffuse in the market. In the following, we focus on firms’ innovation behaviour.

In this section, we have assumed that there is only one kind of product in the market. In our model, the innovation behaviour is divided into two aspects: (i) enhancing the level of production technology to reduce the production cost (process technology); and (ii) upgrading the generation of the product to obtain higher profits (product technology). With the birth of a new product generation, the agent’s technology level will improve by $\lambda$ per cent:

$$h_g = (1 + \lambda) h_{g-1} = (1 + \lambda)^{g-1} h_1,$$

(13)

where $g$ represents the generation in the technology sequence and $h_g$ represents the quality level of generation $g$. A similar format of sequential technology can be used to present the process technology improvement. Let $\zeta$ represent the reduction rate of the cost. Then,
where $c$ represents the fixed cost of the product, $v$ represents the production level, $\tilde{c}_g$ represents the basic production cost of generation $g$, $c_0$ represents the initial cost of the minimum generation product in the technology sequence, and $\Delta c$ represents the increased cost of the new generation product compared to the previous generation product.

The initial price of a new generation product always depends on its cost. It is assumed that each new generation product shares the same price-cost ratio $\eta$. Thus, the basic price of a new generation product can be given by $P_{cg} = \eta$.

From the given equations, we can ascertain that the price of the product will be reduced along with the decrease of its cost. Moreover, the market price $P_g$ is also affected by the number of its producers $n_g$ and the change of its supply $S_{g(t)}/S_{g(t-1)}$. Indeed, the emergence of new generation technology will affect the price of old generation products. Therefore, we can conclude the following:

$$P_g = \tilde{P}_g \left[1 - 0.1 \left(1 - \frac{1}{n_g} \right) \right] \left[1 - 0.05 \left( \frac{S_{g(t)}}{S_{g(t-1)}} - 1 \right) \right].$$

To obtain higher profits, firms invest in research on advanced process technologies and secure patents of new generation products. Thus, Wang et al. (2010) define two types of R&D model, namely, product-innovation and process-innovation. Whereas product-innovation consists of independent innovation, imitation and purchases, process-innovation focuses on reducing the fixed cost during the production process by improving the process technology level. In the simulation system, we assume that agents invest a part of their capital in R&D if and only if they gain profits thereby. Based on the state of the R&D process and strategy, firms will decide how to invest in R&D activities. The specific equations are as follows:

$$\begin{cases} K_{t+1} = K_t (1-\delta) + [1-n_t]\pi_t + K_{cf} \\ N_{t+1} = N_t + n_t\pi_t \\ K_{t+1} = K_t (1-\delta) + \pi_t + K_{cf} \end{cases} \text{ when } \pi_t > 0,$$

$$\begin{cases} K_{t+1} = K_t (1-\delta) + \pi_t + K_{cf} \text{ when } \pi_t \leq 0 \end{cases}$$

where $n_t$ represents the proportion of the R&D investment in step $t$, $\pi_t$ represents the profit, $N_{t+1}$ means the cumulative R&D investment, and $\delta$ is the capital depreciation rate.

However, the probability of innovation depends on the comprehensive ability of the agent, its capital, the target generation of the technology, etc. The judgment whether specific innovation is finished depends on the investment’s threshold value. Let $\zeta_p$, $\zeta_c$ respectively denote the thresholds of product innovation and process innovation, and define the respective thresholds of the process innovation and the product innovation as follows:

$$\zeta_p = \zeta(\tilde{H}_p) = \pi g^{p\theta} K^{p\theta} e^{1-h_k},$$

$$\zeta_c = \zeta(\tilde{V}) = c_0 g^{c\theta} V^{c\theta} K^{c\theta} e^{1-h_k}.$$
If successful, the firm upgrades the generation of its product and continues to invest in a superior new generation product. If the upgrade has failed, a part of the investment will be discounted. However, the agent could learn from its failures, and in that case, the probability that the firm will be successful the next time will increase.

When investment in the process innovation reaches the threshold \( (N_c) > \xi_\tilde{C} \), the firm can realize the process innovation and upgrade its production technology. The R&D cost equals the innovation thresholds and should be deducted from the cumulative investment as \( N_{t+1} = N_t - \xi \).

In the procedure of innovation and imitation, the agents will choose to transfer their behaviours to deal with changes in the external environment and their own internal economic conditions. In Appendix A, the detailed regulations of these behaviours’ transformation are listed.

2.4 The technology diffusion

Advanced technologies can diffuse through imitations and purchasing behaviours, which will result in a phenomenon called knowledge spillover. During the process of diffusion, firms will choose their R&D behaviour to obtain more profits based on their own situations.

2.4.1 Technology search

The technology that firms adopt must meet the following two conditions: (i) the target technology level must be higher than the firm’s own; and (ii) the target technology must be able to be absorbed by the agent. Hence, the difficulty of the target generation must be smaller than the absorbing ability of the firm agent.

There is often a dominant economic entity known as a group leader in a local economy, and this leader has closer relationships with other external economies and is often the technical leader. These leaders search for target technology in the whole market, whereas the other, normal agents in the same area search for their target technologies in their own group unless their technology level is the highest in their group.

2.4.2 Technology selection

Based on the above step, firms will select their imitation targets based on three factors: the spatial interaction, the gap of their technology levels and the habitual dependency.

The spatial interaction \( E_d \) indicates that the closer the distance between two agents is, the stronger their spatial interaction is. We use Wilson’s model to calculate the spatial interaction intensity as \( E_d = \exp(-\eta r_{ij}) \) (Wang et al. 2004).

\( E_g \) is used to represent the differentiation of firms’ technology levels. In this model, the interaction-intensity formula of knowledge network nodes is adopted. It is assumed that \( \Delta g_{ij} = g_j - g_i > 0 \) is the technology gap between agent \( i \) and agent \( j \). Thus, these agents’ technology differentiation can be given as \( E_g = \mu e^{\nu_0 (\xi_j - \xi_i)} \), where \( \mu \) is the intensity parameter and \( \nu_0 \) is the interaction parameter.

In addition, \( E_z \) is used to represent the habitual dependency, which is a result of the past co-operation and the willingness to maintain this co-operation. This dependency can be given by \( E_z = \nu e^{\nu_0 z_{ij}} \), where \( \nu \) is the strength parameter and \( \nu_0 \) is the interaction parameter.
Thus, the total attractive strength \( E_s \) depends on the spatial distance, the technology gap and psychological tendencies, and it provides a basis for deciding to imitate or buy the target technology. This strength can be given as

\[
E_s = \kappa \exp(-\sigma d_{ij}) + \mu e^{\eta_k}(1 - \Delta_{ij}) + \nu e^{\rho_k} z_{ij}.
\]

(19)

2.4.3 Technology adoption

In addition to the above two steps, firms need to consider their own conditions and compare the different situations to make decisions. For imitating firms, if an imitation is less expensive than independent innovation, it is worthwhile for the agent to adopt the imitation.

Assuming that firm \( i \) has accumulated imitation investment \( N_{p(i)} \) and innovation investment \( N_{p\text{,ino}(i)} \) is the independent innovation threshold of agent \( i \) and \( \zeta_{\text{p\_ino}(j)} \) is the independent innovation threshold of firm \( j \). Furthermore, \( z_{ij} \) is the co-operation time. If the situation meets the following conditions, firm \( i \) will decide to imitate the technology of firm \( j \):

\[
(1 - W)(\zeta_{\text{p\_ino}(j)} - N_{p(i)})/s + W(\zeta_{\text{p\_ino}(j)} - N_{p(i)}) < \zeta_{\text{p\_ino}(j)} - N_{p(j)},
\]

(20)

Then, the imitation threshold of agent \( i \) can be determined as \( \zeta_{\text{p\_imit}(i)} = \zeta_{\text{p\_ino}(j)} \).

Equation (20) indicates that the R&D activities of firm \( i \) are decomposed into \( 1 - W \) parts of imitation at a rapid R&D speed \( s \), and the other \( W \) parts must be finished by the imitator itself. The normal R&D speed is 1. Here, \( s \) is defined as the R&D speed of imitation, which indicates that imitating agents should invest in imitation R&D to obtain the accumulated effect.

For purchasing firms, whether they adopt the target technology depends on their accepted price and the purchase price. If the purchasing cost is less than the cost of independent innovation, they will adopt a purchasing strategy. Inasmuch as the purchase of the technology can immediately enhance the firm’s product and production level, it can be accepted if the price is less than the half of the agent’s capital plus its profit at the current step.

Similarly, it is assumed that firm agent \( i \) decides to purchase the technology of firm \( j \). The asking price \( P_i \) of the target agent is inversely proportional to the number of patents of the target technology and the co-operation times between these two firms. We use \( P_j \) to represent the accepted purchase price.

\[
P_j = 2\zeta_{\text{p\_ino}(j)}/n_g (1 - 0.05z_{ij}),
\]

(21)

\[
P_j = \max(\zeta_{\text{p\_ino}(j)} - N_{p(j)}, 0.5K_{t(j)} + \pi_j).
\]

(22)

If \( P_b \geq P_o \), firm \( j \) will adopt the target technology, and the transaction price can be given as \((P_a + P_b)/2\).

3 Simulation

Based on the model proposed in Section 2, simulations have been performed to research the spread of technology innovation in China and its influence on economic development. In one respect, the purpose of this research is to try to solve problems in the Chinese regional economies. However, a more important purpose is to propose an exploration in the application
of modelling. Because of the randomness of agent-based simulation, most of the results in this study are obtained by averaging 10 simulation outcomes. Of course, averaging 10 simulation outcomes may still be insufficient. However, this method has achieved significant results.

In this study, 31 provinces in mainland China (including autonomous regions) are chosen as area groups. Moreover, 362 prefecture-level cities and autonomous regions are treated as capital-organization agents. Provincial capital cities and cities with regional economic activity such as Shenzhen, Dalian, Qingdao and Xiamen are defined as group leaders.

The initial simulation conditions in the baseline scenario are set as follows: the group leaders are set as the initial alive capital organizations, and their initial technology generations are assumed to be 1. In the process of technology diffusion, the default spatial interaction model is the Wilson Spatial Attractiveness Model, the space damping factor of labourer migration is set as 0.002, and the space damping factor of the capital flow is set as 0.02. There are three innovation behaviours in this study: independent innovation, imitation and purchasing. Independent innovation is the source of technology improvement and spillover, whereas imitation and purchasing promote technology diffusion. Both innovations and their diffusions increase the whole technical level of the market. Each simulation has 100 steps, and every step corresponds to one economic settlement period, which equals one season in reality. In the baseline scenario, there is no preferential tax policy.

The evolutionary process of the regional technology diffusion is indicated in Figure 1, which shows the proportion of different innovation behaviours that are undertaken by firm agents in the market in every step. In Figure 1, ‘innovation’ indicates the proportion of firm agents that engage in independent innovation; ‘imitation’ indicates the proportion of agents that imitate technologies from other firms; ‘purchase’ indicates the proportion of agents that purchase technologies; lastly, ‘others’ indicates the proportion of agents that do not engage in any activities to improve their product technology.

It can be seen that after step 40, the proportion of the firms that engage in independent innovation is almost stable and relatively small, which indicates that the investment risk of independent innovation and the ‘bankruptcy rate’ of innovation-oriented firms are both higher. In fact, independent innovations require firm agents to have high research levels and a strong economy at the same time. Thus, only a few firms will choose this innovation strategy.

![Fig. 1. The proportion of different innovation behaviours of agents in the market](image-url)
In contrast, after step 40 the proportion of the firms that engage in imitation is growing. These firm agents can imitate the new technologies with a lower R&D cost after the innovations have already been made. Hence, the difficulty of imitation is much smaller than the difficulty of independent innovation, and furthermore, imitation’s success probability is higher. Thus, updating technology levels through imitation is a stable method for small firms. It is also an efficient and economical method to accomplish technology development. Therefore, because it has the smallest investment risk, this strategy has been adopted by most firms in the market.

Firms that engage in purchasing only need to pay certain fees to acquire a new technology and immediately accomplish technology development. Therefore, this strategy will also be adopted by some firm agents to upgrade their technologies. With increasing technology generations, the difficulty of R&D activities also increases, as does the purchase fee. Thus, after approximately 60 steps only a few firms choose purchasing as their innovation strategy to accomplish technology improvement because of high purchase fees.

Although only a small proportion of firm agents engage in independent innovation, the technology levels in the market are pushed forward by them. The improvement of the highest technology generation in the market is entirely promoted by independent innovations. The variations of the highest and lowest technology generations in the process of simulation are shown in Figure 2. It can be seen that the highest generation improves in the simulation process, which reaches nearly 10 in step 100 from generation 1 at the initial step. After the first 40 steps, the lowest generation also improves and reaches nearly 5.5 at the end of the simulation. That result can be considered as the result of technology diffusion and spreading because according to the innovation model, imitation and purchasing are preferred by firms that have low technology levels. The technology diffusion causes the overall technology level to be gradually upgraded. Because there are many agents whose technology generation remains in generation 1 before step 40, the market structure will not be stable until step 40. To achieve a better representation of the effect of technology innovation diffusion, most of the following analysis will begin from step 40.

![Fig. 2. The changes of the maximum and minimum technology generation in the market](image)
It is also worth noticing that in Figure 2, the gap between the highest-tech generation and the lowest-tech generation is maintained at approximately four or five generations after step 45, which is after the market has been stable and the lowest generation has begun to improve. This result has universal significance.

To those firms that engage in independent innovation, we measure their innovation capacities by the numbers of their patents. In this study, the natural geographic conditions of China are imported into the simulation, and the results of innovation acquisitions in the East, Middle, West and Northeast of China are obtained. The obtained-patent distributions at step 50 and step 100 are depicted in Figures 3 and 4, respectively. It can be seen that regardless of the step, the East acquires many more patents than the other areas. Hence, it can be concluded that the East is both the primary area of independent innovation and the source of new technologies. Although they also innovate, the other areas primarily play the role of receiving the technology diffusion from the East. By comparing the patent distributions between step 50 and step 100, the proportions of the innovation acquisitions acquired in the Middle are stable. The patent proportion of the East clearly increases in step 100, when this area assumes a dominant position in the independent innovation. The proportions of the West and the Northeast are both smaller, especially the Northeast, which has a larger decreasing rate. This decline can explain the recession of the

![Fig. 3. The patent-proportions of the four areas in step 50](image1)

![Fig. 4. The patent-proportions of the four areas in step 100](image2)
Northeast from the industrialized area in the early years in reality; the main reason is the lack of appropriate innovation capabilities and location conditions, which are determined by the regional natures (Krugman 1993; Xia and Wang 2012).

The capital stocks and populations in regions change in the process of simulation. According to subsection 2.2, the regional capital stock in step $t$ is determined by the profit, the depreciation of capital, the R&D investment and the capital flow in step $t+1$. Thus, the change of the capital will be influenced by the inflow and outflow of capital. The capital distribution in step 100 under the logistic spatial mode is depicted in Figure 5. It can be observed that Beijing, Shanghai, Nanjing, Wuhan, and Chongqing have higher capital stocks and become the capital centres (the highest degree). Although most of the capital cities are located in the East, Chongqing in the West also shows significant economic strength. In addition, there are several sub-capital centres, for example, Tianjin, Jinan, and Hangzhou. These sub-centres have a more even distribution compared to the capital centres, and most of these sub-centres are provincial capitals at the initial step. It is worth noticing that most living agents are located at the east side of the HuHuangyong-Line, which means that the basic spatial lock-in of China has not been broken in the simulation. The initial natural conditions still significantly affect the regional economic development.

Capital agglomeration can be seen in the Shanghai-centred Yangzi River Delta. Shanghai, Nanjing and Hangzhou are three major capital centres and cities in this urban circle have higher capital stocks. This pattern indicates that a relatively mature industry cluster has emerged in the

![Image showing capital distribution](Fig. 5. The distribution of the capital in step 100)
Yangzi River Delta at the end of the baseline scenario. City agglomeration can also be seen in the Sichuan Basin, where the cities form an independent urban circle. However, unlike the Yangzi River Delta, the main reason for the formation of the Sichuan Basin Circle is the huge difference between the inside and outside of the basin.

The change of the capital reflects the change of the regional economic status, which will change the migration behaviour of the local labourers. The distribution of the population in step 100 in the baseline scenario is presented in Figure 6. Corresponding to the outcomes of the capital distribution, Beijing, Shanghai, Wuhan, Nanjing and Chongqing have the highest levels of population and become the population centres, and most of the initial provincial capitals and more developed cities like Xiamen and Qingdao form the sub-centres of population. The spatial lock-in presented by the HuHuangyong-Line still determines the basic structure of the population distribution. However, the population agglomeration is not so obvious. The distribution of the population is relatively even compared to the capital distribution. Even in the Yangzi River Delta, except for the centres and sub-centres, the population distributions are very similar to the distributions of other regions. However, the Sichuan Basin Circle still forms, which is partly because the rough traffic conditions prevent the labourers from leaving the Basin.

It should be pointed out that the spillover between Hong Kong and the Chinese Mainland is neglected in this study. Thus, there are some deviations in the simulation results for Guangdong Province.
4 Policy analysis

Local preferential policies are usually implemented by the government. Preferential policies play an important role in the development of a regional economy. This paper describes a study on the influence of preferential policies on regional economic development and both innovation and technology diffusion. The preferential tax policy scenario is set as follows: the preferential policies will be implemented from step 60 to step 70, and they give a 10 per cent tax discount to those firm agents that are in the Middle and the Northeast; the firms in the West have a 15 per cent discount in this period; lastly, there is no preferential policy for the East. Then, compared with the outcomes of the baseline scenario, the simulation results are analysed to discern how preferential policies affect the regional economic development and the innovation diffusion in the following subsections.

4.1 Analysis of the effect of preferential policies on innovation diffusion

Figure 7 shows a comparison of the average highest and lowest technology generations in two scenarios. Accordingly, the preferential policies outlined above have great influence on the lowest technology generation. Before the preferential policies are implemented, the trends of the lowest generations in the two scenarios are similar. However, after step 60 the average lowest generation in the preferential scenario improves significantly. Thus, the economic environment of the firm agents in the Middle, West and Northeast improves, and these firms have more investment funds to improve their technologies and survive in the market. Conversely, we found that the average highest generation in the preferential scenario is similar to the one in the baseline scenario, and in some periods they nearly form a cross-distribution. The reason is that it is assumed in the model that independent-innovation firms are excused from taxes. Thus, the preferential tax itself has no influence on the development of new technologies. However, because of the rise of small firms under tax-discount policies, the competition pressures of

![Fig. 7. The contrast of the highest and lowest technology generations between the normal scenario and the preferential tax scenario](image-url)
independent-innovation firms also rise, which accelerates the development of new technologies. Thus the average highest generation in the preferential scenario is usually slightly higher than the one in the baseline scenario after step 60.

Considering the average technical levels of the entire market, after step 60 the average technical level in the preferential scenario grows higher than in the basic scenario (Figure 8). This distinction indicates that the preferential policies are also conducive to the improvement of the overall technology level.

4.2 Analysis of a preferential policy on regional economic development

The purpose of the implementation of preferential policies is to narrow the gaps among areas. Figures 9 and 10 show the economic development of the four studied areas in different scenarios. The gross output is used to measure the levels of economic development in different areas. It can be seen from both figures that the output value of the East in step 100 in the preferential scenario is less than in the baseline scenario, whereas the outputs of the Middle and the West are both higher. Hence, preferential policies have an effect on narrowing the economic gaps between the East and other areas, though the economy of the East will be hurt. However, the preferential policy seems to be useless in the Northeast because there is no obvious output increase there.

It is worth noting that although a more preferential tax-discount policy has been implemented in the West, the gross output value of the Middle increases more rapidly and exceeds the West in step 70 after the implementation of a preferential policy in step 60, whereas the output of the Middle is slightly smaller than the West in the simulation process in the baseline scenario. Thus, the Middle is more sensitive to the employed preferential policies.

By comparing Figure 5 to Figure 11, the inner-area economic development changes can be clearly understood. The economic strength has been improved in the Middle, and Zhengzhou
and Changsha become the new capital centres (the highest level) in step 100. In Figure 11, the capital agglomeration in the Yangzi River Delta is weakened, and the capital degrees of the cities beside Shanghai decline. Therefore, the preferential policy weakens the economic status of the East in some ways.

Although new capital centres emerge, the inner-area development gaps in the Middle are even enlarged under the preferential policy. Compared to Figure 5, the capital degrees of some cities beside the new capital centres Zhengzhou and Changsha have declined one or two degrees in the legend of the map, especially the regions neighbouring Zhengzhou. As a result, a preferential tax policy can improve the economic strength of the centre cities in the Middle by having a capital-agglomerating effect in these centres. However, their neighbours will face a lower development speed and a larger development gap with respect to the adjacent centre.

4.3 Analysis of the effects of preferential policies on labourers’ migration

In this model, labourers migrate among regions in every step, and they select their destinations to maximize their benefits. After the implementation of a preferential policy, the economic
development level and technology level of regions have changed, which leads to a change in a typical labourer’s migration direction. If the regional economy improves, labourers may prefer to stay even if the economic conditions of other regions are better.

Because of the better local economic conditions, the population in the East increases quickly in the baseline scenario, whereas in the other regions the populations decline in the simulation. It can clearly be seen from Figure 12 that the main labourer migration destinations are in the East. The loss of labourers in the middle regions is especially serious because they are more adjacent to the eastern regions and suffer more from the labour attractiveness of the East.

However, after implementing the preferential policy in step 60 the increasing growth of the population in the East starts to slow, as does the decline in the other areas. From Figure 13, it can be seen that the downtrend of the population in the Middle is prevented from step 60. Moreover, the major labourer flow from the Middle to the East has been reduced, and the population gaps between the East and other areas are narrowed in step 200. This trend is more obvious between the East and the Middle. Compared to the outcomes in the baseline scenario, after implementing a preferential policy, the originally divergent trends of their populations stop immediately, and the population difference remains almost the same until the end of the simulation. This result indicates that the preferential policy has significant effectiveness for increasing the labour attractiveness and guiding the labourers to stay in the Middle. However, this policy is not as effective for the West and the Northeast because these areas are more remote from the major migration destinations in the East.

Fig. 11. The distribution of the capital in step 100 under a preferential tax policy
The inner-area population changes can be seen by comparing Figure 6 to Figure 14. After the implementation of the preferential tax policy, the labour attractiveness of the centre cities in the Middle, West and Northeast have been improved. Cities like Changsha and Zhengzhou obtain a large number of labourers and become population centres (which are colored as the highest degree) in the Middle, whereas in the baseline scenario they are both second-degree cities in step 100. Similar results can be seen from Harbin in the Northeast and Nanning in the West. However, the unbalance of the inner-area population distribution is intensified, as in the outcomes of the capital-distribution simulation. The population degrees of the regions that neighbour new centres decline, especially in the regions beside Changsha. Although it is not obvious, a similar situation occurs in the Northeast (Harbin) and the Chongqing-Chengdu city group.

This result shows that although a simple preferential tax policy can improve the overall economic strength and attractiveness of an area, the inner-area differences may even be
enlarged. Thus, a more detailed and complex policy mix is necessary to both improve the economic development and narrow the inner and inter-area economic gaps.

5 Conclusions and discussion

Innovation is one of the major motive powers for maintaining the economic growth in one country. Innovation diffusion balances inter-regional technology differences and improves the whole market’s technology level. This study reports a research that is intended to discover the mechanisms for the dissemination of innovation diffusion and its influence on the economic development in China.

In this study, an agent-based complex model is built. In this model, individual firm agents who have different innovation capacities, capital stocks and spatial positions are defined and macroeconomic characteristics emerge from the micro interactions of the agents. Through scenario simulations that are based on this model, the innovation and learning behaviours of firm agents that have different innovation levels are simulated, as is the aggregate economic growth in multiple regions. The results indicate that agent-based simulations are useful for analysing the complexity of a multi-economy system.

In this study, 362 prefecture-level cities in China are regarded as innovative regions and individual firm agents, and the nationwide diffusion of technologies and the regional economic development is studied. Several interesting results and conclusions are obtained from the scenario simulations.
As the results show, only a small number of firm agents adopt independent innovation or purchasing as their innovation strategies. Most firms improve their technology levels by imitation because of the lower cost and higher success probability, and this practice is especially prevalent for small firms in the Middle, West or Northeast. Similar results were obtained in the work of Marz et al. (2006). It is worth noticing that the gap between the highest and lowest technology generation is maintained at approximately four or five generations during the simulation after the stabilization of the market in step 40. This result shows a weed-out effect of new emerging technologies for the old ones, and this conclusion can also reflect the lifecycle of a technology generation.

From the perspective of the spatial structure, the regions in the East obtain the largest number of patents from independent innovations, which are both the motive force of technological progress and the source of innovation diffusion. The patents gained by the regions in other areas are obviously smaller in number, which is partly because of the lack of innovation capacities, the location conditions and even the natural conditions. Thus, most of the small firms in these areas adopt imitation strategies. It can be found from the outcomes of the baseline scenario that the gaps of the economic aggregation level and labourer attractiveness between the East and the other three areas are significant. Thus, the regions in the East have a much better economic environment than the other areas. To survive in the market, imitation becomes a better choice for those firms that are in the Middle, West and Northeast. Improving the survival conditions for the small firm increases the competitive pressure of independent-innovation firms and leads to slight growth of the average highest technology.

After the implementation of preferential tax policies, the overall spatial economic pattern is changed. The results show that the preferential policies improve the overall technology level, especially for those small firms that are in less developed areas.

The regions in the middle gain most of the benefits from the preferential policies we simulated. After these policies’ implementation, Zhengzhou and Changsha in the Middle grow to become capital and population centres. The economic strength of the Middle increases rapidly and exceeds the level of the West in step 70. Furthermore, labourers are prevented from emigrating to the East massively, which happens in the baseline scenario. The aggregated population of the Middle tends to gradually become stable after step 60. However, such policies do not have the same effects in the West and the Northeast, though the regions in the West have a higher tax discount. That distinction is partly because the regions in the West and the Northeast are relatively far from the East and less affected by the preferential policy despite any technology diffusion or loss of labourers and capital. Thus, a preferential policy can help the regions in the Middle to increase their economic strengths and keep their labour forces and capital at the same time.

Although the overall economic strength and average technology level have been improved after the implementation of the preferential policy, the inner-area gaps are enlarged. The development of new centre cities results in the decline of their neighbours. Thus, a more detailed policy mix is needed to balance the inner-area differences and promote more balanced economic development. We leave those topics for our further work.

Appendix A

*The transformation of a firm agent’s innovation behaviour*

The transformation of a firm agent’s innovation behaviour is controlled by the following rules. First, the behaviour styles of firms are defined as conservative, positive, skilled at imitation and steady, which are presented as the matrix \( style \{1,2,3,4\} \). Meanwhile, the R&D statuses of firms...
are defined as process innovation, independent innovation, imitation and purchasing, which are presented as the matrix $RD^{1,2,3,4}$.

The firm agent will choose imitation or purchasing in the situation that an agent does not have an innovation target, its style is not positive, its profit in this step is smaller than before and the technology it uses in the process of producing is the highest technology it has. Then, the agent chooses its strategy based on its style: it will choose imitation if its style is skilled at imitation, and it will choose purchasing if its style is steady. Otherwise, the agent will choose independent innovation.

If the style of an agent is not positive and there exist agents who have gained the next generation technology and input it into their production processes, this agent draws a number from a Uniform distribution on $[0; 1]$; if this number is contained in the interval $[0; p]$, the agent will choose purchasing as its R&D activity. Note that $p = \frac{1}{(1 + 20 \cdot EXP(-1 \cdot NT_{TP}(g + 1)))}$ and $NT_{TP}(g + 1)$ means the number of agents that are in the R&D process of generate $g$ technology. Otherwise, the agent will choose imitation.

The firm agent will choose independent innovation if the style of the agent is positive and there are more than five owners of the next generation technology in the situation that an agent does not have an innovation target, its style is not positive and its profit in this step is smaller than before. Otherwise, the agent will draw a random number from a uniform distribution on $[0; 1]$, and if this number is contained in the interval $[0; p]$, the agent will still choose independent innovation as its R&D activity, where $p = \frac{he}{2}$ and $he$ is the R&D ability of this agent. Thus, the higher the R&D ability of an agent is, the higher the probability is that it will choose independent innovation, and in that situation, the agent will speed up its R&D. If the number is not contained in this interval, there is a 50 per cent chance for the agent with a positive style to choose imitation or purchasing as its R&D activity.

While the profit of this step is not smaller than the last step and the agent has no newer technology, the agent will draw a random number from a Uniform distribution on $[0; 1]$. If this number is contained in the interval $\left[0; \frac{he}{2}\right]$, the agent will choose independent innovation as its R&D activity and conduct research on the next generation technology by itself.

Appendix B

The major cities in China

The major cities, including municipalities, provincial capitals and other cities, that have important economic statuses are depicted in Figure B1.
References


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Resumen. Se ha desarrollado un modelo de innovación-difusión a partir de modelización basada en agentes (MBA); el modelo se utiliza para estudiar la innovación técnica y su proceso de difusión en China. Los resultados son los siguientes: sólo una pequeña fracción de las empresas realizan una innovación de producto independiente, y la mayoría de las empresas prefieren la imitación o la adquisición; la mayoría de las empresas innovadoras se encuentran en el Oriente; aproximadamente tres o cuatro productos de generación de tecnología pueden coexistir en el mercado; las políticas preferenciales pueden acelerar el proceso de difusión de la innovación y mejorar la economía de las zonas menos desarrolladas, especialmente en la parte central de China; por último, las políticas preferenciales también pueden mejorar el atractivo laboral de las zonas Central, Occidental y Nororiental y reducir la emigración al Oriente.