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Diffusion of Public Responsible Innovation Behavior in Multiplex Networks

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Abstract: *The past century was a period of highly active innovation activities, which greatly promoted economic development and social progress. However, with the emergence of gene editing babies, data leakage, environmental pollution and other events, people gradually realized the negative impact of innovation, and thus responsible innovation was born. As the public is one of the important participants in responsible innovation, it is necessary to study the diffusion of the public's responsible innovation behavior. In this paper, a new infectious epidemic model based on two-layers is proposed to explore the influence of information on responsible innovation behavior diffusion. In this paper, the microscopic Markov chain (MMCA) method is used for analysis, and the Monte Carlo (MC) is used for verification. It is found that the transmission rate of information, the forgetting rate of information and other factors will affect the scale and burst threshold of responsible innovation. Through the research on the influencing factors of the diffusion of responsible innovation, we can get inspiration to draw policy inspiration, so as to promote the diffusion of responsible innovation in the public.*

Keywords: *Responsible innovation, Behavior diffusion, Multiplex networks*

1. Introduction

The past century has witnessed rapid development. Scientific and technological innovation represented by nuclear energy, communication technology and the Internet has promoted economic growth and social progress at an unprecedented rate. However, while enjoying the huge benefits brought by innovation, people gradually felt the negative impact brought by innovation, and many appalling events emerged[1], such as London smoke pollution in the UK, Yahoo 3 billion user data leakage, Fukushima nuclear power plant radiation in Japan, and Chinese gene editing babies. With the reports of these negative news, people began to realize that scientific and technological innovation could not be "barbaric" and that letting it grow freely would pose many threats to the environment and society. At the same time, the government and researchers found that the existing policies, systems, laws and regulations could not prevent and solve the adverse effects of innovation, and there was a serious lack of functions to deal with ethics, ecological environment, social values, etc., which triggered extensive discussion and research on the duality of technological innovation.

In response to the above problems, Von Schomberg, a scholar of the European Commission, took the lead in proposing "Responsible Research and Innovation" in 2011, that is, a transparent and interactive research and innovation process, in which the actors assume responsibility to achieve the (ethical) acceptability, sustainability, and social satisfaction of the innovation process and market output products.[2]. The European Commission also further recognized this concept as "Responsible Innovation" in the Horizon 2020 program, emphasizing the exploration of the future through collective management of existing science and innovation[3]. Since then, the topic of "responsible innovation" has attracted extensive attention from scholars, and has been discussed and studied. This paper adopts the AIRR model of responsible innovation proposed by Stilgoe, that is, responsible innovation is composed of four dimensions, namely, This paper adopts the AIRR model of responsible innovation proposed by Stilgoe, that is, responsible innovation is composed of four dimensions, namely, anti licensing, reflexivity, inclusion and responsiveness, reflexivity, inclusion and responsiveness[3].

With the further popularity of research on responsible innovation, more and more scholars try to apply responsible innovation to practice in order to solve practical problems; At the same time, the characteristics of multidisciplinary integration and development of responsible innovation are further evident. In terms of research fields, foreign scholars focus on many industries, including biological medicine, genetic engineering[4], artificial intelligence[5] and other industries that have their own ethical disputes, as well as traditional industries such as agriculture[6-8], food[9]. In terms of research contents, there are generally three categories: first, from the perspective of governance, for example, Inigo and others have combined the circular economy (CE) with responsible innovation and provided a responsible innovation governance framework to strengthen the CE framework[10]; Second, research and innovation subjects, such as Halme, conducted empirical research on 13 Nordic SMEs to explore what resources small enterprises need to carry out responsible innovation[11]; Third, for public research, Childers and others established a new framework of interrelated paths and relevant standards from four ways, and reshaped public participation through science and democracy in a more experimental, reflective, prospective and responsible way[12]. However, the number of studies on the public is very small, and only a small number of studies only consider the importance and possible path of public participation. In order to better promote the practice of responsible innovation[13], we must pay attention to the important role of the public. It is very urgent for the public to understand the concept of responsible innovation and implement responsible innovation.

In addition, the infectious disease model is a very classical mathematical model, and the emergence of complex network science provides a new direction and tool for the dynamic model of infectious diseases. Therefore, more and more scholars and researchers combine the relevant knowledge of complex networks with the practice of information dissemination. Moore and Newman took the lead in combining the small world network with the epidemic model, obtained the epidemic dynamics model on the small world network, and solved the threshold[14], laying a good foundation for future research. On this basis, Zanette first constructed a rumor propagation model on the small world network[15], and then combined this rumor propagation model with the dynamics of infectious diseases to study the characteristics of information propagation on the dynamic small world network[16]. Of course, scholars also paid attention to other complex network models, such as scale-free models. Pastor and Vespigani took the lead in studying the dynamics of infectious disease transmission on scale-free networks[17].

With the development of Internet technology, social tools such as Facebook have become common communication tools for people, and the scenes of information transmission have become more and more complex. A single network cannot accurately depict the path of information transmission, so multi-layer complex networks have begun to enter the vision of scholars. Granel and others took the lead in bringing information factors into the study of disease diffusion, constructed a double-layer complex network of "online virtual+ physical contact", and studied different behaviors of different individuals in the process of disease diffusion[18]; On this basis, the coupling diffusion model of information and disease was further studied by adding influencing factors of mass media[19]. On this basis, scholars have expanded the information behavior coupling diffusion model. For example, Zheng improved the model proposed by Granel, considered the individual immunity, and proposed the UAU-SIR coupling diffusion model[20]. Silva et al. studied the SIR model under the influence of consciousness on the heterogeneous network[21], similar to Xia et al.[22] and Wang et al.[23, 24].

To this end, we propose a novel epidemic model to investigate the influence of information on behavior diffusion in a networked population. First, we model the responsible innovation behavior diffusion under the influence of responsible innovation information by using the two-layered multiplex networks, one layer for the responsible innovation behavior diffusion and the other for information spreading. Then, by analyzing the proposed model based on the microscopic Markov chain approach (MMCA), we derive the analytical expression of the diffusion threshold. Moreover, we compare the results obtained by MMCA and Monte Carlo (MC) methods and find that MMCA can accurately predict the outbreak of behavior diffusion. We also verified the impact of responsible innovation information on behavior diffusion through a large number of numerical simulations, thus revealing the impact on public responsible innovation behavior diffusion.

2. Behavior Diffusion Mode Couple With Information

2.1. The Two-Layered Multiplex Networks

The change of individual behavior is a complex process. Considering the impact of information on individual behavior, this paper uses a two-layer multiplex networks model to depict the diffusion path of responsible innovation behavior in the public under the influence of responsible innovation information, as shown in *Figure 1*. The upper network layer A is the information communication layer, representing the communication path of responsible innovation related information in the public; The lower network layer B is the behavior diffusion layer, representing the diffusion path of responsible innovation behavior in the public. There are N nodes in the two-layer multiplex networks, which means there are N individuals in total, and the nodes in the two-layer multiplex networks are one-to-one correspondence, that is, individuals are active in the two-layer multiplex networks at the same time. The connection of individuals in each layer is a solid line, which represents the social connection between individuals; The connecting lines between layers are dotted lines, representing the same individual. For the convenience of research, it is assumed that all edges are powerless and undirected. Considering that the set of neighbor nodes of the behavior diffusion network and the information dissemination network of the same individual is usually different, the upper and lower layers of networks have different network structures in the two-layer multiplex networks model in this chapter.

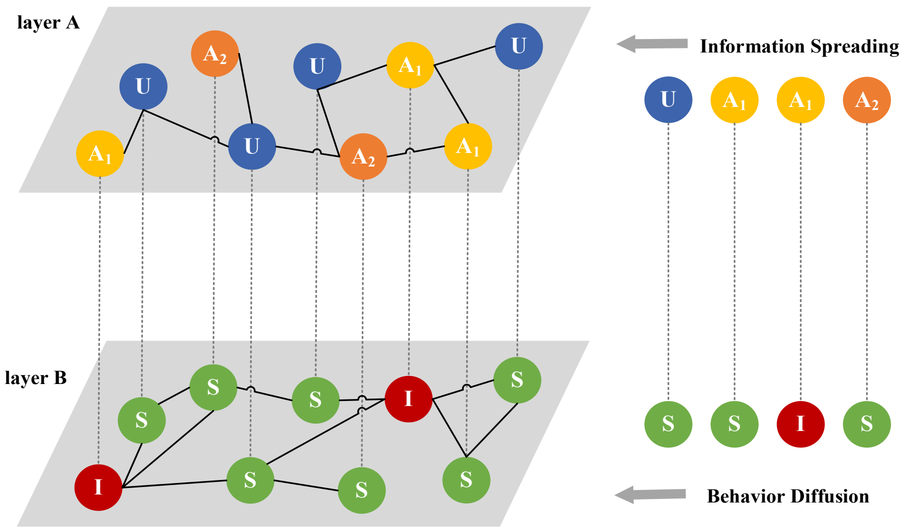

Figure 1: Two-layer multiplex networks model of responsible innovation behavior diffusion.

2.2. Behavior Diffusion Model

As shown in *Figure1*, in the responsible innovation information dissemination network, based on the idea of UAU-SIS model and the practice of responsible innovation information dissemination, the node states in the upper responsible innovation behavior network are divided into three categories, as follows:

Unaware state (U): the node in this state does not know the relevant information of responsible innovation or waits for its neighbors to pass on information due to factors such as forgetting;

Positive state (A_1): the node in this state has learned the relevant information of responsible innovation, and will spread the relevant information to the neighbor in the unknown state with a certain probability;

Negative state (A_2), the node in this state has learned about the relevant information of responsible innovation, but will not spread the relevant information to its neighbors due to reasons such as uninterested or disapproved.

In the lower level responsible innovation behavior network, based on the idea of UAU-SIS model and the actual diffusion of responsible innovation behavior, node states are divided into two categories, as follows:

Susceptible state (S): the node in this state has not implemented responsible innovation or has given up implementing responsible innovation for various reasons;

Implementation state (I): the node in this state implements responsible innovation behavior and will affect the neighbor in the wait-and-see state with a certain probability.

To sum up, individuals in the model may have six states: US, UI, A_1S, A_1I, A_2S and A_2I. However, when individuals implement responsible innovation, they usually already know the responsible innovation information; Individuals who have a negative attitude towards responsible innovation usually do not carry out responsible innovation, so we exclude UI and A_2I, which are not in line with the actual situation. Therefore, there are four states of individuals in the model: US (unknown responsible innovation without behavior), A_1S (recognized responsible innovation without behavior), A_1I (recognized responsible innovation with behavior), and A_2S (not recognized responsible innovation without behavior). For each individual, the mutual transformation process between these four states is

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shown in *Figure 2*.

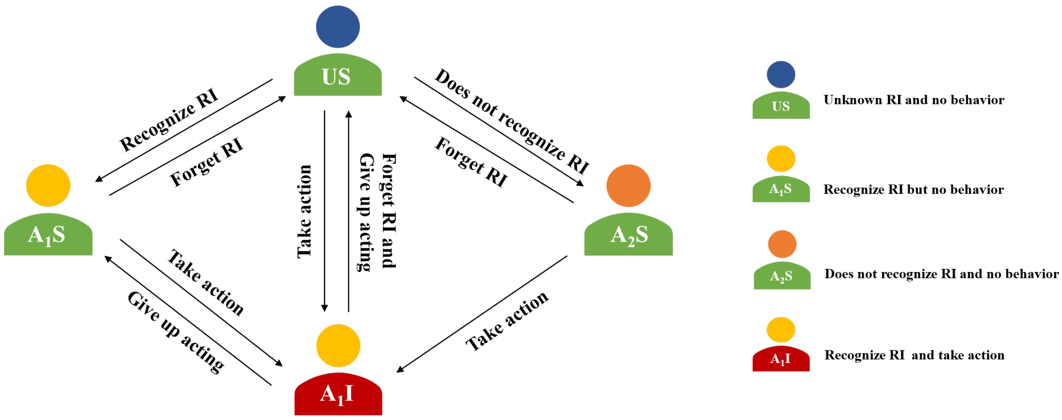

Figure 2: Diagram of transition model between states in behavior diffusion process.

In the information communication network, the UA$_1$A$_2$U communication model is adopted. Different from the traditional UAU model, we subdivide state A into A$_1$ and A$_2$, and use probability θ to represent individual preferences, and use δ_1, δ_2 to represent forgetting probability. In the behavior diffusion network, the traditional infectious disease model SIS model is used. Individuals in US, A$_1$S and A$_2$S are affected by individuals in A$_1$I with probability of β^U, β^{A_1} and β^{A_2}, respectively, and are transformed into A$_1$I, and satisfy $\beta^U=\gamma_1\beta$, $\beta^{A_1}=\beta$, $\beta^{A_2}=\gamma_2\beta$ where γ_1 and $\gamma_2\left(0\le\gamma_2\le\gamma_1\le 1\right)$ represent the attenuation factor of the impact. In addition, individuals generally do not directly change their attitudes towards responsible innovation, so state A$_1$S and state A$_2$S cannot be transferred to each other, and state A$_1$I cannot be directly transferred to A$_2$S.

3. Theoretical Analysis Based On MMCA

3.1. Kinetic Equation Of Behavior Diffusion

Note that a_{ij} and b_{ij} are the adjacency matrices of the upper information dissemination network layer A and the lower behavior diffusion network layer B, respectively. Note that the probability of *i* in the state US, A$_1$S, A$_1$I and A$_2$S at time step *t* is $P_i^{US}(t)$, $P_i^{A_1S}(t)$, $P_i^{A_1I}(t)$ and $P_i^{A_2S}(t)$ respectively, and $P_i^{US}(t)+P_i^{A_1S}(t)+P_i^{A_1I}(t)+P_i^{A_2S}(t)=1$.

In the information dissemination network, for an individual *i* with any status U, if he/she does not get any information about responsible innovation from his/her neighbors in the time step, the probability is recorded as $r_i(t)$. In the behavior diffusion network, if the individual *i* whose status is U is not affected by the neighbor's responsible innovation behavior, and thus conducts responsible innovation behavior, its probability is recorded as $q_i^U(t)$; Similarly, individuals in A1 (A$_2$) status are not affected by the neighbor's responsible innovation behavior, so the probability of responsible innovation behavior is $q_i^{A_1}(t)$ and $q_i^{A_2}(t)$. The transmission rate of responsible innovation information is λ, and the specific formula is as follows:

$$\begin{cases} r_i(t)=\prod_j\left[1-a_{ji}P_j^{A_1}(t)\lambda\right] \\ q_i^{A_1}(t)=\prod_j\left[1-b_{ji}P_j^{A_1I}(t)\theta\beta^{A_1}\right] \\ q_i^{A_2}(t)=\prod_j\left[1-b_{ji}P_j^{A_1I}(t)(1-\theta)\beta^{A_2}\right] \\ q_i^{U}(t)=\prod_j\left[1-b_{ji}P_j^{A_1I}(t)\beta^{U}\right] \end{cases} \tag{1}$$

ISSN 2616-5775 Vol. 5, Issue 14: 100-112, DOI: 10.25236/AJCIS.2022.051416

Especially, $P_j^{A_1}(t) = P_j^{A_1S}(t) + P_j^{A_1I}(t)$, $P_j^{A_2} = P_j^{A_2S}(t)$.

For individuals in US status, if they do not know the responsible innovation information within time step t and are not affected by their neighbors who implement responsible innovation, they will continue to maintain US status; If the responsible innovation information is known within time step *t* and is not affected by its neighbors who implement responsible innovation, it may change to status A_1S or A_2S; If the neighbor who has implemented the responsible innovation influences the responsible innovation behavior and then implements the responsible innovation behavior, it will change to state A_1I, and the specific state transition probability is defined as follows:

$$\begin{cases} \phi_i^{US\leftarrow US}(t) = r_i(t)q_i^U(t) \\ \phi_i^{A_1S\leftarrow US}(t) = \theta\left[1-r_i(t)\right]q_i^{A_1}(t) \\ \phi_i^{A_2S\leftarrow US}(t) = (1-\theta)\left[1-r_i(t)\right]q_i^{A_2}(t) \\ \phi_i^{A_1I\leftarrow US}(t) = r_i(t)\left[1-q_i^U(t)\right] + \theta\left[1-r_i(t)\right]\left[1-q_i^{A_1}(t)\right] \\ \qquad +(1-\theta)\left[1-r_i(t)\right]\left[1-q_i^{A_2}(t)\right] \end{cases} \tag{2}$$

For individuals in A1S status, if they forget the responsible innovation information within time step *t* and are not affected by their neighbors who implement responsible innovation, they will change to US status; If the responsible innovation information is not forgotten in time step t and is not affected by its neighbors who implement responsible innovation, the A_1S status will be maintained; If the neighbor who has implemented the responsible innovation influences the responsible innovation behavior and then implements the responsible innovation behavior, it will change to state A_1I, and the specific state transition probability is defined as follows:

$$\begin{cases} \phi_i^{US\leftarrow A_1S}(t) = \delta_1 q_i^U(t) \\ \phi_i^{A_1S\leftarrow A_1S}(t) = \left(1-\delta_1\right)q_i^{A_1}(t) \\ \phi_i^{A_1I\leftarrow A_1S}(t) = \delta_1\left[1-q_i^U(t)\right] + \left(1-\delta_1\right)\left[1-q_i^{A_1}(t)\right] \end{cases} \tag{3}$$

For individuals in A_2S status, if they forget the responsible innovation information within time step *t* and are not affected by their neighbors who implement responsible innovation, they will change to US status; If the responsible innovation information is not forgotten in time step t and is not affected by its neighbors who implement responsible innovation, the A_2S status will be maintained; If the neighbor who has implemented the responsible innovation influences the responsible innovation behavior and then implements the responsible innovation behavior, it will change to state A_1I, and the specific state transition probability is defined as follows:

$$\begin{cases} \phi_i^{US\leftarrow A_1S}(t) = \delta_1 q_i^U(t) \\ \phi_i^{A_1S\leftarrow A_1S}(t) = \left(1-\delta_1\right)q_i^{A_1}(t) \\ \phi_i^{A_1I\leftarrow A_1S}(t) = \delta_1\left[1-q_i^U(t)\right] + \left(1-\delta_1\right)\left[1-q_i^{A_1}(t)\right] \end{cases} \tag{4}$$

For individuals in A_1I status, if they forget the responsible innovation information and give up the neighborhood influence of implementing responsible innovation within time step *t*, they will change to US status; If the responsible innovation behavior is abandoned within the time step t, it will change to the A_1S state; Otherwise, the A_1I state will be maintained. The specific state transition probability is defined as follows:

$$\begin{cases} \phi_i^{US\leftarrow A_1I}(t) = \delta_1\mu \\ \phi_i^{A_1S\leftarrow A_1I}(t) = \left(1-\delta_1\right)\mu \\ \phi_i^{A_1I\leftarrow A_1I}(t) = 1-\mu \end{cases} \tag{5}$$

According to the model constructed in Section 2.2, the transfer probability tree is drawn as follows, as shown in Figure 3:

ISSN 2616-5775 Vol. 5, Issue 14: 100-112, DOI: 10.25236/AJCIS.2022.051416

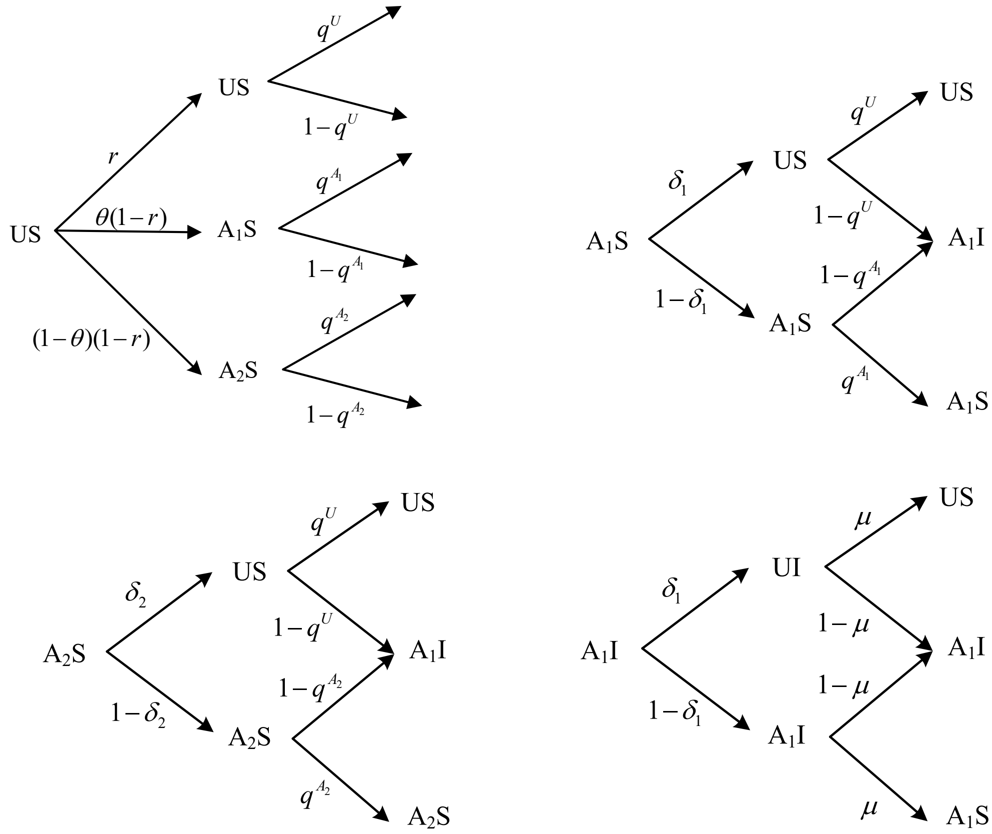

Figure 3: State transition probability tree.

According to MMCA, the dynamic equation of responsible innovation behavior diffusion can be obtained as follows:

$$\begin{cases} P_i^{US}(t+1) = P_i^{A_1S}(t)\phi_i^{US\leftarrow A_1S}(t) + P_i^{A_2S}(t)\phi_i^{US\leftarrow A_2S}(t) + P_i^{A_1I}(t)\phi_i^{US\leftarrow A_1I}(t) \\ \qquad + P_i^{US}(t)\phi_i^{US\leftarrow US}(t) \\ P_i^{A_1S}(t+1) = P_i^{A_1S}(t)\phi_i^{A_1S\leftarrow A_1S}(t) + P_i^{A_1I}(t)\phi_i^{A_1S\leftarrow A_1I}(t) + P_i^{US}(t)\phi_i^{A_1S\leftarrow US}(t) \\ P_i^{A_1I}(t+1) = P_i^{A_1S}(t)\phi_i^{A_1I\leftarrow A_1S}(t) + P_i^{A_2S}(t)\phi_i^{A_1I\leftarrow A_2S}(t) + P_i^{US}(t)\phi_i^{A_1I\leftarrow US}(t) \\ \qquad + P_i^{A_1I}(t)\phi_i^{A_1I\leftarrow A_1I}(t) \\ P_i^{A_2S}(t+1) = P_i^{A_2S}(t)\phi_i^{A_2S\leftarrow A_2S}(t) + P_i^{US}(t)\phi_i^{A_2S\leftarrow US}(t) \end{cases} \tag{6}$$

Collate the formula to get:

$$\begin{cases} P_i^{US}(t+1) = P_i^{A_1S}(t)\delta_1 q_i^U(t) + P_i^{A_2S}(t)\delta_2 q_i^U(t) + P_i^{A_1I}(t)\delta_1\mu \\ \qquad + P_i^{US}(t) r_i(t) q_i^U(t) \\ P_i^{A_1S}(t+1) = P_i^{A_1S}(t)(1-\delta_1) q_i^{A_1}(t) + P_i^{A_1I}(t)(1-\delta_1)\mu \\ \qquad + P_i^{US}(t)\theta[1-r_i(t)] q_i^{A_1}(t) \\ P_i^{A_1I}(t+1) = P_i^{A_1S}(t)\left\{\delta_1\left[1-q_i^U(t)\right] + (1-\delta_1)\left[1-q_i^{A_1}(t)\right]\right\} \\ \qquad + P_i^{A_2S}(t)\left\{\delta_2\left[1-q_i^U(t)\right] + (1-\delta_2)\left[1-q_i^{A_2}(t)\right]\right\} \\ \qquad + P_i^{US}(t)\left\{r_i(t)\left[1-q_i^U(t)\right] + \theta[1-r_i(t)]\left[1-q_i^{A_1}(t)\right] \right. \\ \qquad \left. + (1-\theta)[1-r_i(t)]\left[1-q_i^{A_2}(t)\right]\right\} + P_i^{A_1I}(t)(1-\mu) \\ P_i^{A_2S}(t+1) = P_i^{A_2S}(t)(1-\delta_2) q_i^{A_2}(t) + P_i^{US}(t)[1-r_i(t)](1-\theta) q_i^{A_2}(t) \end{cases} \tag{7}$$

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And $P_i^{US}(t+1)$, $P_i^{A_1S}(t+1)$, $P_i^{A_1I}(t+1)$, $P_i^{A_2S}(t+1)$ is the probability that individual i is in US, A_1S, A_1I and A_2S at the next time step.

3.2. Threshold of Behavior Diffusion

When the system reaches steady state, the individual state in the network will not change any more, then:

$$\begin{cases} P_i^{US}(t+1) = P_i^{US}(t) = P_i^{US} \\ P_i^{A_1I}(t+1) = P_i^{A_1I}(t) = P_i^{A_1I} \\ P_i^{A_1S}(t+1) = P_i^{A_1s}(t) = P_i^{A_1S} \\ P_i^{A_2S}(t+1) = P_i^{A_2S}(t) = P_i^{A_2S} \end{cases} \tag{8}$$

P_i^{US}, $P_i^{A_1I}$, $P_i^{A_1S}$ and $P_i^{A_2S}$ respectively represent the four possible states of individuals after the system reaches a stable state.

According to the idea of infectious disease model SIS, when it is infinitely close to the threshold, the proportion of individuals (infected individuals) carrying out responsible innovation in the system is close to 0 in the steady state, that is, $P_{\mathrm{i}}^{AI} = \epsilon_i \ll 1$, there are:

$$\begin{cases} q_i^{A_1} = \prod_j \left[1 - b_{ji} P_j^{A_1I}(t)\theta\beta^{A_1}\right] \approx 1 - \theta\beta^{A_1} \sum_j b_{ji}\epsilon_j \\ q_i^{A_2} = \prod_j \left[1 - b_{ji} P_j^{A_1I}(t)(1-\theta)\beta^{A_2}\right] \approx 1 - (1-\theta)\beta^{A_2} \sum_j b_{ji}\epsilon_j \\ q_i^{U} = \prod_j \left[1 - b_{ji} P_j^{A_1I}(t)\beta^{U}\right] \approx 1 - \beta^{U} \sum_j b_{ji}\epsilon_j \end{cases} \tag{9}$$

In order to simplify the derivation, note $\alpha_i^{A_1} = \beta^{A_1}\sum_j b_{ji}\epsilon_j$, $\alpha_i^{U} = \beta^{\mathrm{U}}\sum_j b_{ji}\epsilon_j$, then $q_i^{A_1} \approx 1-\alpha_i^{A_1}$, $q_i^{A_2} \approx 1-\alpha_i^{A_2}$, $q^{U} \approx 1-\alpha_i^{U}$, then Formula (7) can be simplified as:

$$\begin{cases} P_i^{A_1S} = P_i^{A_1S}\left(1-\delta_1\right)\left(1-\alpha_i^{A_1}\right) + P_i^{A_1I}\left(1-\delta_1\right)\mu \\ \qquad + P_i^{US}\theta\left(1-r_i^{A_1}\right)\left(1-\alpha_i^{A_1}\right) \\ P_i^{A_1I} = P_i^{A_1S}\left[\delta_1\alpha_i^{U} + \left(1-\delta_1\right)\alpha_i^{A_1}\right] + P_i^{A_2S}\left[\delta_2\alpha_i^{U} + \left(1-\delta_2\right)\alpha_i^{A_2}\right] \\ \qquad + P_i^{US}\left[r_i^{A_1}\alpha_i^{U} + \theta\left(1-r_i^{A_1}\right)\alpha_i^{A_1} + \theta\left(1-r_i^{A_1}\right)\alpha_i^{A_2}\right] \\ \qquad + P_i^{A_1I}(t)(1-\mu) \\ P_i^{A_2S} = P_i^{A_2S}\left(1-\delta_2\right)\left(1-\alpha_i^{A_2}\right) + P_i^{US}(1-\theta)\left(1-r_i^{A_1}\right)\left(1-\alpha_i^{A_2}\right) \end{cases} \tag{10}$$

Ignoring the higher-order term, Formula (10) is further simplified as:

$$\begin{cases} P_i^{US} = P_i^{A_1S}\delta_1 + P_i^{A_2S}\delta_2 + P_i^{US} r_i^{A_1} \\ P_i^{A_1S} = P_i^{A_1S}\left(1-\delta_1\right) + P_i^{US}\theta\left(1-r_i^{A_1}\right) \\ P_i^{A_2S} = P_i^{A_2S}\left(1-\delta_2\right) + P_i^{US}\left(1-\theta\right)\left(1-r_i^{A_1}\right) \\ \epsilon_i = P_i^{A_1S}\left[\delta_1\alpha_i^{U} + \left(1-\delta_1\right)\alpha_i^{A_1}\right] + P_i^{A_2S}\left[\delta_2\alpha_i^{U} + \left(1-\delta_2\right)\alpha_i^{A_2}\right] \\ + P_i^{US}\left[r_i^{A_1}\alpha_i^{U} + \theta\left(1-r_i^{A_1}\right)\alpha_i^{A_1} + \theta\left(1-r_i^{A_1}\right)\alpha_i^{A_2}\right] + \epsilon_i\left(1-\mu\right) \end{cases} \tag{11}$$

Substitute P_i^{US}, $P_i^{A_1S}$, $P_i^{A_2S}$ into the last formula of Formula (11), and simplify to get:

$$\begin{aligned}\mu\epsilon_i &= P_i^{A_1S}\alpha_i^{A_1} + P_i^{A_2S}\alpha_i^{A_2} + P_i^{US}\alpha_i^{U} \\ &= P_i^{A_1S}\beta^{A_1}\sum_j b_{ji}\epsilon_j + P_i^{A_2s}\beta^{A_2}\sum_j b_{ji}\epsilon_j + P_i^{US}\beta^{U}\sum_j b_{ji}\epsilon_j \\ &= \left[P_i^{A_1S}\theta + P_i^{A_2S}\gamma_2(1-\theta) + \gamma_1 P_i^{US}\right]\beta^{A_1}\sum_j b_{ji}\epsilon_j\end{aligned} \tag{12}$$

Note $P_i^{A_1S} + P_i^{A_1I} = P_i^{A_1}$, $P_i^{A_2S} = P_i^{A_2}$. When β is infinitely close to the threshold β^c, and the proportion of individuals engaging in responsible innovation in the system is close to 0 in the steady state, then there are $P_i^{A_1S} + P_i^{A_2S} \approx P_i^{A_1} + P_i^{A_2}$ and $P_i^{US} \approx 1-\left(P_i^{A_1} + P_i^{A_2}\right)$, which can be obtained by substituting Formula (12):

$$\begin{aligned}\mu\epsilon_i &= \left\{P_i^{A_1}\theta + P_i^{A_2}\gamma_2(1-\theta) + \gamma_1\left[1-\left(P_i^{A_1} + P_i^{A_2}\right)\right]\right\}\beta^{A_1}\sum_j b_{ji}\epsilon_i \\ &= \beta^{A_1}\left\{\gamma_1 - (\gamma_1-\theta)P_i^{A_1} - \left[\gamma_1 - \gamma_2(1-\theta)\right]P_i^{A_2}\right\}\sum_j b_{ji}\epsilon_i\end{aligned} \tag{13}$$

After sorting out, we can get:

$$\sum_j\left\{\beta^{A_1}\left[\gamma_1 - (\gamma_1-\theta)P_i^{A_1} - \left(\left(\gamma_1-\gamma_2(1-\theta)\right)\right)P_i^{A_2}\right]b_{ji} - \frac{\mu}{\beta^{A_1}}\sigma_{ji}\right\}\epsilon_j = 0 \tag{14}$$

Where σ_{ji} is the element in the identity matrix. $\Lambda_{max}(H)$ is the maximum eigenvalue of the matrix, and the elements of the matrix are $\left\{\gamma_1 - (\gamma_1-\theta)P_i^{A_1} - \left[\gamma_1 - \gamma_2(1-\theta)\right]P_i^{A_2}\right\}b_{ji}$. Therefore, we can get that the burst threshold of behavior diffusion in this model is:

$$\beta_c = \beta_c^{A_1} = \frac{\mu}{\Lambda_{max}(H)} \tag{15}$$

4. Simulation Result

4.1. Monte Carlo (MC) Simulation

In order to verify the accuracy of the MMCA method, this section uses Monte Carlo (MC) simulation to compare the evolution of responsible innovation behavior diffusion between the two. In order to better describe the results of the diffusion of responsible innovation behavior, $\rho^{A_1} = \left[\sum_i\left(P_i^{A_1I} + P_i^{A_1S}\right)\right]/N$ and $\rho^{A_2} = \left(\sum_i P_i^{A_2S}\right)/N$ are introduced to represent the density of individuals who have positive and negative attitudes towards the concept of responsible innovation in the information dissemination network, and $\rho^{I} = \left(\sum_i P_i^{A_1I}\right)/N$ is introduced to represent the density of individuals who implement responsible innovation behavior in the behavior diffusion network. For MC simulation, there are $\rho^{A_1} = N_{A_1}/N = \left(N_{A_1S} + N_{A_1I}\right)/N$, $\rho^{A_2} = N_{A_2}/N = N_{A_2S}/N$, $\rho^{I} = N_I/N = N_{A_1I}/N$.

In the experiment in this section, there are 10000 individuals in the two-layer multiplex networks. To ensure the accuracy of the experiment results, all simulation results are the average value after 100 independent runs. Considering the small world and scale-free nature of the real network structure, this section constructs a two-layer small world networks with an average degree of 6 (WS-WS network) and a two-layer scale-free networks with an average degree of 6 (BA-BA network) respectively.

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Set the experimental parameters $\lambda = 0.6$, $\delta_1 = \delta_2 = 0.3$, $\mu = 0.5$, $\theta = 0.6$. *Figure 4* shows the change of individual density ρ^I, ρ^{A_1} and ρ^{A_2} with β in state I, A_1 and A_2 in a two-layer small world networks (WS-WS network). The parameters in *Figure 4(a)* are set as $\gamma_1 = 0.5$, $\gamma_2 = 0$; The parameters in Figure 4.4 (b) are set as $\gamma_1 = 0.8$, $\gamma_2 = 0.3$. By comparing the experimental results, it can be seen that the results obtained by MMCA method and MC simulation have good consistency.

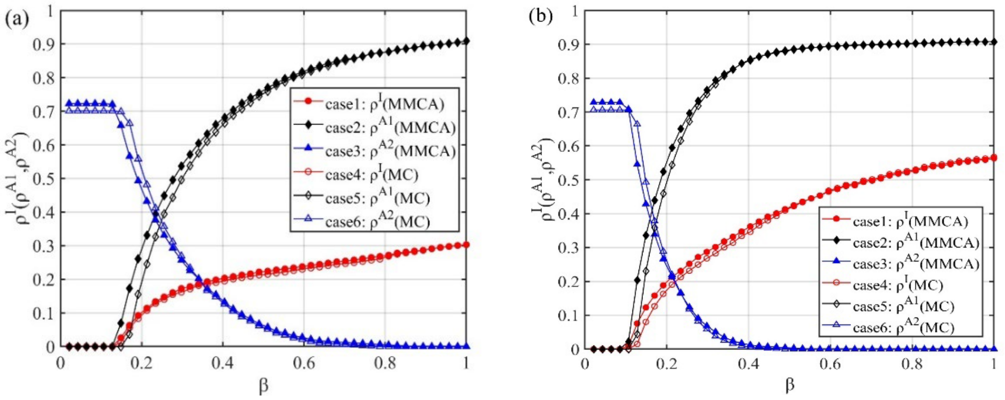

Figure 4: Comparison Diagram of MMCA and MC in WS-WS Networks.

In order to further test the effectiveness of the MMCA method and exclude the influence of the network structure on the experimental results, the experimental parameters were set as densities, $\delta_1 = \delta_2 = 0.3$, $\mu = 0.5$, $\theta = 0.6$, $\gamma_1 = 0.8$, $\gamma_2 = 0.3$. Two methods were used to compare the changes of individual densities ρ^I, ρ^{A_1} and ρ^{A_2} with β in the state I, A_1 and A_2 of the two-layer scale-free networks (BA-BA network). *Figure 5* shows that MMCA still has good accuracy in BA-BA network. In addition, by comparing *Figure 4(b)* and *Figure 5*, we can see that responsible innovation is more likely to spread in scale-free networks.

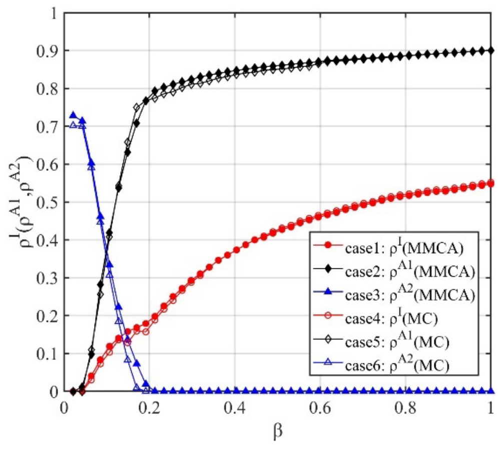

Figure 5: Comparison Diagram of MMCA and MC in BA-BA Networks.

4.2. Influencing Factors of Behavior Diffusion Scale

Set the experimental parameters $\lambda = 0.6$, $\delta_1 = \delta_2 = 0.3$, $\mu = 0.5$, $\gamma_1 = 0.8$, $\gamma_2 = 0.3$ to explore the impact of individual preference $\theta = 0.2, 0.4, 0.6, 0.8, 1$ on the diffusion scale of responsible innovation behavior (ρ^I) in WS-WS network and BA-BA network respectively. *Figure 6* shows that when β is small and the individual preference θ is greater, the diffusion scale of the ultimate responsible innovation behavior is larger; However, if β exceeds a certain value, the change of individual preference θ has little impact on the diffusion scale of responsible innovation behavior, and the final diffusion scale of responsible innovation behavior tends to a similar level. In addition, by comparing the two networks, it can be seen that when β is large, the responsible innovation behavior is easier to spread in the scale-free network under the same individual preference θ.

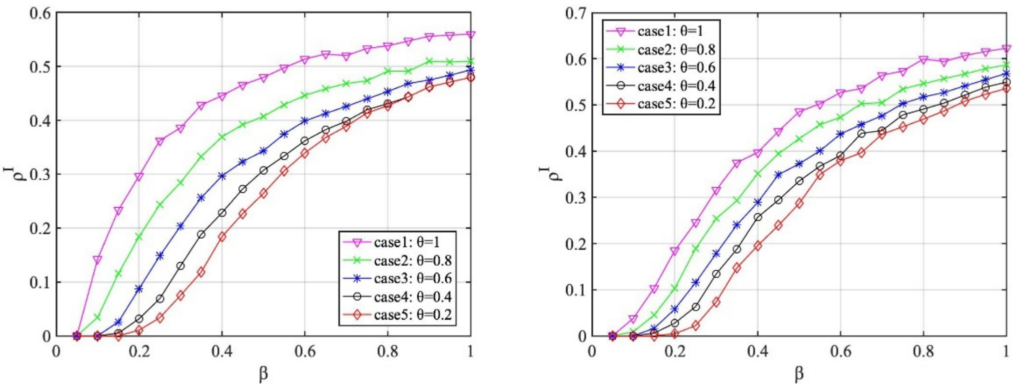

Figure 6: Influence of Different Individual Preference θ *on Diffusion Scale* ρ^I.

Set experimental parameter $\delta_1 = \delta_2 = 0.3$, $\mu = 0.4$, $\theta = 0.5$, $\gamma_1 = 0.8$, $\gamma_2 = 0.3$, and explore the impact of information transmission rate $\lambda = 0.2, 0.4, 0.6$ on the diffusion scale (ρ^I) of responsible innovation behavior in WS-WS network and BA-BA network respectively. Through the simulation experiment, it can be seen that the diffusion scale of responsible innovation behavior (ρ^I) in WS-WS network and BA-BA network increases with the increase of information transmission rate λ , indicating that the more popular responsible innovation information is in the upper information communication network, the more public have the awareness of responsible innovation, the more willing to implement responsible innovation, and the more public the corresponding behavior diffusion layer implements responsible innovation. This shows that the dissemination of responsible innovation information can effectively promote the diffusion of responsible innovation behavior, as shown in Figure 7.

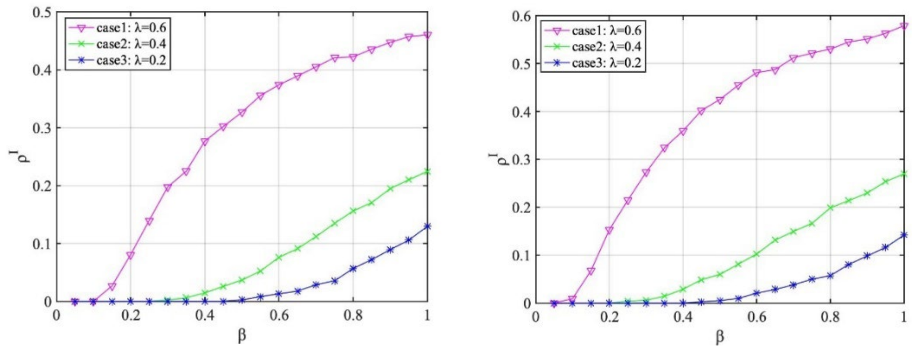

Figure 7: Influence of information transmission rate λ *on diffusion scale* ρ^I.

4.3. Influencing Factors of Behavior Diffusion Threshold

Different from the traditional infectious disease model, the larger the threshold of infectious disease outbreak is, the better, while the smaller the threshold of responsible innovation behavior diffusion is, the better. Set the experimental parameter $\theta = 0.5$, and explore the impact of different information transmission rate A and forgetting rate A on the threshold A of responsible innovation behavior diffusion in the two networks, as shown in *Figure (8).* Wherein, *Figure 8 (a)* and *Figure 8 (b)* show the simulation experiment results of WS-WS network, and *Figure 8 (c)* and *Figure 8 (d)* show the experiment results of BA-BA network; *Figure 8 (a)* and *Figure 8 (c)* set attenuation factors $\gamma_1 = 0.5$, $\gamma_2 = 0$, and *Figure 8 (b)* and *Figure 8 (d)* set attenuation factors $\gamma_1 = 0.8$, $\gamma_2 = 0.3$. The simulation experiment shows that the diffusion threshold β_c of responsible innovation behavior decreases with the increase of information transmission rate λ , and increases with the increase of forgetting rate δ . Therefore, in order to promote the diffusion of responsible innovation, we should enhance the public's attention to responsible innovation information through various publicity methods, and we should continuously promote responsible innovation to reduce the rate of forgetting. At the same time, it can be seen that the reduction of recovery rate μ will also reduce the threshold of diffusion of responsible innovation behavior. Therefore, the government should reduce the public's abandonment of responsible innovation behavior through various policies to promote the better diffusion of responsible innovation behavior among the public. By comparing *Figure 8 (a)* and *Figure 8 (c)*, it can be seen that the greater the attenuation factor γ, the greater the diffusion threshold β_c of responsible innovation behaviour, that is, the stronger the public's sense of recognition of responsible innovation, the more it can promote the diffusion of responsible innovation behavior. In addition, by comparing *Figure 8 (a)* and *Figure 8 (c)* and *Figure 8 (b)* and *Figure 8 (d)*, it can be found that, with the same other parameters, the diffusion threshold of responsible innovation in scale-free networks is always small, indicating that responsible innovation is easier to diffuse in scale-free networks.

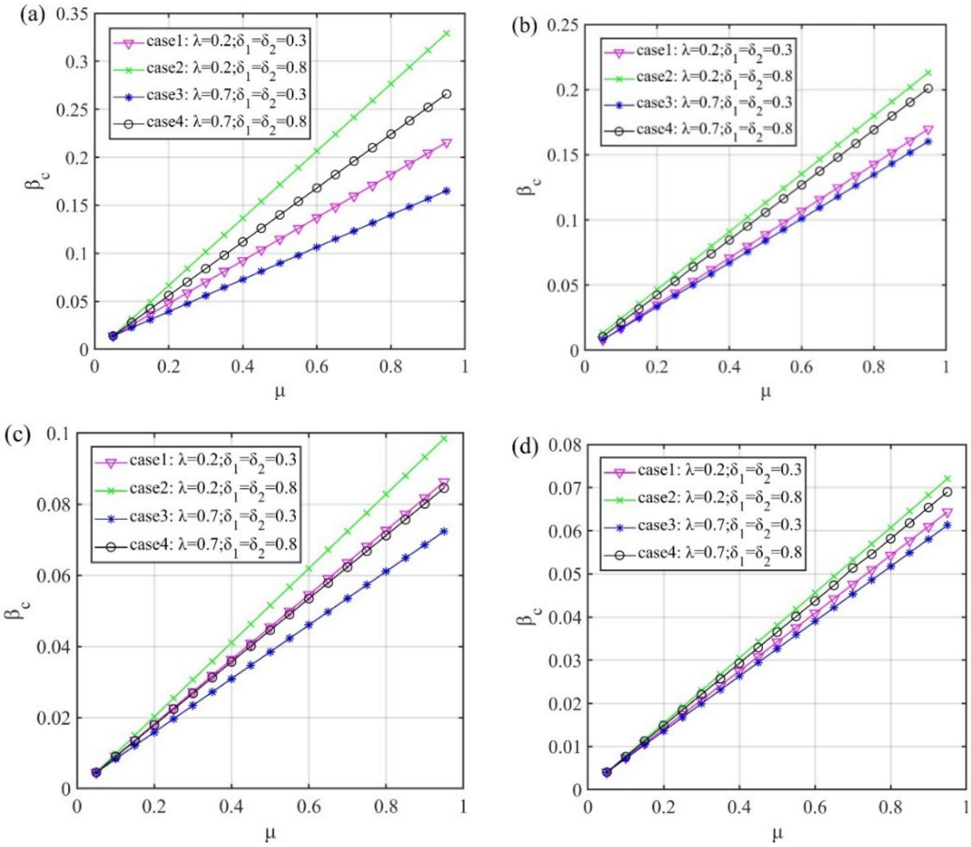

Figure 8: Influence of information transmission rate λ *and forgetting rate* δ *on diffusion threshold* β_c.

Set the experimental parameters $\lambda = 0.6$, $\delta_1 = \delta_2 = 0.3$, $\theta = 0.5$, and explore the impact of different attenuation factors γ_1 and γ_2 on the threshold A of responsible innovation behavior diffusion in the two networks, as shown in *Figure 9*. It can be seen from the experiment that the more it can promote the diffusion of responsible innovation behavior. It is worth noting that when $\gamma_2 = 0$, individuals who express a negative attitude towards responsible innovation are unlikely to be affected by the responsible innovation behavior of their neighbors and stick to their own position. At this time, the threshold of responsible innovation diffusion behavior is the largest, which is the most unfavorable for the diffusion of responsible innovation behavior. However, when $\gamma_1 = 1$ and $\gamma_2 = 1$, no matter what the individual's attitude towards responsible innovation is, they will be affected by their neighbors and may implement responsible innovation behavior. Therefore, the threshold of responsible innovation behavior diffusion is the minimum.

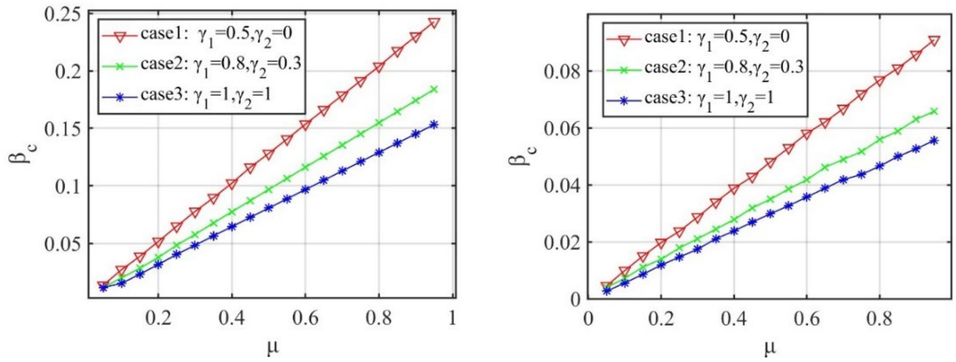

Figure 9: Influence of attenuation factor γ *on diffusion threshold* β_c.

5. Conclusions

Based on the two-layer network, this paper studies the dynamic characteristics of the diffusion of responsible innovation behavior. Firstly, through the analysis of the interaction mechanism between responsible innovation information dissemination and responsible innovation behavior diffusion, and through the description of MMCA, the threshold of responsible innovation behavior diffusion is deduced. Then a large number of simulation experiments are used to analyze and verify the theoretical model, and the validity of the model is verified through MC simulation. At the same time, in the two-layer small world network and the two-layer scale-free network, we studied the influence of individual preference and information dissemination rate on the diffusion scale of responsible innovation behavior, and explored the influence of information dissemination rate, forgetting rate and attenuation factor on the diffusion threshold of responsible innovation.

The research finds that: first, the information dissemination rate is positively related to the diffusion scale of responsible innovation behavior, and negatively related to the diffusion threshold. The greater the information dissemination rate, the more conducive to the diffusion of responsible innovation behavior. Secondly, the degree of individual preference will also significantly affect the behavior diffusion of responsible innovation. The degree of individual preference is positively related to the behavior diffusion scale of responsible innovation, and negatively related to the diffusion threshold. The greater the degree of individual preference, the more conducive to the behavior diffusion of responsible innovation. Thirdly, forgetting rate is positively related to the threshold of diffusion of responsible innovation behavior. The greater the forgetting rate is, the more unfavorable the diffusion of responsible innovation behavior is. Finally, the attenuation factor is negatively related to the threshold of diffusion of responsible innovation behavior. The greater the forgetting rate is, the more conducive to the diffusion of responsible innovation behavior is.

To sum up, through this study, in order to better promote the spread of public responsible innovation, we can draw three policy implications: First, the government should increase the publicity of responsible innovation, and should continue to publicize, to prevent the public from forgetting information about responsible innovation or losing interest in responsible innovation. Second, the government should seize the groups that are easy to identify with responsible innovation, encourage them to take responsible innovation behavior, and encourage them to actively promote it to people around them. Third, the government should also pay attention to the public who have a negative attitude towards responsible innovation, listen to their opinions and actively improve.

Finally, the network studied in this paper is a static network, and the diffusion of responsible innovation behavior on the dynamic network has not been studied. Future research can be conducted on the dynamic complex network. With the development of responsible innovation, the role of different individuals in the network will become more and more distinct. Based on this, the research is more practical and the conclusions drawn are more valuable.

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