Hindawi
Discrete Dynamics in Nature and Society
Volume 2022, Article ID 5796428, 13 pages
https://doi.org/10.1155/2022/5796428

Research Article

The Whistleblower's Dilemma: An Evolutionary Game Analysis of the Public Health Early Warning System

Feng Cao,[1] Ling Zhang,[1] and Yihan Wu[2]

[1]*School of Economics and Management, Fuzhou University, Fuzhou, China*
[2]*School of Social Development, Nanjing Normal University, Nanjing, China*

Correspondence should be addressed to Yihan Wu; yihan818@outlook.com

Received 10 August 2022; Accepted 6 September 2022; Published 21 September 2022

Academic Editor: Juan L. G. Guirao

Although the ability to manage public health emergencies in China has improved significantly, there are still many challenges to the existing information transmission mechanism in pandemic early warning systems. In this context, a tripartite evolutionary game model composed of the local government, the whistleblower, and the public is formulated. By using Matlab, the dynamic evolution path of the game model is stimulated under different conditions. Stable strategies for an early warning system for public health emergencies are also explored. The results indicate that the cost of whistleblowing, the cost of response, and the benefit of attention significantly influence strategic decisions among three parties. This study highlights the importance of whistleblowing in managing public health emergencies. Yet, our findings provide theoretical support for policy recommendations for promoting public health emergency preparedness.

1. Introduction

The outbreak of disease not only has a huge impact on socioeconomic order and people's safety and property but also brings severe challenges to the public health emergency management system in China. Although our emergency preparedness shows good overall progress after experiencing infectious diseases, such as SARS and H7N9, and the Wenchuan earthquake, gaps remain in the implementation of an effective early warning system [1]. For example, unexplained pneumonia cases were reported in a hospital in Wuhan as early as December 2019. Unfortunately, the local government did not make appropriate judgments and efficiently respond to the early warning information reported by those medical professionals. In this context, considering the potential harm to the public caused by the infected and suspected cases, the medical professionals chose to announce the early warning information to a small portion of the population. They violated public health ethics, said the truth about COVID-19, and were relevantly penalized by the local government. Such reasons and facts led to the failure to effectively manage COVID-19 in the early stages. The whistleblower's ethical dilemma in medicine and public health and the behavior of whistleblowing are likely to influence strategic decisions about public health emergencies [1–5].

Many scholars assume that in classical games of public health decision-making, especially in relation to early warning information management, participants do not always have symmetric information about an event and that most participants have bounded rationality [6–9]. Therefore, evolutionary game theory is becoming an effective tool for exploring public health early warning systems. This is because it combines classical games with evolutionary biology, in which the total rationality of participants becomes bounded rationality and information shifts from perfect to imperfect symmetry [10]. In the literature, Fan et al. [6] studied the behavioral strategies among the government, community, and residents and proved that the dynamic reward and punishment mechanism can effectively suppress the fluctuation problem in the process of public health decision-making. Xu et al. [9] analyzed the strategic behaviors of the government, enterprises, and the public in the management of public health emergencies based on game theory. In the context of the COVID-19 epidemic, Jia et al. [8] used the dynamic game model to demonstrate that the strategic evolution of the public mainly depends on stochastic factors, cost-benefit, and the number of the public. The government's strategies could influence the speed of the public choosing a negative strategy.

However, the evolutionary approach to public health is still a new challenge. Many scholars only consider the interactions between the government and the public [1, 4, 6, 7, 9, 11–15] in the process of decision-making. The current literature also places more emphasis on the general decision-making of the public than on the impact of the public's concerns and preferences on administrative public health decisions. The public's attention is an important influencing factor in the process of decision-making [12, 16] and thus key to the effectiveness of early warning systems. Besides, different information content and transmission pathways may lead to different administrative decision-making. As a crucial transmitter of information about a disease and the main body of an early warning system [16], the dynamic behavior strategy of the whistleblower is very important to public health administrative decision-making.

Therefore, research focusing on the interactions between the local government, the whistleblower, and the public in pandemic early warning games has been found wanting. Hence, the purpose of this study is to solve the whistleblower's dilemma in a public health emergency. To deal with this, this study applies evolutionary game theory to construct a tripartite evolutionary game model of these three parties. Furthermore, this study will conduct simulation analysis to explore the specific factors affecting the evolution of behavioral strategies among three parties under different conditions. By doing so, this study hopes to provide economic means and policy recommendations for implementing an effective early warning system for public health emergencies.

The rest of this paper is organized as follows. In Section 2, we briefly discuss China's early warning system and the potential dilemma of whistleblowers in public health emergencies. In Section 3, we construct a tripartite evolutionary game model including assumptions and a payoff matrix, and in Section 4, we conduct the evolutionary stability analysis and stimulation analysis using Matlab to illustrate the impact of factors on behavioral strategies among three parties under different cases. Finally, in Section 5, the conclusions and the implications of this study are proposed.

2. Literature Review

2.1. China's Early Warning System. Public health emergencies such as SARS, H7N9, and Ebola have occurred frequently in the past two decades. After experiencing the SARS outbreak in 2003, China established a multiple-level system for prevention and control of public health emergencies [1]. By doing this, China's public health system's capability to respond to infectious diseases has been comprehensively improved. The vertical reporting of pandemic information in the multiple-level system ensures the accuracy and comprehensiveness of information and thus reduces social panic [17]. However, this kind of mechanism would influence the timeliness of publishing pandemic information to a certain extent and is prone to distort and misjudge the early warning information during transmission [18]. As a result, it might cause remarkable deficiencies in pandemic prevention, control, and management. From another perspective, the local government can help the public better understand the infectious disease through timely disclosure of information, reducing social confusion and panic, and promoting the public's voluntary participation in preventing and controlling the disease. Therefore, timely disclosure of early warning information has a significant positive effect on the public's trust and satisfaction in government [18, 19]. Thus, there is an inherent contradiction between the timeliness and accuracy of information disclosure, and the game equilibrium between the two becomes an important consideration for the local government to respond to early warning information.

Given that the rapid development of self-media (i.e., independently operating social media accounts) in China is accelerating the spread of public opinion on early warning information [14], and timely response to the information is helpful to guide and shape public opinion and reduce the infodemic (the rapid and widespread dissemination of both accurate and incorrect information about a pandemic), as well as enhance the credibility of the local government and prevent falling into the Tacitus trap (a credibility and legitimacy crisis for the government due to the loss of trust of the people). Nevertheless, China's public health policy requires the local government to make evidence-based decisions. Thus, the local government places greater emphasis on the authenticity and reliability of early warning information [1, 15]. Under the framework of evidence-based governance, managing public health emergencies is divided into three stages, namely, the early warning period, the controlling period, and the reconstructing period. Among these, the core tasks of the early warning period are to scientifically evidence the risk information and then announce it to the public in a timely manner. The core tasks of medical professionals are to ensure that early warning information can be delivered to decision-makers and the public in a timely and accurate manner [15, 16]. However, blocking and filtering of key evidence may occur during the vertical or upward transmission of information, which may affect the local government's efficiency in administrative decision-making and the accuracy of judging early warning information.

2.2. The Whistleblower's Dilemma. Due to the combined impacts of strategic decisions and information transmission mechanisms, the whistleblower's dilemma exists in managing public health emergencies. In particular, the contradiction between the timeliness and accuracy of information is the root cause of the whistleblower's dilemma. Before exploring the whistleblower's dilemma, it is necessary to understand the context in which the whistleblower lives.

Since existing laws and regulations in China lack clear rules and guidelines on the party and content of information disclosure, it brings great challenges to China's early warning system. Nevertheless, the relevant laws clearly specify the subjects of the early warning system and their authority. That is, the subject of deciding and issuing an early warning information of a pandemic is limited to the national health administrative department, the provincial government, and its health administrative department. Local governments, institutions, or individuals have no such authority below the provincial level [1, 5]. Considering the evidence-based principle of public policy in China, administrative information disclosure is related to the social stability of a society, so the disclosure needs to be carefully considered by the government. Therefore, from an institutional perspective, one of the reasons that puts the whistleblower in a difficult position (i.e., a dilemma) is that the institution of reporting early-earning information to the government is overly complex and time-consuming [1, 17]. When a pandemic risk shows a sign of continuous spread, the higher authorities are still cautiously assessing or evaluating the risk information, while the local government is waiting for the higher authorities' decisions [2, 15, 16]. Therefore, the absence of the distribution of the rights and responsibilities of the local government in public health emergencies reflects the absence of the right to disclose information at the assessment stage. In fact, the institution of vertically reporting the risk information reflects more of a cautious attitude of the local government towards information disclosure. The rapid development of social media has made the public more sensitive to risk information than in the past. Phenomena such as infodemics have emerged, which undoubtedly amplify the cautious response strategy adopted by the local government [14].

As the key transmitter of information in public health emergencies, the role of the whistleblower cannot be overlooked in public health emergencies as this group can receive risk information in the first instance [5]. Hence, in the early warning game system, the whistleblower has two kinds of strategic decisions. One is to report the early warning information to the government and wait for the decisions to be announced, while the other is to announce the information and raise an alarm to the public or a small portion of the population. However, given the need to maintain social stability, the voices of this group of people may be unable to affect the public's perception of the potential risk of a pandemic [20, 21]. They may even be penalized by the local government for spreading "rumors" or for breaking the regulations, leading to a situation where the spread of the pandemic is uncontrollable [5]. Thus, the local government is also challenged with two strategic decisions. One is to actively respond to the early warning information and prepare a contingency plan, while the other is to cautiously respond to the early warning information but just wait for the decisions made by the upper authorities.

The strategies of multiple parties together constitute a profile in the early warning game system. Hence, the whistleblower's dilemma takes two forms: One is the behavioral difference between the whistleblower and the public. For example, the whistleblower calls for the public to take preventive measures but is ignored by the public. The action of the announcement may be even mistakenly perceived as disturbing social order by the local government. The other is the discrepancy between administrative information and public opinion. For example, in the early stages of the COVID-19 pandemic, a number of unidentified cases emerged one after another, and public opinion started to pay wide attention to this potential risk. The local government, on the other hand, chose to maintain social order and stability when it had not yet received a decision from the upper authorities and failed to prepare a protective plan for the potential risk in time [19]. Ultimately, the whistleblower announced the early warning information to the public with limited effect on pandemic management [15, 16].

3. Materials and Methods

3.1. Participants and Strategic Decisions. The parties involved in the pandemic early warning system are the local government, the whistleblower, and the general public. The whistleblowers are a group of medical professionals who can grasp the risk information about a pandemic for the first time. The local government is the regional administrations that show signs of a pandemic, including governments below the provincial level and local health administrations in China [22]. In the game system, the whistleblower detects the suspected case and pandemic early warning information and reports it to the local government, who is subject to the observance of the law and regulations. However, the whistleblower may choose to announce the risk information to the public if they are stuck in a dilemma [5]. Therefore, the whistleblower's strategic decisions are to announce the early warning information and not to announce the early warning information.

The local government can conduct an appropriate evaluation and report the risk information to higher-level authorities in a timely and proactive manner. However, in the process of reporting information to higher authorities, local governments may face multiple sources of information, such as public opinions and opinions from expert panels. In order to make a prudent strategic decision, the government may be cautious in responding to the information provided by the whistleblower. To avoid causing social panic and fear, the local government may also punish the whistleblower for the information disclosure [4, 13, 19]. Therefore, two strategic decisions for the local government to deal with the early warning information are the active response strategy and cautious response strategy in the initial stage of a pandemic.

It is important to note that even if the local government chooses not to announce information about the pandemic in the initial stage, the potential risk may still attract the public's attention due to the increase of the suspected cases, and the information disclosed by the whistleblower, and public opinion on the Internet [11]. The public's attention is an important factor in improving the efficiency of making informed decisions and responding quickly [5, 12]. In order to maintain the stability of social order, the public's attention may put the local government in the position of having to announce the risk information. Thus, in this case, the public's strategic decisions are to pay attention to the early warning system and not to pay any attention to the early warning system.

The local government's active response strategies include paying full attention to the early warning information and timely preparing a contingency plan if deemed necessary. The probability of choosing the active response strategy by the local government is $x\,(0 \le x \le 1)$; the cautious response strategies include delaying the public announcement of warnings and punishing whistleblowers for information disclosure. Thus, the probability of choosing the cautious response strategy by the government is $1 - x$. The whistleblower's strategies include announcing the early warning information to the public or not. The probability of choosing to announce the early warning information to the public is noted as $y\,(0 \le y \le 1)$; the probability of choosing not to announce the early warning information to the public is noted as $1 - y$. The probability of the public staying informed is recorded as $z\,(0 \le z \le 1)$; the probability of the public choosing not to pay any attention to the early warning system is recorded as $1 - z$.

3.2. Basic Assumptions and Modelling. In order to analyze the strategic decisions among three parties, the following basic assumptions are made.

Assumption 1. In a pandemic early warning game model, the participants are the local government, the whistleblower, and the public. Each party is risk-neutral bounded rationality and is subject to maximizing their interests.

Assumption 2. The cost to the local government of choosing the active response strategy after receiving the early warning information is π_1. Accordingly, the cost of choosing the cautious response strategy is π_2; if the local government adopts an active response strategy and timely prepares an effective plan, then the credibility of the local government is enhanced by the public, which is denoted by C_1. On the contrary, the credibility of the local government is signified by C_2.

Assumption 3. The cost to the whistleblower of choosing not to announce the early warning information to the public is π_3. On the contrary, the cost of choosing to announce the early warning information to the public is π_4. The additional income that the public can bring to the whistleblower is Q. If the whistleblower's behavior of hiding early warning information is found out by the local government in the evolution of actively responding to a pandemic, then the local government imposes certain punishments P on the whistleblower.

Assumption 4. The cost of the public's failure to pay attention to the early warning information delivered by the whistleblower is denoted by π_5. When the local government chooses the active response strategy, the behavior of staying informed is encouraged, and thus the public will receive the award of R from the local government. Under the strategy of cautious response, if the whistleblower remains silent to the public, while the public pays attention to the early warning information, then the level of reputation obtained by the whistleblower is denoted by R_1. On the contrary, the level of reputation obtained by the whistleblower is denoted by R_2. The utility that the general public can obtain by paying attention to early warning information is denoted by U_1. On the contrary, the utility obtained by the public is denoted as U_2.

Based on the above discussions and assumptions, the local government, the whistleblower, and the public constantly adjust their strategic decisions in the tripartite evolutionary game with finite rationality. The payoff matrix of the three parties under strategic interactions can be obtained as shown in Table 1.

4. Results

4.1. Evolutionary Stability Analysis

4.1.1. The Local Government's Evolutionary Stability Strategy. Based on the assumptions of this study, the probability of the local government choosing the active response strategy is x, and the probability of choosing the cautious response strategy is $(1 - x)$. E_{11} and E_{12} are used to represent the expected benefit of the local government that chooses the active response strategy and cautious response strategy, respectively, and $\overline{E_1}$ represents the overall expected benefit of the local government.

The expected benefit of the active response strategy selected by the local government is

$$\begin{aligned} E_{11} &= yz\left(P - \pi_1 - R + C_1\right) + (1-y)z\left(-\pi_1 + C_1\right) \\ &\quad + y(1-z)\left(P - \pi_1\right) + (1-y)(1-z)\left(-\pi_1\right). \end{aligned} \tag{1}$$

The expected benefit of the cautious response strategy selected by the local government is

$$\begin{aligned} E_{12} &= yz\left(-\pi_2 + C_2\right) + (1-y)z\left(-\pi_2 + C_2\right) \\ &\quad + y(1-z)\left(-\pi_2\right) + (1-y)(1-z)\left(-\pi_2\right). \end{aligned} \tag{2}$$

According to equations (1) and (2), the overall expected benefit of the two government's strategic decisions is

$$\overline{E_1} = xE_{11} + (1-x)E_{12}. \tag{3}$$

According to equation (3), the replicator dynamics equation of the local government can be calculated as

$$\begin{aligned} F(x) &= \frac{\mathrm{d}x}{\mathrm{d}t} = x(1-x)\left(E_{11} - E_{12}\right) \\ &= x(1-x)\left(yP + z\left(C_1 - C_2\right) - yzR - \left(\pi_1 - \pi_2\right)\right). \end{aligned} \tag{4}$$

Rather than Bernoulli's equation, the core idea of the replicator dynamics equation is that one's decision will eventually bias towards a particular strategy as the environment around them evolves [23]; thus, it is given an economic meaning by incorporating mean payoff. To further analyze the impact of the size of the local government with different decisions on the stable equilibrium of the strategic

Table 1: The payoff matrix of the local government, the whistleblower, and the public.

		The public	The local government: Active response strategy (x)	The local government: Cautious response strategy $(1-x)$
The whistleblower	Strategy of announcing the early warning information (y)	Strategy of paying attention to the early warning system (z)	$P-\pi_1-R+C_1$ $Q-P-\pi_4+R_2$ $U_2-Q-\pi_5+R$	$-\pi_2+C_2$ $Q-\pi_4+R_2$ $U_2-Q-\pi_5$
		Strategy of not paying any attention to the early warning system $(1-z)$	$P-\pi_1$ $Q-P-\pi_4$ U_2-Q	$-\pi_2$ $Q-\pi_4$ U_2-Q
	Strategy of not announcing the early warning information $(1-y)$	Strategy of paying attention to the early warning system (z)	$-\pi_1+C_1$ $Q-\pi_3+R_1$ $U_1-Q-\pi_5$	$-\pi_2+C_2$ $Q-\pi_3+R_1$ $U_1-Q-\pi_5$
		Strategy of not paying any attention to the early warning system $(1-z)$	$-\pi_1$ $Q-\pi_3$ U_1-Q	$-\pi_2$ $Q-\pi_3$ U_1-Q

evolution, we can obtain the derivative of the replicator dynamics equation with respect to x,

$$F'(x)=(1-2x)\left(yP+z\left(C_1-C_2\right)-yzR-\left(\pi_1-\pi_2\right)\right). \quad (5)$$

Thus, for the local government, we can make the following summary according to the above equation.

When $y=y^*=(\pi_1-\pi_2)-z(C_1-C_2)/P-zR$, $F(x)\equiv 0$, in this case, any proportion x that the local government chooses randomly is an evolutionary stable strategy.

When $0<y<y^*=(\pi_1-\pi_2)-z(C_1-C_2)/P-zR$, $F(0)=0$, $F(1)=0$, $F'(0)<0$, and $F'(1)>0$, the evolutionary stability strategy of the local government is $x^*=0$. In this case, when the proportion of the whistleblower that chooses the strategy of announcing the early warning information is lower than $(\pi_1-\pi_2)-z(C_1-C_2)/P-zR$, the local government tends to choose the cautious response strategy. Otherwise, if the active response strategy is chosen, the local government may incur additional costs.

When $(\pi_1-\pi_2)-z(C_1-C_2)/P-zR=y^*<y<1$, $F(0)=0$, $F(1)=0$, $F'(0)>0$, and $F'(1)<0$, the evolutionary stable strategy of the government group is $x^*=1$. In this case, when the proportion of the whistleblower that chooses the strategy of announcing the early warning information is higher than $(\pi_1-\pi_2)-z(C_1-C_2)/P-zR$, the local government tends to choose the active response strategy. The reason is the higher proportion of the whistleblowing may affect the standard prevention and control methods, so the local government shall choose the certain active response strategy to ensure the normal development of society.

Based on the above analysis, we can draw a dynamic replication phase diagram of the local government as shown in Figure 1.

4.1.2. The Whistleblower's Evolutionary Stability Strategy. Based on the assumptions of this study, the probability of the whistleblower choosing to announce the early warning information is y, and the probability of choosing not to announce the early warning information is $(1-y)$. E_{21} and E_{22} are used to represent the expected benefit of the whistleblower chooses the strategies of announcing or not announcing the early warning information, and $\overline{E_2}$ represents the overall expected benefit of the whistleblower.

The expected benefit when the whistleblower chooses to announce the early warning information is

$$\begin{aligned}E_{21}&=xz\left(Q-P-\pi_4+R_2\right)+(1-x)z\left(Q-\pi_4+R_2\right)\\&\quad+x(1-z)\left(Q-P-\pi_4\right)+(1-x)(1-z)\left(Q-\pi_4\right).\end{aligned} \quad (6)$$

The expected benefit when the whistleblower chooses not to announce the early warning information is

$$\begin{aligned}E_{22}&=xz\left(Q-\pi_3+R_1\right)+(1-x)z\left(Q-\pi_3+R_1\right)\\&\quad+x(1-z)\left(Q-\pi_3\right)+(1-x)(1-z)\left(Q-\pi_3\right).\end{aligned} \quad (7)$$

According to equations (6) and (7), the overall expected benefit of the two whistleblower's strategic decisions is

$$\begin{aligned}\overline{E_2}&=yE_{21}+(1-y)E_{22}\\&=y\left(xz\left(Q-P-\pi_4+R_2\right)+(1-x)z\left(Q-\pi_4+R_2\right)+x(1-z)\left(Q-P-\pi_4\right)+(1-x)(1-z)\left(Q-\pi_4\right)\right)\\&\quad+(1-y)\left(xz\left(Q-\pi_3+R_1\right)+(1-x)z\left(Q-\pi_3+R_1\right)+x(1-z)\left(Q-\pi_3\right)+(1-x)(1-z)\left(Q-\pi_3\right)\right).\end{aligned} \quad (8)$$

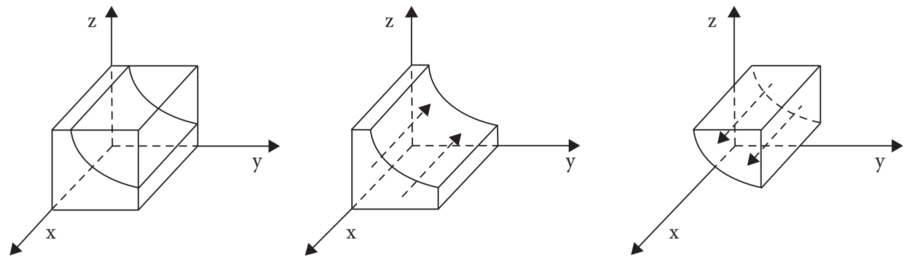

Figure 1: Dynamic replication phase diagram of the evolution of the local government's strategic decisions.

According to equation (8), the replicator dynamics equation of the whistleblower can be calculated as

$$F(y) = \frac{dy}{dt} = y(1-y)\left(z(R_2 - R_1) - Px + (\pi_3 - \pi_4)\right). \quad (9)$$

To further analyze the impact of the size of the whistleblower with different decisions on the stable equilibrium of the strategic evolution, we can obtain the derivative of the replicator dynamics equation with respect to y as follows:

$$F'(y) = (1-2y)\left(z(R_2 - R_1) - Px + (\pi_3 - \pi_4)\right). \quad (10)$$

Thus, for the whistleblower, we can make the following summary according to the above equation:

When $x^* = z(R_2 - R_1) + (\pi_3 - \pi_4)/P$ and $F(y) \equiv 0$, in this case, any proportion y that the whistleblower chooses randomly is an evolutionary stable strategy.

When $0 < x < x^* = z(R_2 - R_1) + (\pi_3 - \pi_4)/P$, $F(0) = 0$, $F(1) = 0$, $F'(0) > 0$, and $F'(1) < 0$, the evolutionary stability strategy of the whistleblower is $y^* = 1$. In this case, when the proportion of the local government that chooses the active response strategy is lower than $z(R_2 - R_1) + (\pi_3 - \pi_4)/P$, the whistleblower tends to choose not to announce the early warning information. Because there may be a greater cost for the whistleblower choosing to announce the information.

When $x^* = z(R_2 - R_1) + (\pi_3 - \pi_4)/P < x < 1$, $F(0) = 0$, $F(1) = 0$, $F'(0) < 0$, and $F'(1) > 0$, the evolutionary stable strategy of the whistleblower is $y^* = 0$. In this case, when the proportion of the local government that chooses the active response strategy is higher than $z(R_2 - R_1) + (\pi_3 - \pi_4)/P$, the whistleblower tends to choose to announce the early warning information.

Based on the above analysis, we can draw a dynamic replication phase diagram of the local government as shown in Figure 2.

4.1.3. The Public's Evolutionary Stability Strategy. Based on the assumptions of this study, the probability of the public choosing to pay attention to the early warning system is z, and the probability of choosing not to pay any attention to the early warning system is $(1 - z)$. E_{31} and E_{32} are used to represent the expected benefit of the public that chooses the strategies of paying or not paying any attention to the early warning system, and $\overline{E_3}$ represents the overall expected benefit of the public.

The expected benefit when the public chooses to pay attention to the early warning system is

$$\begin{aligned} E_{31} &= xy(U_2 - Q - \pi_5 + R) + x(1-y)(U_1 - Q - \pi_5) \\ &\quad + (1-x)y(U_2 - Q - \pi_5) + (1-x)(1-y)(U_1 - Q - \pi_5). \end{aligned} \quad (11)$$

The expected benefit when the public chooses not to pay any attention to the early warning system is

$$\begin{aligned} E_{32} &= xy(U_2 - Q) + x(1-y)(U_1 - Q) + (1-x)y(U_2 - Q) \\ &\quad + (1-x)(1-y)(U_1 - Q). \end{aligned} \quad (12)$$

According to equations (11) and (12), the overall expected benefit of the two whistleblower's strategic decisions is

$$\begin{aligned} \overline{E_3} &= zE_{31} + (1-z)E_{32} \\ &= z\left(xy(U_2 - Q - \pi_5 + R) + x(1-y)(U_1 - Q - \pi_5) + (1-x)y(U_2 - Q - \pi_5) + (1-x)(1-y)(U_1 - Q - \pi_5)\right) \\ &\quad + (1-z)\left(xy(U_2 - Q) + x(1-y)(U_1 - Q) + (1-x)y(U_2 - Q) + (1-x)(1-y)(U_1 - Q)\right). \end{aligned} \quad (13)$$

According to equation (13), the replicator dynamics equation of the public can be calculated as

$$F(z) = \frac{dz}{dt} = z(1-z)(xyR - \pi_5). \quad (14)$$

To further analyze the impact of the size of the public with different decisions on the stable equilibrium of the strategic evolution, we can obtain the derivative of the replicator dynamics equation with respect to z as follows:

$$F'(z) = (1-2z)(xyR - \pi_5). \quad (15)$$

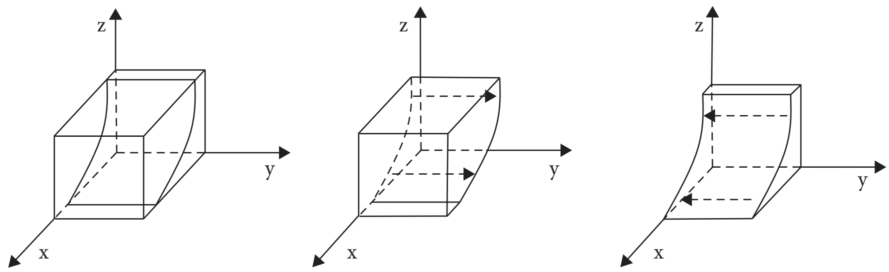

Figure 2: Dynamic replication phase diagram of the evolution of the whistleblower's strategic decisions.

Thus, for the public, we can make the following summary according to the above equation:

When $y = y^* = \pi_5/xR$ and $F(z) \equiv 0$, in this case, any proportion z that the public chooses randomly is an evolutionary stable strategy.

When $0 < y < y^* = \pi_5/xR$, $F(0) = 0$, $F(1) = 0$, $F'(0) < 0$, and $F'(1) > 0$, the evolutionary stability strategy of the public is $z^* = 0$. In this case, when the proportion of the whistleblower that chooses to announce the early warning information is lower than π_5/xR, the public tends to choose not to pay any attention to the early warning system. At this stage, the less information is made publicly available, thus leaving the public less informed and therefore inclined to believe that the level of risk is low.

When $\pi_5/xR = y^* < y < 1$, $F(0) = 0$, $F(1) = 0$, $F'(0) > 0$, and $F'(1) < 0$, the evolutionary stable strategy of the public is $z^* = 1$. In this case, when the proportion of the whistleblower that chooses the strategy of announcing the early warning information is higher than $y = y^* = \pi_5/xR$, the public tends to choose to pay the attention to the early warning system.

Based on the above analysis, we can draw a dynamic replication phase diagram of the local government as shown in Figure 3.

4.1.4. Stability Analysis of Mix-Strategy Equilibrium. To explore the mutual interaction among the local government, the whistleblower, and the public, we integrate the above three replicator dynamic equations into a three-dimensional replicator dynamic game system of the pandemic early warning system,

$$\begin{cases} F(x) = \dfrac{\mathrm{d}x}{\mathrm{d}t} = x(1-x)\left(yP + z\left(C_1 - C_2\right) - yzR - \left(\pi_1 - \pi_2\right)\right), \\ F(y) = \dfrac{\mathrm{d}y}{\mathrm{d}t} = y(1-y)\left(z\left(R_2 - R_1\right) - Px + \left(\pi_3 - \pi_4\right)\right), \\ F(z) = \dfrac{dz}{dt} = z(1-z)\left(xyR - \pi_5\right). \end{cases} \quad (16)$$

Let $F(x) = \mathrm{d}x/\mathrm{d}t = 0$, $F(y) = \mathrm{d}y/\mathrm{d}t = 0$, and $F(z) = \mathrm{d}z/\mathrm{d}t = 0$; concurrently, we can get nine equilibrium points of system (16). They are E_1 (0, 0, 0), E_2 (0, 1, 0), E_3 (0, 0, 1), E_4 (0, 1, 1), E_5 (1, 0, 0), E_6 (1, 0, 1), E_7 (1, 1, 0), E_8 (1, 1, 1), and $E_9(x^*, y^*, z^*)$. Evidently, E_1 to E_8 are pure Nash equilibria, while point E_9 is a mixed Nash equilibrium. For the reason that any strict Nash equilibrium must be a pure strategy, it is enough to discuss the stability of equilibrium solutions E_1 to E_8, and E_9 cannot be stable.

Hence, the stability of each equilibrium solution is analyzed through leveraging the Jacobian matrix of the above three-dimensional replicator dynamic game system (equation (15)),

$$J = \begin{bmatrix} \dfrac{\partial F(x)}{\partial x} & \dfrac{\partial F(x)}{\partial y} & \dfrac{\partial F(x)}{\partial z} \\ \dfrac{\partial F(y)}{\partial x} & \dfrac{\partial F(y)}{\partial y} & \dfrac{\partial F(y)}{\partial z} \\ \dfrac{\partial F(z)}{\partial x} & \dfrac{\partial F(z)}{\partial y} & \dfrac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} \left((1-2x)\left(yP + z\left(C_1 - C_2\right) - yzR - \left(\pi_1 - \pi_2\right)\right)\right) & x(1-x)(P - zR) & x(1-x)\left(C_1 - C_2 - yR\right) \\ -y(1-y)P & (1-2y)\left(z\left(R_2 - R_1\right) - Px + \left(\pi_3 - \pi_4\right)\right) & y(1-y)\left(R_2 - R_1\right) \\ yz(1-z)R & xz(1-z)R & (1-2z)\left(xyR - \pi_5\right) \end{bmatrix}. \quad (17)$$

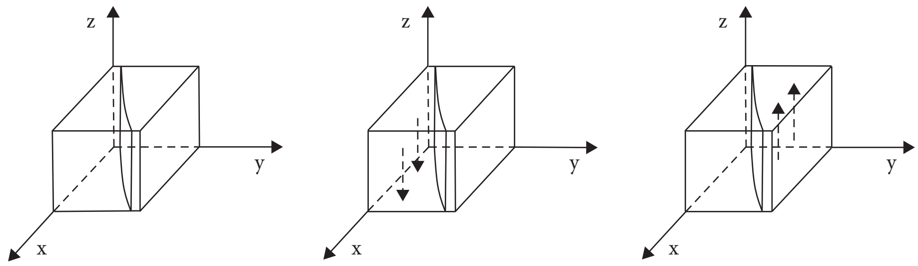

Figure 3: Dynamic replication phase diagram of the evolution of the public's strategic decisions.

The eigenvalues of the Jacobian matrix at eight equilibrium points are shown in Table 2.

If the local government adopts the active response strategy, such as organizing medical professionals to carry out timely research and evaluation, and improving the efficiency of information publication, which will bring a positive effect on the credibility of the local government (6). While the local government chooses the cautious strategy, such as relaxing the vigilance or not paying full attention to early warning information, which will bring a negative impact on the credibility of the local government and seriously hinder the management of the pandemics (6, 12). At the same time, the whistleblower, as the first party with access to information about a potential risk, will have a high reputation for timely early warnings. Therefore, taking into account real-life scenarios, $C_1 > C_2$ and $\pi_5 > 0$ are satisfied. During the early days of the pandemic, the strategic decisions made by the whistleblower have a profound impact on the local government's risk management. First, considering the accuracy of the information, if the initial assessment is that the early warning information is wrong, the whistleblowing may lead to an information pandemic on the Internet, and thus social panic (7, 11). Consequently, the local government is more inclined to choose the cautious response strategy.

Hence, in the replicator dynamic game system of the local government, the whistleblower, and the public, the behavioral strategies of the three parties are influenced by multiple factors. Thus, we begin by looking at the local government's strategic decisions and constructing game paths for the early warning system under the conditions $\pi_1 - \pi_2 < 0$ and $\pi_1 - \pi_2 > 0$.

Case 1. When the conditions $\pi_1 - \pi_2 < 0, C_1 > C_2$, and $\pi_5 > 0$ are all satisfied, E_4 (1, 0, 0), E_5 (1, 1, 0), and E_8 (1, 1, 1) are the potential evolutionary stable strategies. From the condition, we can observe that the cost to the government for choosing the cautious response strategy is much greater than the cost of choosing the active response strategy. At the same time, there is the outbreak risk of pandemics. The stability of the equilibrium points in Case 1 is shown in Table 3.

To be specific, when the conditions $\pi_1 - \pi_2 > 0$ and $(\pi_3 - \pi_4) < P$ are all satisfied, E_4 (1, 0, 0) is the only one evolutionary stable strategy. That is, the local government chooses the cautious response strategy when the cost of the cautious response strategy is lower than the cost of the active response strategy. The whistleblower chooses the strategy of not announcing the early warning information when the cost of announcement is relatively higher. Concurrently, the public may choose not to pay any attention to the early warning system. When the conditions $\pi_1 - \pi_2 < 0$, $R < \pi_5$, and $P - (\pi_3 - \pi_4) < 0$ are all satisfied, E_5 (1, 1, 0) is the only one evolutionary stable strategy. That is, the local government chooses the active response strategy when the cost of the active response strategy is relatively lower. The whistleblower chooses the strategy of announcing the early warning information when the cost of the announcement is relatively lower as well. Because the public has limited access to information, the public will stabilize on a strategy of not paying any attention to the early warning system when it maintains an optimistic judgment about the country's public health emergency preparedness (i.e., $R < \pi_5$). When the conditions $\pi_1 - \pi_2 < 0, R > \pi_5$, and $(R_2 - R_1) + (\pi_3 - \pi_4) > P$ are all satisfied, E_8 (1, 1, 1) is the only one evolutionary stable strategy. That is, the local government chooses the active response strategy, while the whistleblower tends to choose the strategy of announcing the early warning information because of its lower cost. In this regard, the public chooses the strategy of paying attention to the early warning system because it might be helpful in saving the lives and property [16]. In other words, if all three parties adopt a proactive strategy to reduce the potential losses, the game system of pandemic early warning will reach an optimal equilibrium.

There is an alternative hypothesis: The cost of the local government's active response strategy is relatively higher. This means that the early warning information is of questionable accuracy (i.e., $\pi_1 - \pi_2 > 0$). In other words, there is an infodemic risk in this case. As facts, rumors, and fears get together and disperse, it becomes difficult for the public to find trustworthy sources and guidance, thus affecting the public's judgment and health [11].

Case 2. When the condition is satisfied, the cost to the government of choosing the cautious response strategy is lower than the cost of choosing the active response strategy. The stability of the equilibrium points in Case 2 is shown in Table 4.

To be specific, when conditions $\pi_1 - \pi_2 > 0$ and $\pi_3 - \pi_4 < 0$ are all satisfied, E_1 (0, 0, 0) is the only one evolutionary stable strategy. That is, the local government chooses the cautious response strategy when the cost of the cautious response strategy is lower than the cost of the active

Table 2: Eigenvalues of the Jacobian matrix.

Equilibrium points	λ_1	λ_2	λ_3
E_1 (0, 0, 0)	$-(\pi_1-\pi_2)$	$(\pi_3-\pi_4)$	$-\pi_5$
E_2 (0, 0, 1)	$(C_1-C_2)-(\pi_1-\pi_2)$	$(R_2-R_1)+(\pi_3-\pi_4)$	π_5
E_3 (0, 1, 0)	$P-(\pi_1-\pi_2)$	$-(\pi_3-\pi_4)$	$-\pi_5$
E_4 (1, 0, 0)	$(\pi_1-\pi_2)$	$-P+(\pi_3-\pi_4)$	$-\pi_5$
E_5 (1, 1, 0)	$-(P-(\pi_1-\pi_2))$	$P-(\pi_3-\pi_4)$	$R-\pi_5$
E_6 (1, 0, 1)	$-((C_1-C_2)-(\pi_1-\pi_2))$	$(R_2-R_1)-P+(\pi_3-\pi_4)$	π_5
E_7 (0, 1, 1)	$P+(C_1-C_2)-R-(\pi_1-\pi_2)$	$-((R_2-R_1)+(\pi_3-\pi_4))$	π_5
E_8 (1, 1, 1)	$-(P+(C_1-C_2)-R-(\pi_1-\pi_2))$	$-((R_2-R_1)-P+(\pi_3-\pi_4))$	$-(R-\pi_5)$

Table 3: Stability of the equilibrium points in Case 1.

Equilibrium points	λ_1	λ_2	λ_3	Stability	Conditions
E_1 (0, 0, 0)	>0	—	<0	Unstable	N/A
E_2 (0, 0, 1)	—	—	>0	Unstable	N/A
E_3 (0, 1, 0)	>0	—	<0	Unstable	N/A
E_4 (1, 0, 0)	<0	—	<0	Evolutionary stable strategy	$(\pi_3-\pi_4)<P$
E_5 (1, 1, 0)	—	—	—	Evolutionary stable strategy	$R<\pi_5$, $P-(\pi_3-\pi_4)<0$
E_6 (1, 0, 1)	—	—	>0	Unstable	N/A
E_7 (0, 1, 1)	<0	—	>0	Unstable	N/A
E_8 (1, 1, 1)	<0	—	—	Evolutionary stable strategy	$R>\pi_5$, $(R_2-R_1)+(\pi_3-\pi_4)>P$

Table 4: Stability of the equilibrium points in Case 2.

Equilibrium points	λ_1	λ_2	λ_3	Stability	Conditions
E_1 (0, 0, 0)	<0	—	<0	Evolutionary stable strategy	$\pi_3-\pi_4<0$
E_2 (0, 0, 1)	—	—	>0	Unstable	N/A
E_3 (0, 1, 0)	—	—	<0	Evolutionary stable strategy	$p-(\pi_1-\pi_2)<0$, $\pi_3-\pi_4>0$
E_4 (1, 0, 0)	>0	—	<0	Unstable	N/A
E_5 (1, 1, 0)	—	—	—	Evolutionary stable strategy	$p-(\pi_1-\pi_2)>0$, $P-(\pi_3-\pi_4)<0$, $R<\pi_5$
E_6 (1, 0, 1)	—	—	>0	Unstable	N/A
E_7 (0, 1, 1)		—	>0	Unstable	N/A
E_8 (1, 1, 1)	—	—	—	Evolutionary stable strategy	$R>\pi_5$, $P+(C_1-C_2)-(\pi_1-\pi_2)>0$, $(R_2-R_1)-P+(\pi_3-\pi_4)>0$

response strategy. The whistleblower that chooses the strategy of not announcing the early warning information when the cost of announcement is relatively higher. Concurrently, the public may choose not to pay any attention to the early warning system. When the conditions $\pi_1-\pi_2>0$, $p-(\pi_1-\pi_2)<0$, and $\pi_3-\pi_4>0$ are all satisfied, E_3 (0, 1, 0) is the only one evolutionary stable strategy. That is, the local government chooses the active response strategy when the cost of the active response strategy is relatively lower. The whistleblower chooses the strategy of announcing the early warning information when the cost of the announcement is relatively lower as well. In this context, the public will stabilize on a strategy of not paying any attention to the early warning system as official information is not yet released. When the conditions $\pi_1-\pi_2>0$, $p-(\pi_1-\pi_2)>0$, $P-(\pi_3-\pi_4)<0$, and $R<\pi_5$ are all satisfied, E_5 (1, 1, 0) is the only one evolutionary stable strategy. That is, when the penalty of keeping silent (i.e., not announcing the early warning information) is higher than the response cost, while the penalty of keeping silent is also lower than the cost of announcement, the local government will choose the active response strategy and the whistleblower will stabilize on the strategy of announcing the early warning information. Concurrently, the public will stabilize on a strategy of not paying any attention to the early warning system (i.e., $R<\pi_5$). When $\pi_1-\pi_2>0$, $R>\pi_5$, $(R_2-R_1)-P+(\pi_3-\pi_4)>0$, and $P+(C_1-C_2)-(\pi_1-\pi_2)>0$ are all satisfied, E_8 (1, 1, 1) is the only one evolutionary stable strategy. This means that when the behavior of whistleblowing is more meaningful and influential than keeping silent, the whistleblower tends to announce the early warning information, while the local government steadily chooses the active response strategy, and the public is more inclined to choose the strategy of paying attention to the early warning system [5, 21]. In such a situation, the game system of pandemic early warning will reach an optimal equilibrium.

4.2. Simulation Analysis. By using Matlab, we simulate the tripartite evolutionary game model under different conditions.

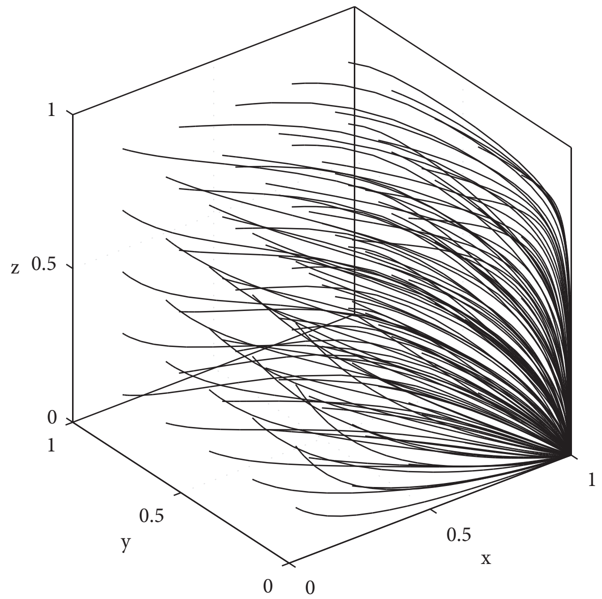

Figure 4: Dynamic evolution path of case 3.

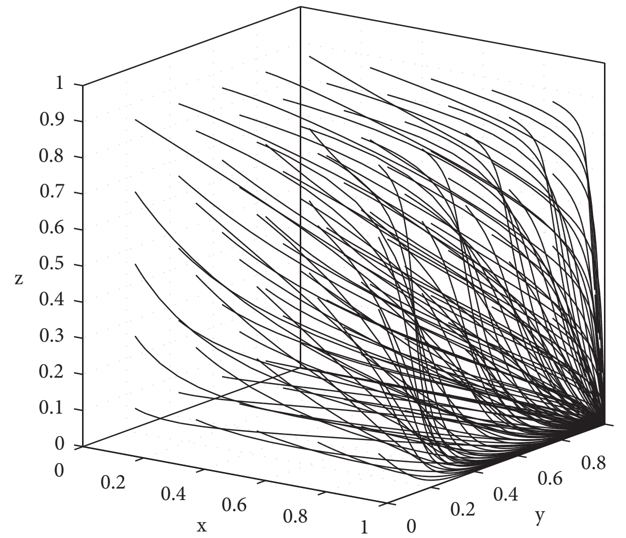

Figure 5: Dynamic evolution path of case 4.

Case 3. The parameters ($\pi_1 = 5, \pi_2 = 10, \pi_3 = 4, \pi_4 = 6$) are set when the cost of the active response strategy is relatively lower and the cost of the early warning announcement is relatively higher. Accordingly, the strategy for the stable state in this case is that the local government actively responds to the pandemic early warning information, the whistleblower remains silent to the public, and the public does not pay any attention to the early warning system. The dynamic evolution path of Case 3 is shown in Figure 4.

Case 4. The parameters ($\pi_1 = 5$, $\pi_2 = 10$, $\pi_3 = 10$, $\pi_4 = 4$, $\pi_5 = 5$, $P = 4$, and $R = 3$) are set when the public's attention is relatively lower, the cost of the active response strategy is relatively lower, and the cost of keeping silent is relatively higher. Accordingly, the strategy for the stable state in this case is that the local government actively responds to the pandemic early warning information, and the whistleblower announces the early warning information, but the public does not pay any attention to the early warning system. The dynamic evolution path of case 4 is shown in Figure 5.

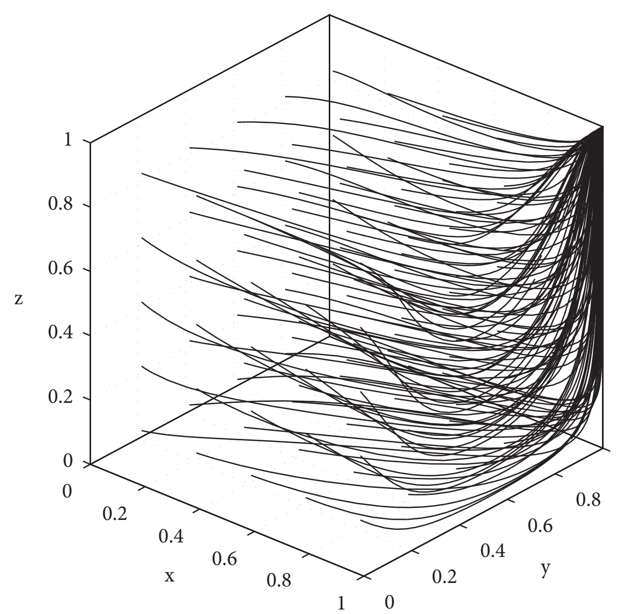

Figure 6: Dynamic evolution path of case 5.

Case 5. The parameters ($\pi_1 = 5$, $\pi_2 = 10$, $\pi_3 = 12$, $\pi_4 = 5$, $\pi_5 = 3$, $P = 4$, $R = 3$, $R_1 = 8$, and $R_2 = 6$) are set when the benefit of attention is relatively higher, the cost of the active response strategy is relatively lower, and the cost of announcement is relatively lower. Accordingly, the strategy for the stable state in this case is that the local government actively responds to the pandemic early warning information, the whistleblower announces the early warning information, and the public also pays full attention to the early warning system. The dynamic evolution path of Case 5 is shown in Figure 6.

Case 6. The parameters ($\pi_1 = 10$, $\pi_2 = 5$, and $\pi_3 = 6$) are set when the cost of the cautious response strategy is relatively lower, but the cost of announcement is relatively higher. Accordingly, the strategy for the stable state in this case is that the local government cautiously responds to the pandemic early warning information and the whistleblower does not announce the early warning information, while the public does not pay attention to the early warning system. The dynamic evolution path of Case 6 is shown in Figure 7.

Case 7. The parameters ($\pi_1 = 10$, $\pi_2 = 5$, $\pi_3 = 9$, $\pi_4 = 6$, and $P = 4$) are set when the cost of the cautious response strategy is relatively lower, but the cost of keeping silent is relatively higher. Accordingly, the strategy for the stable state in this case is that the local government cautiously responds to the pandemic early warning information and the whistleblower announces the early warning information, while the public

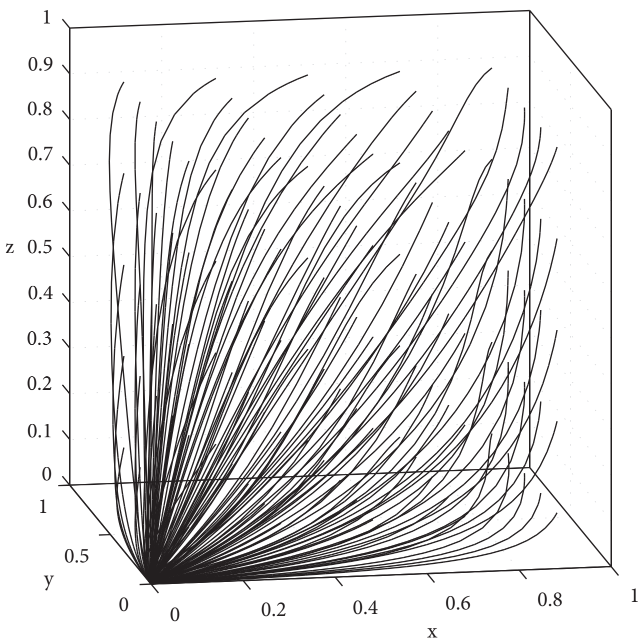

Figure 7: Dynamic evolution path of case 6.

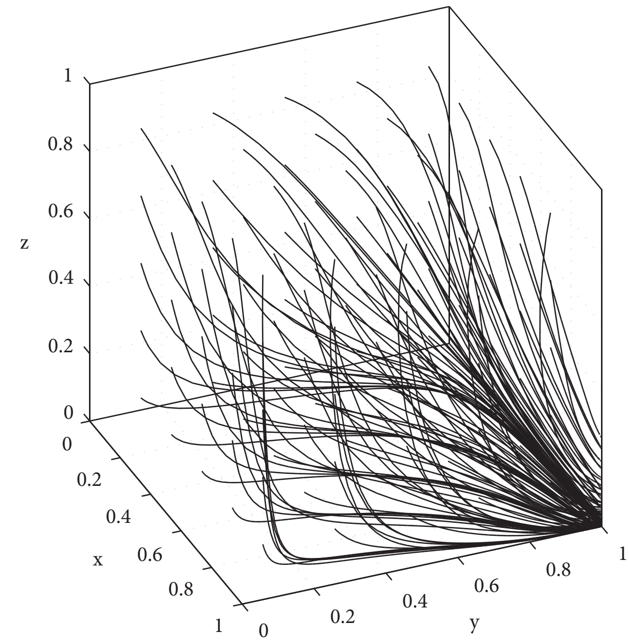

Figure 9: Dynamic evolution path of case 8.

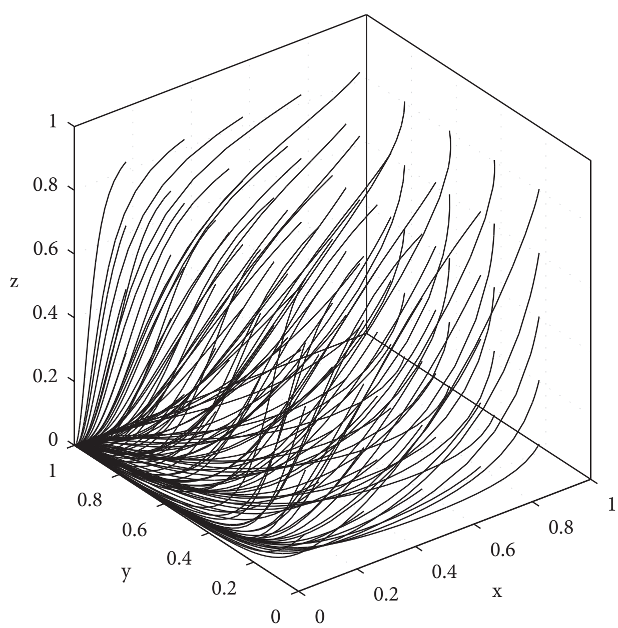

Figure 8: Dynamic evolution path of case 7.

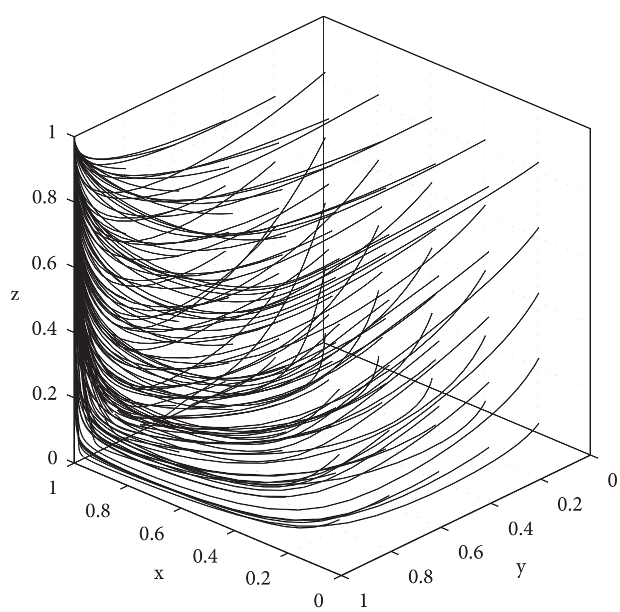

Figure 10: Dynamic evolution path of case 9.

does not pay attention to the early warning system. The dynamic evolution path of Case 7 is shown in Figure 8.

Case 8. The parameters ($\pi_1 = 6$, $\pi_2 = 5$, $\pi_3 = 9$, $\pi_4 = 4$, $\pi_5 = 5$, and $P = 4$) are set when the public's attention is relatively lower, and the cost of keeping silent is much higher than the response cost, while the penalty of keeping silent is lower than the cost of announcement. Accordingly, the strategy for the stable state in this case is that the local government actively responds to the pandemic early warning information, the whistleblower announces the early warning information, but the public does not pay any attention to the early warning system. The dynamic evolution path of Case 8 is shown in Figure 9.

Case 9. The parameters ($\pi_1 = 6$, $\pi_2 = 5$, $\pi_4 = 4$, $\pi_5 = 2$, $P = 4$, $C_1 = 4$, $C_2 = 2$, $R_1 = 6$, $R_2 = 9$, and $R = 3$) are set when the behavior of whistleblowing is more meaningful and influential than keeping silent and the benefit of attention is relatively higher. Accordingly, the strategy for the stable state in this case is that the local government actively responds to the pandemic early warning information, the whistleblower announces the early warning information, and the public pays full attention to the early warning system. The dynamic evolution path of Case 9 is shown in Figure 10.

5. Discussion and Conclusions

With the continuous improvement of China's emergency management system, the capability of addressing public health emergencies has been significantly enhanced. However, there are still numerous challenges in the pandemic early warning system, and a tripartite evolutionary game model composed of the local government, the whistleblower, and the public has emerged in the current study. We also explored the stability of the game model by analyzing the strategic decisions of three parties. By using Matlab, we then stimulated the stable state of strategies in different cases.

In line with previous studies, the current study confirmed that the effectiveness of managing public health emergencies inevitably involves coordination and cooperation between parties, although the strategic choices of participants are greatly influenced by other participants [9, 24, 25]. Inter-organizational collaboration can facilitate the establishment of effective methods of coordination and communication among different groups of participants [24]. This study also agrees well with previous related research, which also found that encouraging the participation of the public can prompt all parties to cooperate in preventing and managing public health emergencies [9]. This study puts forward the crucial position of whistleblowers in the early warning game system. The whistleblower's dilemma in the context of a pandemic is essentially related to the inadequacy of the current early warning system. The cost of announcing the early warning information to the whistleblower, the cost of responding to early warning information for the local government, and the benefit of paying attention significantly influence the behavioral strategies among the three parties. When there is a serious pandemic risk, the local governments tend to adopt an active response strategy in the first instance to reduce possible loss of life and property. When the accuracy of the received early warning information is questionable or hard to judge, the local government tends to adopt a cautious response strategy to reduce the potential loss to society. In this regard, the whistleblower chooses to break the rules and public health ethics to announce the early warning information due to the increased risk of significant harm to the public. As a group with limited access to information, the public's strategic decisions are significantly influenced by the decisions of the local government and the whistleblower. As a result, the whistleblower is potentially faced with a dilemma in the early warning game system. All three parties are likely to simultaneously choose proactive strategies when the effectiveness of the whistleblowing is higher than the penalty of keeping silent and the benefit of attention is higher for the public.

Accordingly, our findings reveal the importance of whistleblowing in the early warning game system. It also stresses that an effective early warning system for public health emergencies is essentially a stable state of strategies reached by the local government, the whistleblower, and the public. The originality of the current study lies in the inclusion of whistleblowing in exploring China's pandemic early warning system. This study concerns three parties' behavioral strategies, providing a new research direction and enhancing the effectiveness of the early warning system by analyzing the tripartite dynamic interactions.

Our findings also provide support for policy recommendations for promoting public health emergency preparedness. First, the government is required to strengthen the pandemic early warning system. Timely response to the whistleblower's early warning information is crucial to controlling the spread of a pandemic [2]. The cost of the whistleblowing and the local government's judgment of the response cost are two important factors affecting the pandemic early warning system. The cost of early warning can also be reduced by implementing a protection policy for whistleblowers. In addition to this, whistleblowing could also be incorporated into the social credit assessment mechanism, and the emergence of infodemics could be reduced through effective constraints and supervision. Second, the assessment of the local government's risk management should be improved. At present, the government's management systems lack the dimension of assessing the capacity to prevent and control risks [1, 3]. This may indirectly cause the spread of pandemics and ultimately put the public in a passive position in health emergencies.

Data Availability

The data used to support the findings of this work are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The research was posted on a preprint server prior to publication in Discrete Dynamics in Nature and Society. The latest preprint version of this article can be found at https://doi.org/10.21203/rs.3.rs-1259423/v3. This work was supported by the National Natural Science Foundation of China (no. 71603054), the Capital Circulation Industry of Beijing Philosophy and Social Sciences Research Base (no. JD-KFKT-2021-003), the Fujian Provincial Department of Science and Technology (no. 2021R01010108), the Social Science Planning Project of Fujian Province (no. FJ2021B150), and the Social Science Planning Project of Fuzhou City (no. 2020C032).

References

[1] Y. Cao, J. Shan, Z. Gong, J. Kuang, and Y. Gao, "Status and challenges of public health emergency management in China related to covid-19," *Frontiers in Public Health*, vol. 8, p. 250, 2020.

[2] L. Zhang, H. Li, and K. Chen, "Effective Risk Communication for Public Health Emergency: Reflection on the Covid-19 (2019-Ncov) Outbreak in Wuhan, China," *Healthcare*, vol. 8, 2020.

[3] A. Kasambara, S. Kumwenda, K. Kalulu et al., "Assessment of implementation of the health management information system at the district level in southern Malawi," *Malawi Medical Journal*, vol. 29, no. 3, pp. 240–246, 2017.
[4] M. M. Kavanagh, "Authoritarianism, outbreaks, and information politics," *The Lancet Public Health*, vol. 5, no. 3, pp. e135–e136, 2020.
[5] J. Zhu, "Is it ethical to be a 'whistleblower' during covid-19 pandemic? Ethical challenges confronted by health care workers in China," *Journal of Advanced Nursing*, vol. 76, no. 8, pp. jan.14376–75, 2020.
[6] R. Fan, Y. Wang, and J. Lin, "Study on multi-agent evolutionary game of emergency management of public health emergencies based on dynamic rewards and punishments," *International Journal of Environmental Research and Public Health*, vol. 18, p. 8278, 2021.
[7] L. Hongyan, "Evolutionary game analysis of emergency management of the middle route of south-to-north water diversion Project," *Water Resources Management*, vol. 31, no. 9, pp. 2777–2789, 2017.
[8] F. Jia, D. D. Wang, and L. Li, "The stochastic evolutionary game analysis of public prevention and control strategies in public health emergencies," 2022.
[9] Z. Xu, Y. Cheng, S. Yao, and S. Vaidyanathan, "Tripartite evolutionary game model for public health emergencies," *Discrete Dynamics in Nature and Society*, vol. 2021, pp. 1–14, 2021.
[10] W. Fan, S. Wang, X. Gu, Z. Zhou, Y. Zhao, and W. Huo, "Evolutionary game analysis on industrial pollution control of local government in China," *Journal of Environmental Management*, vol. 298, Article ID 113499, 2021.
[11] D. Banerjee and K. S. Meena, "Covid-19 as an "infodemic" in public health: critical role of the social media," *Frontiers in Public Health*, vol. 9, Article ID 610623, 2021.
[12] X. Gong, Y. Han, M. Hou, and R. Guo, "Online public attention during the early days of the covid-19 pandemic: infoveillance study based on baidu index," *JMIR Public Health Surveill*, vol. 6, no. 4, Article ID e23098, 2020.
[13] B. Hyland-Wood, J. Gardner, J. Leask, and U. K. H. Ecker, "Toward effective government communication strategies in the era of covid-19," *Humanities and Social Sciences Communications*, vol. 8, no. 1, p. 30, 2021.
[14] S.-F. Tsao, H. Chen, T. Tisseverasinghe, Y. Yang, L. Li, and Z. A. Butt, "What social media told us in the time of COVID-19: a scoping review," *The Lancet Digital Health*, vol. 3, no. 3, pp. e175–e194, 2021.
[15] L. Zhang, K. Chen, and Ji Zhao, "Evidence-based decision-making for a public health emergency in China: easier said than done," *The American Review of Public Administration*, vol. 50, no. 6-7, pp. 720–724, 2020.
[16] Y. Zhu, K.-Wa Fu, K. A. Grépin, H. Liang, and I. C.-H. Fung, "Limited early warnings and public attention to coronavirus disease 2019 in China, january–february, 2020: a longitudinal cohort of randomly sampled weibo users," *Disaster Medicine and Public Health Preparedness*, vol. 14, no. 5, pp. e24–e27, 2020.
[17] X. Duan, Z. Zhang, and W. Zhang, "How is the risk of major sudden infectious epidemic transmitted? A grounded theory analysis based on covid-19 in China," *Frontiers in Public Health*, vol. 9, Article ID 795481, 2021.
[18] R. Lencucha and S. Bandara, "Trust, risk, and the challenge of information sharing during a health emergency," *Globalization and Health*, vol. 17, no. 1, p. 21, 2021.
[19] B. Liu, S. Lin, Qi Wang, Y. Chen, and J. Zhang, "Can local governments' disclosure of pandemic information decrease residents' panic when facing covid-19 in China?" *International Public Management Journal*, vol. 24, no. 2, pp. 203–221, 2021.
[20] M. Powell, "Whistleblowing: still not an issue of social policy, but an issue for social policy," *International Journal of Sociology & Social Policy*, vol. 40, no. 11/12, pp. 1357–1371, 2020.
[21] M. Powell, "The whistleblower stages model in British national health service inquiries," *Journal of Health, Organisation and Management*, vol. 36, no. 3, pp. 314–331, 2022.
[22] K. Zhou and X. Ge, "Who are the front-runners? Unravelling local government responses to containing the covid-19 pandemic in China," *China Review*, vol. 21, no. 1, pp. 37–54, 2021.
[23] P. D. Taylor and L. B. Jonker, "Evolutionary stable strategies and game dynamics," *Mathematical Biosciences*, vol. 40, no. 1-2, pp. 145–156, 1978.
[24] J. Liu, Y. Song, S. An, and C. Dong, "How to improve the cooperation mechanism of emergency rescue and optimize the cooperation strategy in China: a tripartite evolutionary game model," *International Journal of Environmental Research and Public Health*, vol. 19, no. 3, p. 1326, 2022.
[25] X. Xu, J. Liu, S. Ampon-Wireko, H. Asante Antwi, and L. Zhou, "Towards an integrated healthcare system: evolutionary game analysis on competition and cooperation between urban and rural medical institutions in China," *Frontiers in Public Health*, vol. 10, Article ID 825328, 2022.