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Tripartite Evolutionary Game Analysis for Rumor Spreading on Weibo Based on MA-PT

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ABSTRACT With the rapid development of social media, Weibo rumors have increasingly attracted widespread attention. To maintain sustainable development of network ecology, it is necessary to clarify the evolution law of rumor propagation. First, evolutionary game model is applied to examine the interaction mechanisms of complex behaviors between Weibo rumor makers, Weibo users and governments in accordance with MA-PT (Mental Accounts and Prospect Theory). Next, the replication dynamic equation is used to solve the equilibrium strategy points of each player. It was found that the evolution game does not have a stable equilibrium point. Finally, we conduct empirical simulation to verify the model and primary conclusions. Results demonstrate that, 1) The reference value plays an important role in the strategic choices of players. 2) With the high value of psychological satisfaction of ''Herding effect,'' Weibo users choose to repost rumors. 3) Increasing the value of punishment, Weibo rumor makers are less likely to adopt the strategy of making rumors. 4) The higher loss of social unrest can encourage governments to adopt strict management strategies to maintain good online order. The results can guide governments to make better decisions in network governance.

INDEX TERMS Evolutionary game model, mental account, prospect theory, rumor propagation, Weibo.

I. INTRODUCTION

With the risen popularity of the Internet and the rapid development of social media, Internet rumors spread flooding in recent years [1]. During the presidential election, Americans see 3 to 20 fake news on social platform, and even worse, rumors affect the result of the election [2], [3]. French President Emmanuel Macron empowers the media to regulate rumors spread on the platforms. In addition, the British government regards rumor governance as part of the national security system [4]. Therefore, it can be seen that issues of Internet rumors are major challenges facing the world in the 21st century [5]. In present day China, Weibo is one of the most important social networking platforms [6]. Since its launched in 2009, the number of Weibo users maintains explosive growth. According to the latest financial report of Weibo, the number of monthly active users reached 516 million. And the revenue was 16.9 billion dollars in the past 2020 [7]. As a popular social platform in China, the simplicity and anonymity of Weibo allow original ideas to spread quickly and form trending topics with multiple participants, which provide a means for the spread of rumors [8]. Weibo admit that they have sham and duplicate accounts, fake news and fake likes. Account creators use Weibo to spread misleading information and influence the decisions of real users [9]. Weibo has the characteristics of personalized expression, fragmentation of communication content, decentralization and strong social influence. With the birth of ''Internet celebrity economy'' in recent years, social hot events caused by Weibo rumor appear in an endless stream. For example, Weibo user ''Qin Huohuo'' spreads rumors such as ''huge compensation for train accident'' and ''forced donation by the Chinese Red Cross'' through Weibo, which are widely spread by Weibo users and arouse passionate reactions from the masses. During the period of COVID-19, rumors about the epidemic situation [10], such as ''the virus originates from people in Wuhan eating bats'' [11]–[13], ''eating garlic can kill the virus'', and ''Wuhan cuts off the Internet to forbid medical staff to share relevant information'', are frequently seen, and cause a strong panic among the public [14]. Nowadays, Weibo becomes an essential way for the public to express their feelings and opinions, and also provides a platform for the generation and spread of rumors [15]. Therefore, Weibo rumors have

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a growing impact on everyone's life in China. Thus, it is necessary to conduct special research on Weibo and clarify the rules of rumors spreading so as to help rumors control.

Only if Weibo rumor makers do not create and spread misleading information can the problem of rumors dissemination be solved [16]. However, Weibo rumor makers expect to obtain huge benefits from the spread of rumors [17], including material and psychological benefits. Thus, they are unlikely to lose their self-interest and choose not to spread rumors on their own initiative if lack of regulation [18]. Influenced by the ''Herding effect'', Weibo users are prone to blindly believe and spread rumor information, which leads to the further expansion of the negative effect [19]. In the process of rumor spreading, the government is the most effective regulator [18], whose intervention plays a critical role in behavior decisions of Weibo rumor makers and Weibo users. Since Weibo is an important platform for online rumor propagation in China [6], [15], it is critical for governments to explore how to adopt effective strategies to reduce the spread of rumors. Chinese governments have paid great attention to Weibo rumors and promulgated various policy strategies for curbing the spread of rumors [20], [21]. As can be seen, Weibo rumor makers, Weibo users and governments play vital roles in the process of rumor propagation. Under specific conditions, the three parties interact with each other to seek to maximize their own profit. Considering the interactions between different parties, game theory is the powerful means to study their strategic decision [22].

In previous studies, scholars mainly combined the process of rumor spreading with epidemic propagation models for research. The most classic epidemic model for these research is SIR (Susceptible - Infected - Recovered) [23]. On the basis of SIR model, scholars put forward SEINR [24], SD [25], I2S2R [26] , SPNR [6] and other models to simulate and analyze the rumor propagation process. Epidemic models rely on the assumption of a well-mixed population and treat rumor spreading as an objective, natural process of transmission. However, they ignore the important role that people play in spreading rumors. Contrary to the objectivity of disease transmission, people's subjective behavior strategy plays a crucial role in rumor propagation [27]. Evolutionary game theory can clarify the interest conflict and distribution among the players, as well as the strategic evolution mode, which has high theoretical and practical significance [28]. Because of bounded rationality and learning mechanism of human, evolutionary game theory focuses on the decision-making process and the dynamic evolutionary analysis of multiple players [29]. Therefore, under the premise of evolutionary game theory of bounded rationality and dynamic evolution, it is more consistent with the behavior rules and strategic choices of participants in Weibo rumor propagation. Li *et al.* constructed a rumor evolutionary game model with three punishment mechanisms and concluded that punishment is the key factor affecting rumor propagation [30]. Askarizadeh added different attitude towards rumors to the parameter list to build a game model [27]. In the above studies, the game analysis is based on the value of strategy, ignoring the influence of the psychological perceived value and risk preference of different participants in the actual decision-making process. Mental Accounts Theory points out that when people make a choice, they usually make a final decision by directly comparing the gains and losses of the selection results [31], [32]. In addition, Kahneman put forward Prospect Theory from the psychological point of view [33]. This theory can reasonably explain the different psychological perceptions of participants in the face of gains and losses, and can more accurately simulate the psychological characteristics of people in the decision-making process [34]. It can be seen that Mental Accounts and Prospect Theory (MA-PT) can be combined with the bounded rationality of people, which are more suitable for the actual situation when facing the choice of strategies. Therefore, in order to better supervise the issues of Weibo rumors, how to accurately simulate the participants and the game evolution mechanism is a problem worthy of study. This paper can fill the gaps in current research.

Compared with previous studies, the major contributions are as follows. 1) This paper firstly combined evolutionary game with MA-PT to study the behaviors of rumor propagation. From the micro level, the player' perceived value is divided into gain accounts and loss accounts with different reference value, which is more in line with the complex human assumption. In addition, a probability function is constructed by combining the attitudes towards risks. Weibo rumor makers, Weibo users and the government are all considered, and the factors of game players are comprehensively analyzed. At the same time, Weibo users are affected by ''Herding effect'' [19] in cyberspace to avoid expressing their real ideas, which is added to the model as a parameter to make it more realistic. 2) Different from two-player game constructed in the past studies [35], [17], this paper constructs a tripartite game model. According to the Key Stakeholder Theory [36], [37], Weibo users and government face risks caused by the negative impact on rumors spreading. More seriously, the sustainable development of network ecology will be hindered. Thus, it is meaningful to study the management of Weibo by taking Weibo rumor makers, Weibo users and governments as the main players from the perspective of human behavior and analyzing the rules that participants choose risk-taking behaviors. 3) Through a rumor case on Weibo, data assignment and simulation are carried out to clarify the changes between different players in the state of different parameters, so as to obtain the evolution law of the strategies of players, which can explain the changing speed and mode of rumor propagation. This paper studies how to achieve the optimal governance of Weibo rumors, which can promote the healthy and sustainable development of the network and help the government put forward countermeasures and suggestions.

The remainder of this paper is organized as follows. Section 2 shows the current situation of the literature related to Weibo rumor and rumor propagation. In Section 3,

we describe the tripartite evolutionary game model in accordance with MA-PT. In Section 4, we solve the replication dynamic equation and analyze the evolutionary stable state of each player. In Section 5, the feasibility and effectiveness of the model are verified by the numerical simulation of the Weibo rumor event. Finally, Section 6 discusses the results, while Section 7 presents the conclusions and further work.

II. LITERATURE REVIEW

A. WEIBO RUMOR

Weibo rumor is part of the important research contents of network public opinion. In order to better govern the Weibo space and reduce the adverse impact brought by the spread of rumors, scholars have conducted extensive studies. The current research on Weibo rumors mainly focuses on the macroscopic level and identification methods. At the macroscopic level, scholars collect typical cases of Weibo to study its powerful influence. As rumor has a detrimental impact, Jahng *et al.* pointed out that rumor was considered an important organizational problem that should be monitored and managed by Public Relations practitioners [38]. ''New Media Blue Book: China's New Media Development Report No.11 (2020)'' specifically pointed out that Weibo have become prominent carrier and platform for online public opinion [39]. When analyzing the influence of Weibo information on public behavior, researchers believe that Weibo is an important channel for netizens to obtain information, and the information transmitted through Weibo can even change the political landscape. Thus, they point out that the government should attach importance to the role of Weibo [3], [40], [41]. Priya *et al.* pointed out that Weibo is a better choice for studying the evolution of events. In emergency and disaster situations, the availability and dissemination of updated information on Weibo may be key points [8]. In view of the bad consequences of Weibo rumors, scholars put forward management countermeasures and suggestions [42]–[44]. According to the analysis of the above literature, the impact of the Weibo platform can guide and change the interactive relationship between the public and the government, and even influence the political structure. Therefore, Weibo is an essential platform worthy of further study. However, although the above studies can be used in the government's guidance and governance of Weibo, it ignores the specific analysis of the complex behavior and influencing factors of humanity in social network.

In the identification methods, Xu *et al.* proposed a novel Topic-Driven Rumor Detection framework, which can judge the authenticity of public opinion information according to its sources [45]. Yu *et al.* proposed an attention-based convolution method for the identification of Weibo information [46]. Atodiresei *et al.* built a system model to identify fake Weibo users and fake news, so as to test the authenticity of information on the network [9]. Li *et al.* proposed the Rumor Refutation Effectiveness Index, which collected information from 248 rumor blog posts on Weibo platform and established a regression model. The Shapley Additive translation method was adopted to interpret the return results [47]. Aral *et al.* conducted a randomized trial analysis of data from a sample of 1.3 million social media users. The results showed that young users were more susceptible to online rumors than older users [48]. Wang *et al.* used statistics and trend analysis to study the top 10 rumors in China over the years, and pointed out the causes of rumors. And the most fundamental reason is that Chinese media pay more attention to commercial interests in the fierce competition, and users tend to choose the information they are willing to accept [49]. The measures taken by the United States and other countries to suppress rumors occurred after the event. Although the rumor that has been spread can be controlled, it is difficult to play a preventive role [50]. China as a one-party country, needs to play an active role of the government in the control of Weibo rumors. However, the above studies lack dynamic and systematic research methods. Therefore, there is an urgent need to analyze the evolution of the participants' behaviors in Weibo rumor incidents, and then choose appropriate government supervision strategies (strict management or loose management) in advance according to different background conditions. In general, the study of Weibo rumor is in line with the contemporary era background of purifying cyberspace, and is the main direction of improving the governance capacity. With the intensification of the frequency and influence of Weibo rumor events, this paper needs to attract extensive attention.

B. RUMOR PROPAGATION

The law of rumor propagation is very complex, and it always runs through the whole process of latent, outbreak and extinction. To discuss the spread of rumor, it is necessary to grasp the key influencing factors and to analyze the mode of its dissemination. In order to reduce the negative effects of the spread of rumors, scholars have conducted research on the key factors affecting the spread of rumors and put forward management advice. Fang *et al.* argued that populism had an important impact on the spread of online rumor. The GPF-NP model was built to analyze and predict the evolution of netizens' opinions [51]. Kim *et al.* used the social network analysis method to study the relationship between network information dissemination and public opinion, and the results showed that the polarization of Weibo views was correlated with the form of political consciousness [52]. Bodaghi *et al.* found that users with lower followers were more likely to start rumors, while users with higher followers were more likely to keep rumors circulating [53]. Ma *et al.* pointed out that Internet users play an important role in the communication of rumor. Meanwhile, the government needs to do a good job in information release and actively grasp the trend of public opinion to respond to doubts [54]. Through the above research, we can find that the government and network users are closely related to the problem of rumors.

In terms of rumor propagation mode, scholars believe that rumor propagation is similar to epidemic transmission. Therefore, they combined the model with the evolution of

epidemic disease. By constructing a classic SIR (susceptible, infected and recovered) infectious disease model, Li *et al.* analyzed the interaction of three groups of people in time and space, and conducted an empirical study [23]. Jiang *et al.* proposed a two-stage SPNR model to solve the rumor propagation problem on Weibo, and believed that correct guidance of official statements in public events was necessary [6]. The above studies pay attention to the influence of objective factors and ignore the important influence of human subjective behavior on rumor propagation. Because game theory can consider individual interactions and study their optimization strategies, scholars have carried out in-depth research on the combination of game theory and rumor propagation. Qi *et al.* constructed a two-party game model of the government and netizens with the government punishment mechanism. The results showed that the punishment mechanism could restrain the active degree of the masses in the evolution of rumor [18]. Askarizadeh *et al.* constructed a two-player evolutionary game model of user and environment, in which the results showed that leader in an emergency can stop the rumor from spreading [27]. Although the two-player game can simply and intuitively reveal the benefit interaction, it cannot fully describe the complex behavior process of Weibo rumor. Wei *et al.* established a game model for users, operators and government regulatory authorities from the aspects of WeChat rumor management and monitoring [55]. Dong established the SD evolutionary game model of online media, netizens and government in the formation stage of online rumor, and identified the key variables influencing the outcome of the game [25]. Wang *et al.* believed that social media provided a comprehensive platform for the dissemination of opinions. He suggested that enterprises should actively respond to the media crisis and cautiously respond to the public [56]. Through the above literature, we can find that the bounded rationality and dynamic evolution premise of evolutionary game theory conform to the behavior characteristics and decision-making rules of the participants in the rumor propagation on Weibo.

In reality, people's measurement of uncertain gains and losses is mostly based on irrational perception rather than objective utility [57]. Due to the limitations of knowledge background, learning ability, environment and other factors, people are bounded rationality [58]. In the above game analysis, scholars analyzed the interactive relationship of the participants, but did not pay attention to the risk preference factors of the participants. Xiao *et al.* acknowledged the complexity of the participants in making subjective decisions, which is different from the previous perspective of rational expected utility theory [59]. Due to the different risk preference, people with the same punishment or benefits have different perceived values. This paper combines MA-PT for in-depth research [31]. Because of human complexity and dynamic value perception, the existing payoff matrix is still imperfect and needs to be strengthened. This kind of research needs to combine the macro and micro levels and take into account the psychological factors of the public in the Internet space. Therefore, this paper combines MA-PT with evolutionary game theory to build the model. In the parameter setting, this paper considers the influence of psychological factors and adds the Internet following caused by "Herding Effect" into parameter list. In the construction of participants, most studies are based on the premise of binary division to determine players, that is, there are only two participants, such as users and environment [27], and netizens and the government [18]. Even if some scholars go beyond the binary division, such as the tripartite game model proposed by Wei *et al.*, and they analyze the communication of public opinion under the three participants. However, it is still not clear the speed and mode that the participants reach such a result, and did not give effective explanations. Therefore, it is the focus of current and future research to construct a great evolutionary game model of Weibo rumor propagation and study the propagation rules.

Here are the differences between this paper and relevant literature: 1) This paper firstly discusses the spread of rumors from the micro psychological perspective, and investigates the value account and mental account of the key stakeholders in the process of Weibo rumors propagation, which can fully reflect the behavior strategies of the participants. 2) A tripartite evolutionary game model including Weibo rumor makers, Weibo users and government, is built specifically for the problem of Weibo rumors. Each player has continuous learning ability and can update strategies depending on the changing external environment and their self-perceived value. 3) The application practicality of the model is confirmed through numerical simulation of the epidemic Weibo rumor event in China.

III. MODEL ASSUMPTIONS AND PAYOFF MATRIX OF TRIPARTITE EVOLUTIONARY GAME

A. PROBLEM DESCRIPTION AND MODEL ASSUMPTIONS

In the era of new media, the problem of Weibo rumors has emerged in endlessly, affecting all aspects of public life. Weibo rumor makers are groups or organizations that purposefully spread rumors in order to obtain network attention and income [30], [9]. They take advantage of online users' concern about hot events to highlight the urgency and importance of the compiled rumors and thus promote reposting by uninformed users. As for Weibo users, they are easy to follow and repost rumor information on the Internet [60]. When they are misled by rumors, they are prone to generate a crisis of trust towards the government. Considering the additional personal losses caused by rumor misinformation (e.g., damaged personal image, psychological gap), misguided Weibo users possess the attribute of rumor victim, although this is difficult to detect [61], [62]. With the pervasive spread of rumors, it will affect the credibility of the government and lead to social unrest. Therefore, it's the responsibility of the government to supervise Weibo rumor makers, so as to safeguard the rights and interests of Weibo users and maintain social stability [54].

Key Stakeholders refer to the individuals and groups that influence organizational behavior and the realization of organizational goals, or are affected by the realization of organizational goals and their process [36]. Because they have a huge vested interest in the organization, stakeholders can be a great support to the organization [37]. According to the direct correlation of interests, the participants of the dissemination of Weibo rumors mainly include Weibo rumor makers, Weibo users and the government. And the relationships among the key stakeholders are shown in Fig. 1.

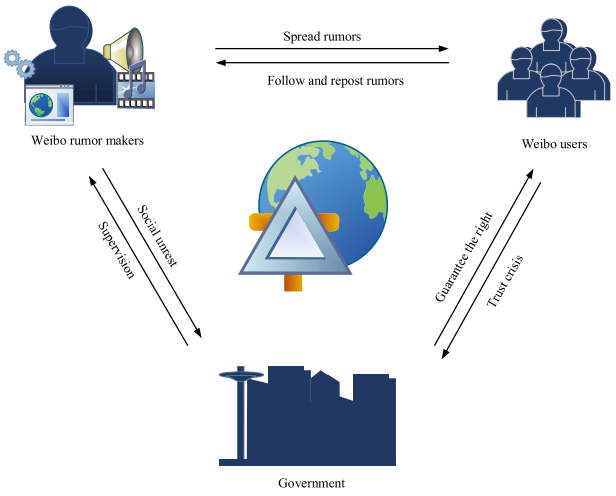

FIGURE 1. The relationship among key stakeholders.

Evolutionary game theory is a method to analyze the strategic behavior of a large and finite group. Players gain competitive advantage through strategic game [29]. This method focuses on the analysis of the evolution of competitive strategies between groups under different external state changes [63]. Based on the above analysis of the key stakeholders, we build a tripartite game model and make the following assumptions.

Assumption 1: We build a large group evolutionary game model, in which Weibo rumor makers, Weibo users and government are the finite and large populations of selected pure strategies respectively. Weibo rumor makers refer to groups and organizations that purposefully spread rumors, which have two possible strategies {M, NM}, and each strategy can be adopted by a proportion. The M strategy denotes make and spread Weibo rumors. The NM strategy means that does not spread rumor. In addition, Weibo users refer to ordinary users who obtain information through Weibo, which have two possible strategies {R, NR}. The R strategy means that Weibo users spread and repost rumor information. And the NR strategy demotes that Weibo users choose not to repost rumors. For the government, there are two strategies {S, L}. The S strategy denotes strict management attitude in network supervision. The L strategy means that the government takes a loose management way to manage the network, which can reduce the cost of supervision.

Assumption 2: We assume that the probability of Weibo rumor makers choosing M strategy is x, then the probability of choosing NM strategy is $1-x$. In the same way, the probability of Weibo users choosing R strategy is y, then the probability of choosing NR strategy is $1-y$. And for the government, the probability of choosing S strategy is z, thus the probability of choosing L is $1-z$. In this assumption, x, y and z are the functions of time t, $0 \le x, y, z \le 1$.

B. MA-PT METHOD

Kahneman and Tversky [33] proposed the prospect theory and believed that perceived value was measured by the prospect value V constituted by value function $v(\Delta w_i)$ and weight function $P(p_i)$, as shown in Equation (1).

$$V = \sum_{i=1}^{n} P(p_i) v(\Delta w_i) \tag{1}$$

As shown above, p_i is the objective probability of the occurrence of event i, and the weight function $P(p_i)$ is the participants' subjective cognition of the occurrence probability of event i. Δw_i is the difference between the actual income obtained by the participants and the reference point after the occurrence of event i. Mental accounts is a psychological process in which people classify, evaluate and budget the results [64]. MA-PT divides the value function $v(\Delta w_i)$ into loss account $L(x)$ and gain account $G(x)$, the function is as follows:

$$L(x) = \begin{cases} \tau (x - U_1)^{\delta}, & x \ge U_1 \\ -(U_1 - x)^{\psi}, & x < U_1 \end{cases} \tag{2}$$

$$G(x) = \begin{cases} (x - U_2)^{\varpi}, & x \ge U_2 \\ -\kappa (U_2 - x)^{\xi}, & x < U_2 \end{cases} \tag{3}$$

Fig. 2(a) shows a value function of the loss account, x denotes the variable of value, and $L(x)$ denotes the value function of paying the loss, which is called loss account. U_1 is the reference value of the loss. τ is the sensitivity of loss aversion. δ and ψ are risk preference coefficients for losses. Fig.2(b) shows the value function of the gain account, and $G(x)$ shows the value function of income, which is called gain account. U_2 is the reference value of income.

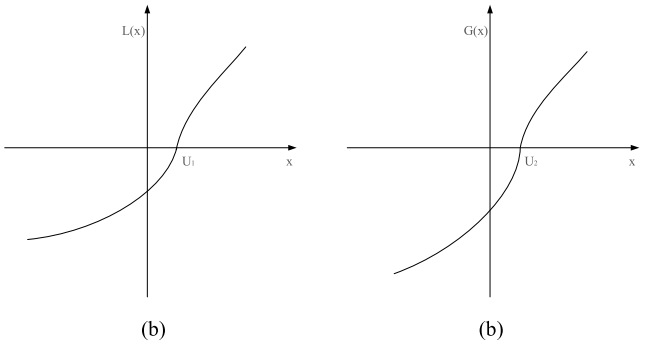

FIGURE 2. The loss-gain value function of MA-PT.

κ is the sensitivity of loss aversion. ϖ and ξ represent the risk preference coefficients for gains.

Moreover, the probability weighting function $P(p)^+$ and $P(p)^-$ is as follows:

$$\begin{cases} P(p)^+ = \dfrac{p^\lambda}{p^\lambda + \left(1-p^\lambda\right)^{1/\lambda}} \\ P(p)^- = \dfrac{p^\eta}{p^\eta + (1-p^\eta)^{1/\eta}} \end{cases} \tag{4}$$

Fig. 3 shows a graph of the loss-gain probability weighting function. p is the objective probability function, $P(p)^+$ represents the decision weight function of the benefit. $P(p)^-$ denotes the decision weight function of loss. $P(p)^+$ and $P(p)^-$ represent the decision maker's subjective judgment of the probability of the occurrence of an event, satisfying $P(0) = 0, P(1) = 1$. λ and η represent decision influence coefficients. The larger the value is, the greater the influence on the probability is.

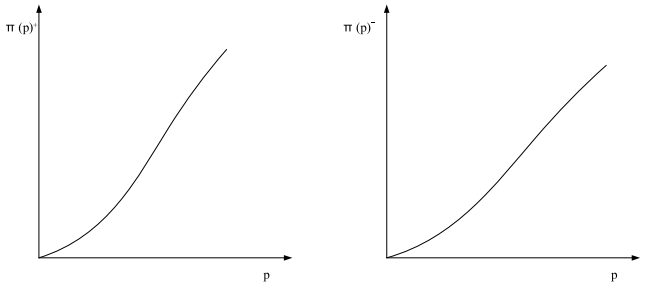

FIGURE 3. The loss-gain probability weighting function of MA-PT.

C. MODEL PARAMETERS

For Weibo rumors makers, spreading rumor requires planning and implementation costs as C_1. While rumors spread in a large range, and the income obtained by Weibo rumor makers is R_1. If under the strict management of the government, the income obtained by Weibo rumor makers will be reduced to nR_1, and n is the risk coefficient of income, of which $0 < n < 1$. For the government, when choosing the loose management strategy L, the cost of management such as people, equipment and capital is C_3. Due to improper management under strategy L, rumors spread widely, and the cost of social unrest is D, and the loss of government credibility is S_1. While choosing the strict supervision strategy M, the management cost is C_2 ($C_2 > C_3$). In order to maintain a good network order, the government punishes Weibo rumor makers with a fine of F_1. Under the strict management strategy M, the loss of government credibility caused by the spread of Weibo rumors is mS_1, m ($0 < m < 1$) is the risk coefficient of the loss. For Weibo user, the cost of forwarding and reposting rumors is C_4, the income of choosing strategy R to repost rumors is R_3, such as "Herding Effect" psychological satisfaction. S_2 represents the cost caused by reposting rumors under the strict management of the government. And we assume that the cost of Weibo users choosing NR strategy, including the value of information collection and verification, is C_5. Under the S strategy of the government, the value of good social environment obtained by Weibo users is R_2. According to the above analysis, the model parameters of the game players are described in Table 1.

TABLE 1. Descriptions of model parameters.

Symbol	Note
C_1	The cost of spreading rumor when Weibo rumor makers choose M
R_1	The income of Weibo rumor makers when rumor spread widely
F_1	Fines for Weibo rumor makers when governments choose S
C_2	The management cost when governments choose S
S_1	The cost of the decreasing government credibility when rumor spread widely
D	The cost of social unrest when rumor spread widely
C_3	The management cost when governments choose L
C_4	The cost when Weibo users choose R
C_5	The cost when Weibo users choose NR
R_2	The income of good network environment obtained by Weibo users when the governments choose S
S_2	The additional cost from Weibo users by reposting the rumors, when the governments choose S
R_3	The income of psychological satisfaction caused by Herding effect when Weibo users choose R
m	Risk coefficient of cost of governments credibility decline
n	Risk coefficient of income of rumor makers

Based on the above assumptions and parameter descriptions, the structure tree of the tripartite evolutionary game is constructed, as shown in Fig. 4. This structure tree intuitively describes the game between Weibo rumor makers, Weibo users and the government. In the process of game, all players hope to maximize their utility, which is the interaction criterion between the subjects. In this structure tree, the rectangles represent the players. The first column represents the information selected by Weibo rumor makers, where the Weibo rumor makers have two choices: to make rumors or not to make rumors. The rectangles in the second column are the selection information of the Weibo users, where Weibo users can choose to repost rumors or not to repost rumors. The rectangles in the third column are information about the government's choices, where the government can choose between strict supervision or loose supervision. The lines between the rectangles represent the strategies that game players can choose. The fourth column of eight numbers represents the end of the game, and these numbers represent their final benefits.

D. PAYOFF MATRIX

According to the model assumptions and parameters descriptions, we can get the payoff matrix of the traditional evolutionary game, as shown in Table 2.

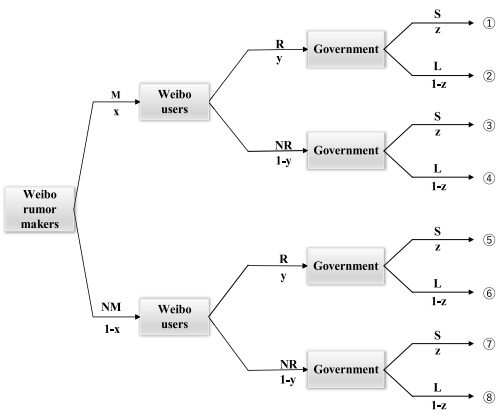

FIGURE 4. The structure tree of tripartite game.

TABLE 2. Payoff matrix of traditional tripartite evolutionary game.

Tripartite game strategies	Payoff
① (M,R, S)	$(nR_1 - C_1 - F_1, R_2 + R_3 - C_4 - S_2, F_1 - C_2 - mS_1)$
② (M,R,L)	$(R_1 - C_1, R_3 - C_4, -C_3 - S_1 - D)$
③ (M,NR,S)	$(-C_1 - F_1, R_2 - C_5, F_1 - C_2)$
④ (M,NR,L)	$(-C_1, -C_5, -C_3)$
⑤ (NM,R,S)	$(0, R_2 - C_4, -C_2)$
⑥ (NM,R,L)	$(0, -C_4, -C_3)$
⑦ (NM,NR,S)	$(0, R_2, -C_2)$
⑧ (NM,NR,L)	$(0, 0, -C_3)$

According to Table 2, we can get traditional payoff results of tripartite evolutionary game. Combined with the theory of MA-PT, the perceived payoff matrix of the game is constructed in Table 3, which fills in the defects of the past results.

IV. MODEL ANALYSIS

A. PERCEIVED PAYOFF FUNCTIONS BASED ON MA-PT

According to the selection probabilities of Weibo rumor makers, Weibo users and the government for different strategies in model assumptions and the perceived payoff matrix in Table 3, we can obtain the perceived value function of three players in the pure strategy based on MA-PT.

When Weibo rumor makers choose strategy M, the perceived value function based on MA-PT is:

$$\begin{aligned} V_{W1} = {} & P(y)\,P(z)\,[G(nR_1) - L(C_1 + F_1)] \\ & + P(y)\,P(1-z)\,[G(R_1) - L(C_1)] \\ & + P(1-y)\,P(z)\,[-L(C_1 + F_1)] \\ & + P(1-y)\,P(1-z)\,[-L(C_1)] \end{aligned} \tag{5}$$

TABLE 3. Perceived payoff matrix of tripartite evolutionary game combined with MA-PT.

Tripartite game strategies	Payoff
① (M,R, S)	$G(nR_1) - L(C_1 + F_1), G(R_2 + R_3) - L(C_4 + S_2), G(F_1) - L(C_2 + mS_1)$
② (M,R,L)	$G(R_1) - L(C_1), G(R_3) - L(C_4), -L(C_3 + S_1 + D)$
③ (M,NR,S)	$-L(C_1 + F_1), G(R_2) - L(C_5), G(F_1) - L(C_2)$
④ (M,NR,L)	$-L(C_1), -L(C_5), -L(C_3)$
⑤ (NM,R,S)	$0, G(R_2) - L(C_4), -L(C_2)$
⑥ (NM,R,L)	$0, -L(C_4), -L(C_3)$
⑦ (NM,NR,S)	$0, G(R_2), -L(C_2)$
⑧ (NM,NR,L)	$0, 0, -L(C_3)$

When Weibo rumor makers choose strategy NM, the perceived value function based on MA-PT is:

$$\begin{aligned} V_{W2} = {} & P(y)\,P(z)\,[0] + P(y)\,P(1-z)\,[0] \\ & + P(1-y)\,P(z)\,[0] + P(1-y)\,P(1-z)\,[0] \end{aligned} \tag{6}$$

Mixed strategy perceived value function of Weibo rumor makers based on MA-PT is:

$$\overline{V}_W = xV_{W1} + (1-x)\,V_{W2} \tag{7}$$

When Weibo users choose strategy R, the perceived value function based on MA-PT is:

$$\begin{aligned} V_{U1} = {} & P(x)\,P(z)\,[G(R_2 + R_3) - L(C_4 + S_2)] \\ & + P(x)\,P(1-z)\,[G(R_3) - L(C_4)] \\ & + P(1-x)\,P(z)\,[G(R_2) - L(C_4)] \\ & + P(1-x)\,P(1-z)\,[-L(C_4)] \end{aligned} \tag{8}$$

When the Weibo users choose strategy NR, the perceived value function based on MA-PT is:

$$\begin{aligned} V_{U2} = {} & P(x)\,P(z)[G(R_2) - L(C_5)] + P(x)\,P(1-z)\,[-L(C_5)] \\ & + P(1-x)\,P(z)\,[G(R_2)] + P(1-x)\,P(1-z)\,[0] \end{aligned} \tag{9}$$

Mixed strategy perceived value function of Weibo users based on MA-PT is:

$$\overline{V}_U = yV_{U1} + (1-y)\,V_{U2} \tag{10}$$

When the government chooses strategy S, the perceived value function based on MA-PT is:

$$\begin{aligned} V_{G1} = {} & P(x)\,P(y)\,[G(F_1) - L(C_2 + mS_1)] \\ & + P(x)\,P(1-y)\,[G(F_1) - L(C_2)] \\ & + P(1-x)\,P(y)\,[-L(C_2)] \\ & + P(1-x)\,P(1-y)\,[-L(C_2)] \end{aligned} \tag{11}$$

When the government chooses strategy L, the perceived value function based on MA-PT is:

$$V_{G2} = P(x)P(y)[-L(C_3+S_1+D)]+P(x)P(1-y)[-L(C_3)] + P(1-x)P(y)[-L(C_3)]+P(1-x)P(1-y)[-L(C_3)] \quad (12)$$

Mixed strategy perceived value function of government based on MA-PT is:

$$\overline{V}_G = zV_{G1} + (1-z)\,V_{G2} \quad (13)$$

In order to find the equilibrium strategy, the replication dynamic equation in Weibo rumor makers, Weibo users and the government is solved respectively.

The evolutionary replication dynamic equation of Weibo rumor makers is:

$$\begin{aligned} f_W(x) &= \frac{dx}{dt} = x\left(V_{W1} - \overline{V}_W\right) = x(1-x)\left(V_{W1} - V_{W2}\right) \\ &= x(1-x)\left[P(y)\,P(z)\left[G(nR_1) - L(C_1+F_1) - 0\right]\right. \\ &\quad + P(y)\,P(1-z)\left[G(R_1) - L(C_1) - 0\right] \\ &\quad + P(1-y)\,P(z)\left[-L(C_1+F_1) - 0\right] \\ &\quad \left. + P(1-y)\,P(1-z)\left[-L(C_1) - 0\right]\right] \\ &= x(1-x)\left[P(y)\,P(z)\,\mathrm{X}_1 + P(y)\,P(1-z)\,\mathrm{X}_2\right. \\ &\quad \left. + P(1-y)\,P(z)\,\mathrm{X}_3 + P(1-y)\,P(1-z)\,\mathrm{X}_4\right] \end{aligned} \quad (14)$$

where X_1 denotes the perceived payoff based on MA-PT of Weibo rumor makers when Weibo users choose strategy R, and the government chooses strategy S. X_2 represents the perceived payoff based on MA-PT of Weibo rumor makers when Weibo users choose strategy R, and the government chooses strategy L. X_3 denotes the perceived payoff based on MA-PT of Weibo rumor makers when Weibo users choose strategy NR, and the government chooses strategy S. X_4 represents the perceived payoff based on MA-PT of Weibo rumor makers when Weibo users choose strategy NR, and the government chooses strategy L.

The evolutionary replication dynamic equation of Weibo user is:

$$\begin{aligned} f_U(y) &= \frac{dy}{dt} = y\left(V_{U1} - \overline{V}_U\right) = y(1-y)\left(V_{U1} - V_{U2}\right) \\ &= y(1-y)\left[P(x)\,P(z)\left[G(R_2+R_3) - G(R_2)\right.\right. \\ &\quad \left. - L(C_4+S_2) + L(C_5)\right] + P(x)\,P(1-z)\left[G(R_3)\right. \\ &\quad \left. - L(C_4) + L(C_5)\right] + P(1-x)\,P(z)\left[G(R_2) - G(R_2)\right. \\ &\quad \left. - L(C_4)\right] + P(1-x)\,P(1-z)\left[-L(C_4) - 0\right]\Big] \\ &= y(1-y)\left[P(x)\,P(z)\,Y_1 + P(x)\,P(1-z)\,Y_2\right. \\ &\quad \left. + P(1-x)\,P(z)\,Y_3 + P(1-x)\,P(1-z)\,Y_4\right] \end{aligned} \quad (15)$$

where Y_1 denotes the perceived payoff based on MA-PT of Weibo users when Weibo rumor makers choose strategy M, and the government chooses strategy S. Y_2 represents the perceived payoff based on MA-PT of Weibo users when Weibo rumor makers choose strategy M, and the government chooses strategy L. Y_3 denotes the perceived payoff based on MA-PT of Weibo users when Weibo rumor makers choose strategy NM, and the government chooses strategy S. Y_4 represents the perceived payoff based on MA-PT of Weibo users when Weibo rumor makers choose strategy NM, and the government chooses strategy L.

The evolutionary replication dynamic equation of government is:

$$\begin{aligned} f_G(z) &= \frac{dz}{dt} = z\left(V_{G1} - \overline{V}_G\right) = z(1-z)\left(V_{G1} - V_{G2}\right) \\ &= z(1-z)\left[P(x)\,P(y)\left[G(F_1) - L(C_2+mS_1)\right.\right. \\ &\quad \left. + L(C_3+S_1+D)\right] + P(x)\,P(1-y)\left[G(F_1)\right. \\ &\quad \left. - L(C_2) + L(C_3)\right] + P(1-x)\,P(y)\left[-L(C_2)\right. \\ &\quad \left. + L(C_3)\right] + P(1-x)\,P(1-y)\left[-L(C_2) + L(C_3)\right]\Big] \\ &= z(1-z)\left[P(x)\,P(y)\,Z_1 + P(x)\,P(1-y)\,Z_2\right. \\ &\quad \left. + P(1-x)\,P(y)\,Z_3 + P(1-x)\,P(1-y)\,Z_4\right] \end{aligned} \quad (16)$$

where Z_1 denotes the perceived payoff based on MA-PT of the government when Weibo rumor makers choose strategy M, and Weibo users choose strategy R. Z_2 represents the perceived payoff based on MA-PT of the government when Weibo rumor makers choose strategy M, and Weibo users choose strategy NR. Z_3 denotes the perceived payoff based on MA-PT of the government when Weibo rumor makers choose strategy NM, and Weibo users choose strategy R. Z_4 represents the perceived payoff based on MA-PT of the government when Weibo rumor makers choose strategy NM, and Weibo users choose strategy NR.

B. DYNAMIC TREND ANALYSIS

In order to clarify the strategic choice of the tripartite game, we analyze the dynamic trend of Weibo rumor makers, Weibo users and the government respectively.

For Weibo rumor makers, Equation (14) can be simplified as follows:

$$\begin{aligned} f_W(x) &= x(1-x)\left[P(y)\,G(R_1) - L(C_1)\right. \\ &\quad \left. - P(z)\left[(1-n)\,P(y)\,G(R_1) + L(F_1)\right]\right] \end{aligned} \quad (17)$$

When $P(z) = \frac{P(y)G(R_1)-L(C_1)}{(1-n)P(y)G(R_1)+L(F_1)}$, then $f_W(x) \equiv 0$. It implies that in this case, any value of x is a local stable strategy. Otherwise, solve for $f_W(x) = 0$, $x = 0$ and $x = 1$ are regard as two local stable points. In order to further understand the strategies of Weibo rumor makers, we take the derivative of $f_W(x)$.

$$\begin{aligned} \frac{df_W(x)}{dx} &= (1-2x)\left[P(y)\,G(R_1) - L(C_1)\right. \\ &\quad \left. - P(z)\left[(1-n)\,P(y)\,G(R_1) + L(F_1)\right]\right] \end{aligned} \quad (18)$$

When $P(z) > \frac{P(y)G(R_1)-L(C_1)}{(1-n)P(y)G(R_1)+L(F_1)}$, then we can get the results that $\frac{df_W(x)}{dx}|_{x=0} < 0$, $\frac{df_W(x)}{dx}|_{x=1} > 0$. In this case, $x = 0$ is the local strategic equilibrium point. And it implies that Weibo rumor makers prefer to choose the strategy NM. And when $P(z) < \frac{P(y)G(R_1)-L(C_1)}{(1-n)P(y)G(R_1)+L(F_1)}$, then we can get the results that $\frac{df_W(x)}{dx}|_{x=0} > 0$, $\frac{df_W(x)}{dx}|_{x=1} < 0$. In this case, $x = 1$ is the local strategic equilibrium point. And it means that Weibo rumor makers prefer to choose the strategy M.

In order to intuitively understand the strategies of Weibo rumor makers, we construct a three-dimensional space A, $A = \{M(x, y, z) | 0 \le x \le 1, 0 \le y \le 1, 0 \le z \le 1\}$, and set the surface G_1 with the boundary points of z: $P(z) = \frac{P(y)G(R_1)-L(C_1)}{(1-n)P(y)G(R_1)+L(F_1)}$. The dynamic trend diagram of the Weibo rumor makers is shown in Fig. 5. Then, the curved surface G_1 divides the space into upper and lower parts, which are respectively marked as space H_{11} and H_{12}. When the initial strategy of the game is in the space H_{11}, the ultimate strategy of Weibo rumor makers is NM. On the contrary, if the initial strategy is in the space H_{12}, the final strategy of Weibo rumor makers is M.

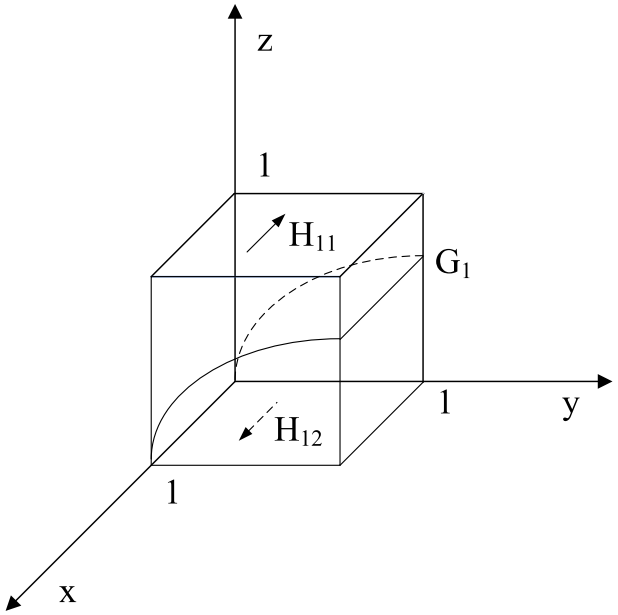

FIGURE 5. Dynamic trend of Weibo rumor makers.

For Weibo users, Equation (15) can be simplified as follows:

$$f_U(y) = y(1-y)[P(x)[G(R_3) + L(C_5) - P(z)L(S_2)] - L(C_4)] \quad (19)$$

When $P(x) = \frac{L(C_4)}{G(R_3)+L(C_5)-P(z)L(S_2)}$, then $f_U(y) \equiv 0$. It implies that in this case, any value of y is a local stable strategy. Otherwise, solve for $f_U(y) = 0$, $y = 0$ and $y = 1$ are regard as two local stable points.

In order to further understand the strategies of Weibo users, we take the derivative of $f_U(y)$.

$$\frac{df_U(y)}{dy} = (1-2y)[P(x)[G(R_3) + L(C_5) - P(z)L(S_2)] - L(C_4)] \quad (20)$$

When $P(x) < \frac{L(C_4)}{G(R_3)+L(C_5)-P(z)L(S_2)}$, then we can get the results that $\frac{df_U(y)}{dy}|_{y=0} < 0$, $\frac{df_U(y)}{dy}|_{y=1} > 0$. In this case, $y = 0$ is the local strategic equilibrium point. And it implies that Weibo users prefer to choose the strategy NR. And when $P(x) > \frac{L(C_4)}{G(R_3)+L(C_5)-P(z)L(S_2)}$, then we can get the results that $\frac{df_U(y)}{dy}|_{y=0} > 0$, $\frac{df_U(y)}{dy}|_{y=1} < 0$. In this case, $y = 1$ is the local strategic equilibrium point. And it means that Weibo rumor users prefer to choose the strategy R.

The dynamic trend diagram of Weibo users is shown in Fig. 6. Setting the surface G_2 with the boundary points of x: $P(x) = \frac{L(C_4)}{G(R_3)+L(C_5)-P(z)L(S_2)}$. The curved surface G_2 splits the space into two parts, which are respectively marked as space H_{21} and H_{22}. When the initial strategy of the game is in the space H_{21}, the final strategy of the Weibo users is R. On the contrary, if the initial strategy is in the space H_{22}, the final strategy of Weibo users is NR.

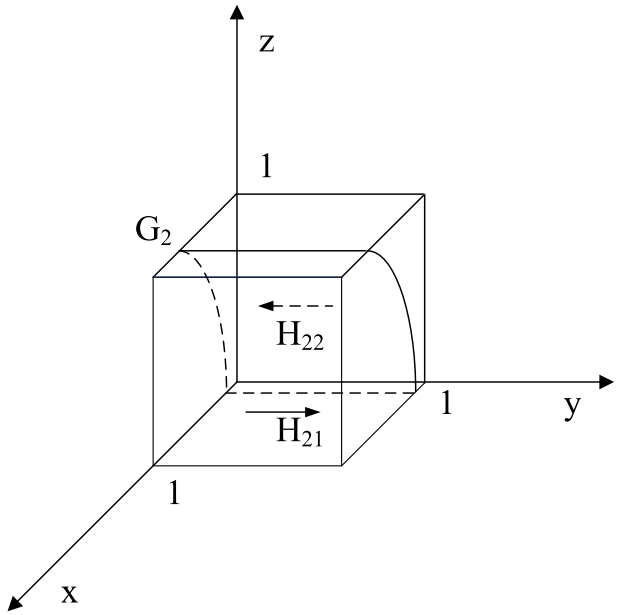

FIGURE 6. Dynamic trend of Weibo users.

For the government, Equation (16) can be simplified as follows:

$$f_G(z) = z(1-z)[P(x)G(F_1) + L(C_3 - C_2) + P(x)P(y)[(1-m)L(S_1) + L(D)] \quad (21)$$

When $P(y) = \frac{L(C_2-C_3)-P(x)G(F_1)}{P(x)[(1-m)L(S_1)+L(D)]}$, then we can get the results that $f_G(z) \equiv 0$. It implies that in this case, any value of z is a local stable strategy. Otherwise, solve for $f_G(z) = 0$, $z = 0$ and $z = 1$ are regard as two local stable points.

In order to further understand the strategies of government, we take the derivative of $f_G(z)$.

$$\frac{df_G(z)}{dz} = (1-2z)[P(x)G(F_1) + L(C_3 - C_2) + P(x)P(y)[(1-m)L(S_1) + L(D)] \quad (22)$$

When $P(y) > \frac{L(C_2-C_3)-P(x)G(F_1)}{P(x)[(1-m)L(S_1)+L(D)]}$, then we can get the results that $\frac{df_G(z)}{dz}|_{z=0} > 0$, $\frac{df_G(z)}{dz}|_{z=1} < 0$. In this case, $z = 1$ is the local strategic equilibrium point. And it means that the government prefers to choose the strategy S. And when $P(y) < \frac{L(C_2-C_3)-P(x)G(F_1)}{P(x)[(1-m)L(S_1)+L(D)]}$, then we can get the

results that $\frac{df_G(z)}{dz}|_{z=0} < 0$, $\frac{df_G(z)}{dz}|_{z=1} > 0$. In this case, $z = 0$ is the local strategic equilibrium point, and the government chooses the strategy L.

The dynamic trend diagram of the Government is shown in Fig. 7. Setting the surface G_3 with the boundary points of y: $P(y) = \frac{L(C_2-C_3)-P(x)G(F_1)}{P(x)[(1-m)L(S_1)+L(D)]}$. Then, the curved surface G_3 splits the space into two parts, which are respectively marked as space H_{31} and H_{32}. When the initial state of the game is in the space H_{31}, the final strategy of the government is S. On the contrary, if the initial state is in the space H_{32}, the final strategy of the government is L.

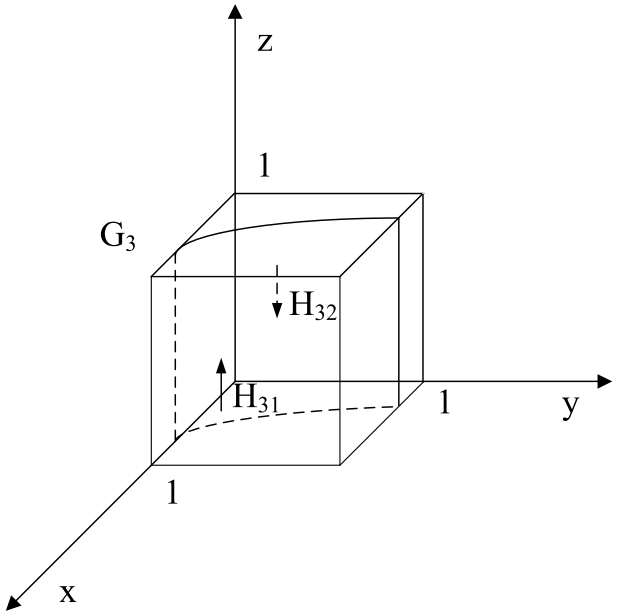

FIGURE 7. Dynamic trend of the government.

According to the analysis of dynamic trend, it can be seen that surface G_1, G_2 and G_3 divide the cube space into 8 parts. The change of a parameter may lead to the change in the strategies of the players, and strategies of the player influence each other. Therefore, from the analysis of these diagrams, the preliminary judgment is made that there is no stable strategy in this tripartite game.

C. EVOLUTIONARY STABILITY ANALYSIS OF THE EQUILIBRIUMS

In order to further discuss the stable strategy in this game, the evolutionary stability analysis of the equilibrium is conducted for in-depth study. When the evolutionary replication dynamic equation equals to zero, then the game system will reach a stable and constant level, which called equilibrium point of the game. When the payoff no longer increases regardless of how the players change their strategies, then the current strategy is called the evolutionary stable strategy (ESS) [29]. By setting $f_W(x)$, $f_U(y)$ and $f_G(z)$ equal to 0, we can obtain eight local equilibrium points as $S_1(0,0,0)$, $S_2(0,0,1)$, $S_3(0,1,0)$, $S_4(0,1,1)$, $S_5(1,0,0)$, $S_6(1,0,1)$, $S_7(1,1,0)$, $S_8(1,1,1)$. Meanwhile, these eight local equilibrium points need to be further judged by Jacobian matrix to analyze if it is ESS. The Jacobian matrix of this tripartite game and the perceived value functions based on MA-PT of its elements is shown as follows:

$$J = \begin{bmatrix} \frac{\partial f_W(x)}{\partial x} & \frac{\partial f_W(x)}{\partial y} & \frac{\partial f_W(x)}{\partial z} \\ \frac{\partial f_U(y)}{\partial x} & \frac{\partial f_U(y)}{\partial y} & \frac{\partial f_U(y)}{\partial z} \\ \frac{\partial f_G(z)}{\partial x} & \frac{\partial f_G(z)}{\partial y} & \frac{\partial f_G(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{13} \\ \pi_{21} & \pi_{22} & \pi_{23} \\ \pi_{31} & \pi_{32} & \pi_{33} \end{bmatrix} \tag{23}$$

$$\begin{cases} \pi_{11} = (1-2x)\left[P(y)P(z)X_1 + P(y)P(1-z)X_2 \right. \\ \left. +P(1-y)P(z)X_3 + P(1-y)P(1-z)X_4\right] \\ \pi_{12} = \left(x-x^2\right)\left[\frac{dP(y)}{dy}P(z)X_1 + \frac{dP(y)}{dy}P(1-z)X_2 \right. \\ \left. -\frac{dP(y)}{dy}P(z)X_3 - \frac{dP(y)}{dy}P(1-z)X_4\right] \\ \pi_{13} = \left(x-x^2\right)\left[\frac{dP(z)}{dz}P(y)X_1 - \frac{dP(z)}{dz}P(y)X_2 \right. \\ \left. +\frac{dP(z)}{dz}P(1-y)X_3 - \frac{dP(z)}{dz}P(1-y)X_4\right] \\ \pi_{21} = \left(y-y^2\right)\left[\frac{dP(x)}{dx}P(z)Y_1 + \frac{dP(x)}{dx}P(1-z)Y_2 \right. \\ \left. -\frac{dP(x)}{dx}P(z)Y_3 - \frac{dP(x)}{dx}P(1-z)Y_4\right] \\ \pi_{22} = (1-2y)\left[P(x)P(z)Y_1 + P(x)P(1-z)Y_2 \right. \\ \left. +P(1-x)P(z)Y_3 + P(1-x)P(1-z)Y_4\right] \\ \pi_{23} = \left(y-y^2\right)\left[\frac{dP(z)}{dz}P(x)Y_1 - \frac{dP(z)}{dz}P(x)Y_2 \right. \\ \left. +\frac{dP(z)}{dz}P(1-x)Y_3 - \frac{dP(z)}{dz}P(1-x)Y_4\right] \\ \pi_{31} = \left(z-z^2\right)\left[\frac{dP(x)}{dx}P(y)Z_1 + \frac{dP(x)}{dx}P(1-y)Z_2 \right. \\ \left. -\frac{dP(x)}{dx}P(y)Z_3 - \frac{dP(z)}{dz}P(1-y)Z_4\right] \\ \pi_{32} = \left(z-z^2\right)\left[\frac{dP(y)}{dy}P(x)Z_1 - \frac{dP(y)}{dy}P(x)Z_2 \right. \\ \left. +\frac{dP(y)}{dy}P(1-x)Z_3 - \frac{dP(y)}{dy}P(1-x)Z_4\right] \\ \pi_{33} = (1-2z)\left[P(x)P(y)Z_1 + P(x)P(1-y)Z_2 \right. \\ \left. +P(1-x)P(y)Z_3 + P(1-x)P(1-y)Z_4\right] \end{cases} \tag{24}$$

The determinant function $\det J$ and the trace function trJ of this Jacobian matrix J are shown in Equation (25) and Equation (26).

$$\begin{aligned} \det J &= \pi_{11}(\pi_{22}\pi_{33} - \pi_{23}\pi_{32}) + \pi_{12}(\pi_{23}\pi_{31} - \pi_{21}\pi_{33}) \\ &\quad + \pi_{13}(\pi_{21}\pi_{32} - \pi_{22}\pi_{31}) \end{aligned} \tag{25}$$

$$trJ = \pi_{11} + \pi_{22} + \pi_{33} \tag{26}$$

Local equilibrium points can be identified as ESS only if the condition $\det J > 0$ and $trJ < 0$ are met. Therefore, according to the model parameters and Jacobian matrix, the ESS of the tripartite game of rumor propagation can be

studied in depth. The results of determinant and trace for eight local equilibrium points are shown in Table 4.

TABLE 4. The results of determinant and trace.

Game equilibrium point	det J	trJ
$S_1(0,0,0)$	$X_4Y_4Z_4$	$X_4+Y_4+Z_4$
$S_2(0,0,1)$	$-X_3Y_3Z_3$	$X_3+Y_3-Z_3$
$S_3(0,1,0)$	$-X_2Y_4Z_3$	$X_2-Y_4+Z_3$
$S_4(0,1,1)$	$X_1Y_3Z_3$	$X_1-Y_3-Z_3$
$S_5(1,0,0)$	$-X_4Y_2Z_2$	$-X_4+Y_2+Z_2$
$S_6(1,0,1)$	$X_3Y_1Z_2$	$-X_3+Y_1-Z_2$
$S_7(1,1,0)$	$X_2Y_2Z_1$	$-X_2-Y_2+Z_1$
$S_8(1,1,1)$	$-X_1Y_1Z_1$	$-X_1-Y_1-Z_1$

In order to analyze the symbols of det J and trJ, we construct constraint conditions for the parameters on account of the actual situation of Weibo rumor propagation.

For Weibo rumor makers,

$$\begin{cases} G(R_1) > L(C_1) \\ L(C_1+F_1) > 0 \\ L(C_1) > 0 \end{cases} \tag{27}$$

$G(R_1) > L(C_1)$ represents that the perceived benefits of making and spreading rumors for Weibo rumor makers are greater than their costs. $L(C_1+F_1) > 0$ and $L(C_1) > 0$ denotes that the perceived cost of making rumors and the penalty is greater than 0.

For Weibo users,

$$\begin{cases} L(C_5) > L(C_4) \\ L(C_5)+G(R_3) > L(C_4) \\ L(C_4) > 0 \end{cases} \tag{28}$$

$L(C_5) > L(C_4)$ can be expressed as the loss perceived value of the cost of not reposting rumors is bigger than that of reposting rumors, because of the additional cost of gathering information. Thus, we can get that $L(C_5)+G(R_3) > L(C_4)$. $L(C_4) > 0$ represents that the loss perceived value of the cost of reposting rumors is greater than 0.

For the government,

$$\begin{cases} L(C_2) > L(C_3) \\ L(D) > L(C_2-C_3) \\ G(F_1)+L(C_3+S_1+D) > L(C_2+mS_1) \end{cases} \tag{29}$$

$L(C_2) > L(C_3)$ can be expressed as the loss perceived value of the cost of strict supervision is greater than that of loose supervision. $L(D) > L(C_2-C_3)$ means that the perceived value of social unrest losses is greater than the difference value between the perceived value of losses from strict government supervision and loose supervision. Thus, we can get that $G(F_1)+L(C_3+S_1+D) > L(C_2+mS_1)$.

Through the above reality analysis, we can get the following results. For the Weibo rumor makers, $X_2 > 0, X_3 < 0, X_4 < 0$. For Weibo users, $Y_2 > 0$, $Y_3 < 0$, $Y_4 < 0$. For the government, $Z_1 > 0$, $Z_3 < 0$, $Z_4 < 0$. If the government imposed severe penalties for spreading rumors, then the value of F_1 is large. Accordingly, the results are found as follows:

$$\begin{cases} L(C_1+F_1) > G(nR_1) \\ G(F_1)+L(C_3) > L(C_2) \end{cases} \tag{30}$$

In the above condition (30), $X_1 < 0$, $Z_2 > 0$. On the contrary, if the government imposed slight penalties for spreading rumors which means that the value of F_1 is small, the following results is found as:

$$\begin{cases} L(C_1+F_1) < G(nR_1) \\ G(F_1)+L(C_3) < L(C_2) \end{cases} \tag{31}$$

In the above condition (31), $X_1 > 0$, $Z_2 < 0$. As for Weibo users, if the perceived value of psychological satisfaction caused by Herding effect, which means the value of R_3, is large. Then, we can get that $G(R_3)+L(C_5) > L(C_4+S_2)$. In this condition, $Y_1 > 0$. On the contrary, if the perceived value of R_3 is small, then it implies $G(R_3)+L(C_5) < L(C_4+S_2)$. It means that $Y_1 < 0$. Combining these two conditions, four cases is constructed as shown in Table 5.

Based on the above constraint conditions and calculation analysis, the stability state for local equilibrium points is analyzed in Table 5. It can be seen that there is no ESS in the tripartite evolutionary game, which indicates that rumor propagation is a complex process of dynamic interaction.

D. RESULTS ANALYSIS

Combined with the above analysis of stability state, there is no evolutionary stability strategy in this game model. In the process of rumor spreading, the key stakeholders, including Weibo rumor makers, Weibo users and the government, are bounded rationality. The bias of perception leads to the wrong choice in the decision-making process, so that the system cannot reach the optimal state. According to the actual situation, we can conclude that in the tripartite game of rumor propagation, the best strategy for the effective governance is that: Weibo rumor makers choose strategy NM to not make rumors, Weibo users choose the strategy NR to not repost rumors, and the government finally chooses the strict management strategy S. The reasons that prevent the game system from reaching its ideal state are analyzed as follows:

1) Weibo rumor makers and Weibo users have a high perceived value of gain with low gain reference value U_2, and the corresponding perceived value of loss is low with high loss reference value U_1. And the perceived loss of government is high with low loss reference value U_1, and the perceived gain of government is low with high gain reference value U_2. For Weibo rumor makers, the widespread of rumors can bring huge benefits (e.g., monetary gains and the increasing attention of Internet users) than the gain reference value U_2 they expected, while choosing the strategy NM does not bring benefits. Thus, Weibo rumor makers prefer to choose the strategy of making rumors. The value of

TABLE 5. Stability state for local equilibrium points.

Cases	Game equilibrium point	det J	trJ	State
Case 1 $X_1<0$ $Y_1>0$ $Z_2>0$	$S_1(0,0,0)$	–	–	Saddle point
	$S_2(0,0,1)$	+	unsure	Saddle point
	$S_3(0,1,0)$	–	unsure	Saddle point
	$S_4(0,1,1)$	–	unsure	Saddle point
	$S_5(1,0,0)$	+	+	Unstable
	$S_6(1,0,1)$	–	unsure	Saddle point
	$S_7(1,1,0)$	+	unsure	Saddle point
	$S_8(1,1,1)$	+	unsure	Saddle point
Case 2 $X_1<0$ $Y_1<0$ $Z_2>0$	$S_1(0,0,0)$	–	–	Saddle point
	$S_2(0,0,1)$	+	unsure	Saddle point
	$S_3(0,1,0)$	–	unsure	Saddle point
	$S_4(0,1,1)$	–	unsure	Saddle point
	$S_5(1,0,0)$	+	+	Unstable
	$S_6(1,0,1)$	+	unsure	Saddle point
	$S_7(1,1,0)$	+	unsure	Saddle point
	$S_8(1,1,1)$	–	unsure	Saddle point
Case 3 $X_1>0$ $Y_1>0$ $Z_2<0$	$S_1(0,0,0)$	–	–	Saddle point
	$S_2(0,0,1)$	+	unsure	Saddle point
	$S_3(0,1,0)$	–	unsure	Saddle point
	$S_4(0,1,1)$	+	+	Unstable
	$S_5(1,0,0)$	–	unsure	Saddle point
	$S_6(1,0,1)$	+	+	Unstable
	$S_7(1,1,0)$	+	unsure	Saddle point
	$S_8(1,1,1)$	–	–	Saddle point
Case 4 $X_1>0$ $Y_1<0$ $Z_2<0$	$S_1(0,0,0)$	–	–	Saddle point
	$S_2(0,0,1)$	+	unsure	Saddle point
	$S_3(0,1,0)$	–	unsure	Saddle point
	$S_4(0,1,1)$	+	+	Unstable
	$S_5(1,0,0)$	–	unsure	Saddle point
	$S_6(1,0,1)$	–	unsure	Saddle point
	$S_7(1,1,0)$	+	unsure	Saddle point
	$S_8(1,1,1)$	+	unsure	Saddle point

loss includes the cost of spreading rumors and government punishment. When creating rumors, Weibo rumor makers have predicted the high reference value of loss U_1, but still choose to create rumors. In addition, if Weibo rumor makers do not care about legal and moral constraints, the perceived value of loss under strategy M will be far less than the gain of rumors spreading, which attracts Weibo rumor makers to make and spread rumors. Therefore, benefits and punishment from rumor propagation are crucial to the final strategy.

For Weibo users, the openness and anonymity of Weibo lead to the low cost of forwarding rumors, compared with the high cost to find out the truth of the rumor event. Thus, they tend to choose the strategy R to repost rumors which can cut down their costs. Meanwhile, under the low gain reference value U_2, Weibo users have a low expectation of gain towards the rumor. However, the psychological satisfaction obtained by the influence of Herding effect is high when following the rumor information. This increases their probability of choosing R strategy. The current network control mechanism does not play an effective role in guiding Weibo users. These barriers make it easy for Weibo users to engage in rumor events and cause large-scale social unrest. Therefore, the perceived value of Herding effect should be given more attention.

For the government, the cost of strict management is higher than that of loose management under a high sense of psychological perception value of loss. Taking cost savings into account, it's reasonable for the government to choose L strategy. Under the low loss reference value U_1, the government does not want to make extra behaviors to regulate rumors. Compared with loose regulation, the strict management needs to put more efforts and money. Thus, the government prefers to choose the strategy of loose management. However, it's the responsibility of the government to maintain social stability. And the spread of evil rumors increases the probability of social unrest. Therefore, the perceived loss of social unrest is a critical factor that influences the final decision.

2) Mental accounts divide the payoff of participants into gain accounts and loss accounts. In addition, people have risk preference for loss account and risk aversion for gain account.

Weibo rumor makers are risk aversion in view of the gains. In this situation, the value of κ is high and the value of ϖ and ε is low. As for the loss accounts, Weibo rumor makers are risk appetite. Under this situation, the value of τ is low and the value of δ and ψ is high. When adopting the strategy of not making rumors, the payoff of Weibo rumor makers is 0. However, there is a low probability of getting punishments but with huge benefits, when facing the strategy of making rumors. Therefore, they tend to make rumors. For Weibo users and the government, they also have the feature of risk preference in the face of strategy choice. When choosing the strategy of not reposting rumors, Weibo users need to pay for the cost of C_5. However, the strategy of reposting rumors can get the benefits of R_3 and pay for the less cost of C_4. Hence, Weibo users tend to choose the strategy of reposting rumors. As for the government, the strict management needs to pay for the higher value of cost than loose management. And there is less likely to lead to the loss of social unrest D under loose supervision. Thus, the government is more likely to choose the strategy of loose supervision.

V. NUMERICAL SIMULATION ANALYSIS

On October 11, 2020, three asymptomatic cases of COVID-19 pneumonia were found in Qingdao, China. Qingdao Municipal Health Commission announced on October 12 that it had started the nucleic acid testing program for all people in Qingdao. Subsequently, rumor makers with ulterior motives posted rumor information exaggerating the number of confirmed COVID-19 cases in Qingdao on

Weibo, claiming that "71 cases have been confirmed in Qingdao", which attracted the attention and reposting of a large number of Weibo users in a short time. On the basis of theoretical analysis, this paper further examines the influence of parameter changes in the model on rumor propagation. In this section, MATLAB numerical simulation software is used to conduct experiments on the evolution process of the game of rumor spreading. As shown in Table 6, the estimated parameter values are kept as a benchmark.

Meanwhile, the relevant preference coefficients of the value function based on MA-PT are set as: $\delta = 0.98, \psi = 0.98, \varpi = 0.88, \varepsilon = 0.88, k = 2, \tau = 2$ [68]. And the decision influence coefficients of probability weighting function are defined as: $\lambda = 0.61, \eta = 0.69$ [33]. The initial probability value of each strategy selected by the three game players is determined as 0.5. Then, (x, y, z) is set as (0.5, 0.5, 0.5), so that the evolution process of the strategy can be observed more intuitively. Next, in order to facilitate the demonstration in the simulation below, we use abbreviations, where W stands for Weibo rumor maker, U stands for Weibo users, and G stands for the government. Through the above parameter settings, this paper simulates the dynamic strategy evolution process of Weibo rumor makers, Weibo users and the government.

A. SIMULATION ANALYSIS OF EVOLUTION STABILITY STATE

First, the evolution stability state of strategies is analyzed in Fig.9. From the evolution results, we can conclude that this game model does not have a stable equilibrium point. Due to the mutual influence and interaction mechanism between players, the results pointed out that there is no evolutionary stable state in the tripartite game model between Weibo rumor makers, Weibo users, and the government, which verified the conclusions of the diagram of dynamic trend and Table 5.

B. SIMULATION ANALYSIS OF GAME REFERENCE VALUES

As shown in Fig.9, the evolution of the different reference values of U_1 and U_2 are analyzed. The value of U_1 ranges from 0.5 to 2. The value of U_2 ranges from 1 to 4. The larger the reference value, the thicker the line. With the decreasing value of U_1 and the increasing value of U_2, W and U gradually converge to 0. It implies that Weibo rumor makers choose not to make rumors. And the probability that Weibo users choose to repost rumors gradually decreases. It can be found that the adjustment of the reference value changes the final evolutionary direction of the strategies of Weibo rumor makers and Weibo users. Under such circumstances, the risk of rumor events can be effectively reduced. At the same time, with the decreasing value of U_2 and the increasing value of U_1, G gradually converges to 1. It represents that the government tends to strictly supervise Weibo rumors. The change of government attitude can realize the effective supervision of rumor events, thus reduce the risk of rumor spreading. Therefore, different reference values have an important impact on the strategy choice of players involved in the game of Weibo rumors.

TABLE 6. Estimated parameter values for Weibo rumor propagation.

Parameter	Value/ MUSD	Rationale
S_1	17	The perceived value of the loss of government credibility was inferred according to the attention of the rumor debunking information of the event. The reading volume of Qingdao epidemic rumor debunking information is 530 million, and we assume that it was 17 million USD.
C_2	9.49	C_2 is measured by the value of people living in Qingdao. Qingdao has a total population of about 9.49 million. Under the government's choice of S Strategy, the regulatory cost per person is assumed to be 1 USD, with a total value of 9.49 million USD.
C_3	4.745	When the government chooses strategy L, the supervision cost per person is less than that under strategy S. Here we assume that the supervision cost per person is 0.5 USD, so that the total supervision cost C_3 is 4.745 million USD.
C_4	3.231	The value of comments resisting rumors in the popular Weibo topic "Rumor Crush" is used to represent the cost of users' forwarding rumors. There were 1.077 million people expressed their views, taking a value of 3 USD per comment. The total value of comment was 3.231million USD.
C_5	6.48	C_5 is measured by the number of readings on the topic of "Qingdao epidemic situation". During the period of rumor spread, the topic reading was 3.24 million. Taking a value of 2 USD per reading, the total value of C_5 was estimated as 6.48 million USD.
R_2	10.35	The value of Weibo fans of Qingdao Police is used to estimate the perceived value of good network environment R_2 . Assuming a value of 5 USD per fan, the total value of its Weibo fans was estimated at 10.35 million USD.
C_1	4	The cost of the M strategy for Weibo rumor makers was difficult to estimate. For this simulation we set this value to 4 million USD.
S_2	15	The cost of reposting rumors for Weibo users includes many factors, such as the negative opinions of other people and the psychological loss after the incident was clarified. Here it was assumed as 15 million USD.
m	0.75	We assumed that the risk coefficient of loss of government credibility due to the widespread spread of rumors was 0.75 [65-67].
n	0.6	We took that under the government S strategy, the income risk coefficient of Weibo rumor makers was 0.6 [27,65].

C. SIMULATION ANALYSIS OF THE PERCEIVED VALUE OF GOVERNMENT PUNISHMENT

The evolution of tripartite strategies under different government punishments F_1 is shown in Fig. 10, where F_1 is

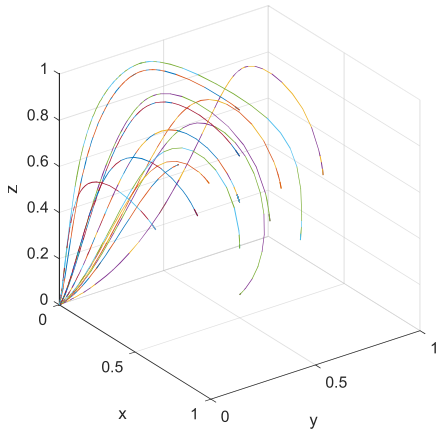

FIGURE 8. Evolution stability state of strategies.

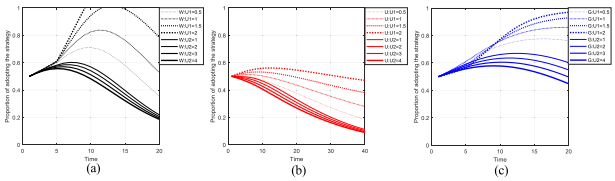

FIGURE 9. Evolution of different reference values.

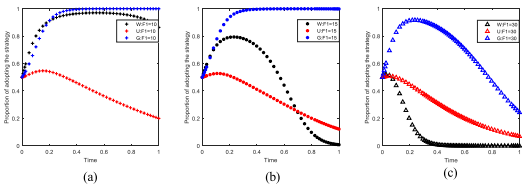

FIGURE 10. Evolution of tripartite strategies under different government punishments F_1.

ranged from 10 to 30. As shown in the figure, the perceived value of punishment has a significant impact on the evolution trend of Weibo rumor propagation. When the government's punishment is relatively light, the value of F_1 is small as $F_1 = 10$. Then, it can be found from Fig.10 (a) that W converges to 1, which means that Weibo rumor makers tend to make and spread rumors. And the government tends to adopt strict management strategy S. In this case, Weibo rumor makers are not afraid of the punishment measures. Thus, the government will take strict management measures to give them serious warnings and change their ideas. When $F_1 = 15$ and $F_1 = 30$, the value of government punishment increases gradually, it can be clearly observed that W gradually converges to 0, that is, Weibo rumor makers tend not to create rumors. Under the premise that the benchmark parameters of this example remain unchanged, an isolate increase in the perceived value of government penalties F_1 will change the direction in which Weibo rumor makers finally converge to the equilibrium state. With the increase of F_1, the government severely punishes those who create rumors, and rumor makers are extremely afraid of the punishment and will not easily create fake information. Changes in the behavior of Weibo rumor makers reduce the risk of the widespread of rumors. Therefore, the government needs to strengthen the network awareness education of netizens, and increase the punishment of those who produce bad rumors, which will help to maintain a reliable network environment.

D. SIMULATION ANALYSIS OF THE PERCEIVED VALUE OF WEIBO RUMOR MAKER' INCOME

The evolution of tripartite strategies under different Weibo rumor makers' incomes R_1 is shown in Fig.11, where R_1 is ranged from 10 to 60. As shown in Fig.11 (a), when Weibo rumor makers' income R_1 is small, as $R_1 = 10$, it can be found that W and G converge to 0. This means that Weibo rumor makers tend not to make rumors. Therefore, the Weibo environment is reliable and harmonious, then the government tends to adopt a loose management strategy L. Under such circumstances, Weibo rumor makers believe that the benefits brought by the dissemination of rumors is small, so that they choose the NM strategy. However, when Weibo rumor makers prefer netizens to pay attention to them and hope to increase the number of fans in exchange for material benefits, then they have a greater perceived value of income. As shown in Fig.11 (b) and Fig.11 (c), when the value of R_1 increases from 30 to 60, W and G are gradually converged to 1. This shows that Weibo rumor makers tend to choose M strategy to create rumors in face of higher profits. The increase of perceived benefits of rumor making changes the direction in which Weibo rumor makers and the government finally coverage to the equilibrium strategy. Driven by high profits, Weibo rumor makers join in creating and spreading rumors, which gradually increase the risk of rumor flooding. Thus, the government tends to adopt strict management S strategies to suppress the spread of rumors, so as to reduce public panic and avoid loss of government image. With the regulation of the government, the risk of rumors can be effectively reduced. Therefore, the government should strengthen the regulation of the benefits from Weibo, in order to enhance the control of rumors. In addition, the construction of physical and spiritual cultures should be reinforced to help the ecological development of the Weibo network.

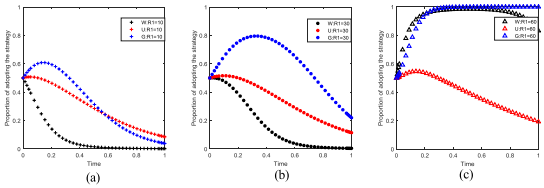

FIGURE 11. Evolution of tripartite strategies under different Weibo rumor makers' incomes R_1.

E. SIMULATION ANALYSIS OF THE PERCEIVED VALUE OF PSYCHOLOGICAL SATISFACTION

The evolution of tripartite strategies under different perceived value of psychological satisfaction is shown in Fig. 12, which R_3 ranges from 10 to 70. If Weibo users have a strong ability

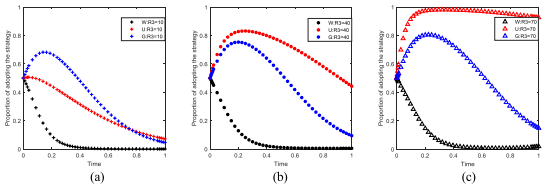

FIGURE 12. Evolution of tripartite strategies under different psychological satisfaction income R_3.

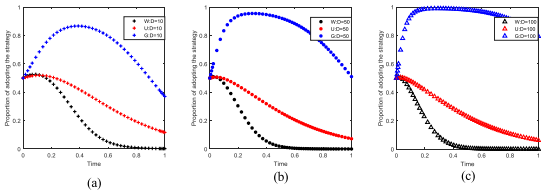

FIGURE 13. Evolution of tripartite strategies under different social unrest loss D.

to distinguish and think about rumors, then Weibo users will not be subject to the influence of Herding effect, and get a small psychological satisfaction value R_3. As in Fig.12 (a), when $R_3 = 10$, U converges to 0, which means that Weibo users have a tendency to choose strategy NM. At this time, Weibo users can objectively identify and analyze the false information. As the perceived value of psychological satisfaction in following rumors gradually increases, as shown in Fig.12 (b) and Fig.12 (c), when $R_3 = 40$ and $R_3 = 70$, it can be clearly observed that U gradually converges to 1. This means that Weibo users tend to blindly forward misleading information and rumors in order to keep pace with popular events. Thus, the increase of psychological perceived benefits U changes the final direction of the strategy evolution of Weibo users. The reposting of the rumor related information will intensify the spread of the rumor, leading to a severe negative social impact. Therefore, strengthening guidance and governance of Weibo users will help Weibo users form dialectical thinking ability and cultivate mature value orientation, which will contribute to the governance of Weibo rumors.

F. SIMULATION ANALYSIS OF THE PERCEIVED VALUE OF SOCIAL UNREST

The evolution of tripartite strategies under different perceived values of social unrest D is shown in Fig.13, which ranges from 10 to 100. The perceived value of social unrest has a significant impact on the evolution of rumor propagation. Specifically, if a rumor involves a hot issue, it is easy to arouse the curiosity of public and spread widely in a short time. Then, the perceived value of social unrest D is big. In the Fig.13 (c) where $D = 100$, G gradually converges to 1. And it means that the government tends to adopt strict management Strategy S. Under the pressure of social unrest, the government needs to adopt strict supervision measures to prevent the further spread of rumors. With the gradual decline of the perceived value of social unrest, such as $D = 50$ and $D = 10$, it can be clearly observed that G gradually converges to 0. It implies that the government tends to adopt loose management strategy L. For the government, it will choose a loose supervision strategy L with the decrease value of social unrest D. The perceived value of social unrest D represents the degree of importance that the government places on a stable social environment. A decrease in the perceived value of social unrest changes the final equilibrium strategy of the government and increases the risk of Weibo rumor makers creating rumors under loose regulation. Therefore, the government needs to enhance the sense of responsibility for social stability and conduct official inspections on hot issues in time to prevent the bad consequences.

VI. DISCUSSION

The governance of Weibo rumor is a multi-party coordinated process involving multiple stakeholders. The key to rumor management is to clarify the evolutionary trend of rumors and conduct effective regulation and guidance [20], [47]. This means that the government needs to coordinate multiple interests to achieve the goal of rumor governance, so as to promote the sustainable development of the network society. The results derived from model analysis and numerical simulation show that there is no evolutionary stable strategy for this game model under any initial conditions. It is different from some symmetric 2 by 2 games (e.g. chicken game) with internal equilibrium [69].

Through dynamic trend analysis, this paper indicates that changes in the strategic behavior of Weibo rumor makers (x) depend heavily on the strategic choice of government (z), that is, x and z are correlated. Likewise, the strategic behavior changes of Weibo users (y) are closely related to x. In addition, the strategic choice of government (z) is closely related to the behavior of y. Therefore, it is concluded that the strategy choices among the three parties influence each other and there is no ESS in this game. Subsequently, local stability analysis of the evolutionary strategy and simulation experiments were performed, and the same conclusions were obtained. In this evolutionary game, there are many factors that affect the interaction of the three parties. Changes in random factors will cause the other party to change their strategy choice, altering the strategy choice of the three parties, and causing the model to evolve toward an unstable strategy. Honner and Babichenko mentioned that there is no uniform way to guide players to even an approximate Nash equilibrium in a game [70], [71]. Jiang *et al.* also pointed out that there is not always an evolutionary stable state in a tripartite evolutionary game. Changes between factors changed the mechanism of the tripartite interaction strategy, leading to the evolution of the game to an unstable strategy [72].

VII. CONCLUSION

The wide spread of rumors on Weibo has a serious negative impact on the society and the government. If effective measures are not taken in time, social harmony and stability

will be affected and the positive image of the government will be damaged. In previous studies, classical game theory did not consider the psychological level and lacked the risk attitude perspective to consider the strategic behavior of players. In this paper, a tripartite game model is established by using the method of evolutionary game theory combined with MA-PT. Firstly, the strategies of game players under the influence of different factors are analyzed. Secondly, the model is solved according to the replicated dynamic equation. Thirdly, the simulation experiment is carried out according to the Weibo case to make explicit analysis and give guidance. This study is helpful for the subsequent supervision of Weibo. The main conclusions and management implications are shown below.

1) Through the model calculation and numerical simulation, it shows that there is no equilibrium stability state in the game of rumor spreading among Weibo rumor makers, Weibo users and the government. The strategic behavior of players is affected by gain and loss factors and cannot reach a stable state.

2) The reference value of gain and loss affects the perceived value of participants. It plays an important role in the strategic choices of players. Increasing the value of gain reference and decreasing the value of loss reference can promote the good behavior of Weibo rumor makers and Weibo users. And the government tends to take strict management strategy under high value of loss reference.

3) With the decrease of perceived value of profit from creating rumor and the increase of perceived value of punishment, the strategy of Weibo rumor makers gradually changes from making rumor to not making rumor. Therefore, it is necessary to strengthen the construction of laws and regulations, and punish those who cause malignant consequences according to law.

4) As the psychological satisfaction of ''Herding effect'' of following the spread of rumor gradually decreases, users will be more inclined to choose not to spread rumor. Therefore, it is necessary to strengthen the ideological education of netizens and cultivate the correct Internet values that do not believe and do not spread rumors.

5) As the perceived value of social unrest gradually increases, the government will gradually change from loose management to strict management. Therefore, during special periods (e.g., during an epidemic), the public is more likely to panic about the inaccurate information in cyberspace, and the government should strengthen the control of cyberspace to stabilize social order.

This study generates insightful guidelines for the governance of Weibo rumors in the micro level. In future research, the control of Weibo rumors can be further discussed with the heterogeneity of human beings' psychological states.

On this basis, we can analyze the optimal punishment and control measures for the government, so as to realize the practical application of the research results.

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