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Evolutionary Game Model of Public Opinion Information Propagation in Online Social Networks

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ABSTRACT The rapid development of communication technology has greatly changed the way of information propagation. While making use of positive public opinion information in online social networks (OSN) to create value, it is necessary to manage and control the propagation of public opinion. Considering the existence of both positive and negative public opinion, we proposed a tripartite evolutionary game model through identifying the relevant stakeholders involved in the public opinion spreading process, discussed the equilibrium conditions of stakeholders' behavior strategies emphatically and carried out simulation experiments. Then, based on the experimental results, the management strategy and the key intervention points of public opinion spreading were proposed. The result shows that the key to management and control public opinion is realizing the interest balance of all stakeholders. That is, the government should increase the benefits of netizens and media spreading (reporting) positive public opinion, and at the same time strengthen the punishment of them spreading (reporting) negative public opinion. This paper further expands the research of public opinion propagation in OSN, and provides theoretical support and decision-making basis for the management and control of public opinion.

INDEX TERMS Online social networks, public opinion information, propagation, evolutionary game theory, management strategy.

I. INTRODUCTION

According to the 45th China Statistical Report on Internet Development published by China Internet Network Information Center (CNNIC), China had 904 millon netizens, of which 897 millon are mobile phone netizens, accounting for 99.3%, by March 28, 2020 [1]. With the rapid development of communication technology and the popularization of the Internet, great changes have taken place in the way of information propagation. In modern society, the information propagation in Online Social Networks (OSN) enables netizens to break through the limitation of time and space in obtaining information, and they can participate in social interaction with various mobile terminals. This convenient way of information interaction greatly improves the speed of information propagation and expands the range of information diffusion.

As the barometer of social development, online public opinion information (the combination of the attitude, emotion, viewpoint and so on expressed by netizens to some social events based on the Internet communication platform, referred to as public opinion) is of great significance for netizens to familiar with social hot events, is also helpful for the government to improve the level of work level and fulfill social functions. While according to the content of public opinion, it can be divided into positive and negative public opinion by the government. Among them, negative public opinion mainly refers to the public opinion which contains illegal, harmful or false information, which may have a negative impact on social stability and the development of economy, for instance, rumor and so on, and the opposite is positive public opinion. Besides, it should be noted that

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in addition to the above two kinds of public opinion, there will be a neutral public opinion in reality, while due to it's little influence on the evolution of social events, so it will not be considered in this paper. Considering the characteristic of public opinion spreading in OSN, such as, fast speed, wide range, remarkable anonymity and strong interaction among netizens, during the spreading process of positive public opinion, it also provides conditions for the dissemination of negative public opinion. And this may lead to the widespread diffusion of negative public opinion, which become the focus of public attention and even affects the harmony and social stability. For instance, rumors about the new crown virus have always gripped people's nerves. Therefore, it is necessary to manage and control the propagation of public opinion in OSN. In other words, while using the positive public opinion to create value, it is necessary to resist the impact caused by the dissemination of negative public opinion.

The spreading mechanism of public opinion is closely related to its management and control. In order to make better use and manage public opinion, it is important to understand its evolution and propagation rules and find the key intervention points. The propagation of public opinion involves many stakeholders who have different motivation of interest, for instances, netizens, media and the government. Therefore, the decision-making process of multiple parties can be analyzed intuitively based on game theory [2], [3].

It should be noted that the bounded rationality of the stakeholders and the dynamics of game model have also led to the complexity of public opinion spreading process. Due to the rational difference among various stakeholders, it is impossible for them to achieve the completely rational conditions in practice. Besides, during the process of public opinion dissemination, the game relationship among netizens, media and the government is not only a dynamic game, but also a long-term game. So it is hard for all players to find the best strategy at the beginning. Instead, they will optimize their strategies constantly according to their interest goals and feedback information, such as imitation and learning. Therefore, it is applicable and reasonable to analyze the propagation and evolution process of public opinion and to find the key intervention point through evolutionary game theory [4], [5]. In addition, considering the solvability of the game model, we propose a three-party evolutionary game model.

At present, there are mainly two kinds of research for the study of public opinion based on game theory. One is micro-research, which focuses on the formation and evolution of public opinion [6]–[12]. Based on attitude change theory, group behavior theory and evolutionary game theory, Yin (2018) proposed an agent-based online opinion formation model, and they concluded that the opinion evolution of controversial topic shows greater uncertainty and sustainability and the ratio of benefit to cost has a significant impact on opinion formation [6]. In order to investigate how the public opinion evolves conformist and manipulative behavior, Estesami (2018) discussed the formation and evolution of public opinion in a discrete-time dynamical opinion network, which better captured a realistic opinion dynamics in social networks [7]. Besides, some scholars also try to discuss the evolution process of public opinion through the combination of game theory with complex networks theory. For example, Zhang *et al.* (2018) [8], Chi and Liu (2019) [9] analyzed the characteristics of public opinion evolution in different spaces and the link between them during the process of evolution, and proposed a public opinion evolution model based on the theory of super-network. And other studies included Lergetporer *et al.* (2017) [10], Rosenkrantz and Hawkins (2017) [11], Kardooni *et al.* (2018) [12] and so on.

This kind of research provides a basis for the identification of stakeholders under different situations, the establishment of game models, and the introduction of public opinion control strategies. While, due to its strong subjectivity, there is a lack of quantitative basis, especially in the quantification of various stakeholders' interests, which are of little practical guidance.

Another type of research is macro-research, which focuses on the propagation process of public opinion and its influence on society [13]–[20]. Compared with micro-research, there are abundant studies on analyzing the propagation process of public opinion based on evolutionary game theory. First of all, in terms of participants, the common game models are two-party game and three-party game. For instance, taking the public opinion caused by the ''8*12 Tianjin Port Explosion'' as a case, Yang (2018) proposed a ''scenario-coping'' model based on the evolutionary game theory, and discussed the evolution process of strategic choices of public opinion propagators and leaders [13]. Besides, through lots of simulation experiments, Guo (2013) concluded that in contrast with rational game, non-rational game can control the scope of public opinion dissemination and have lower computation complexity [14].

The involvement of human-related factors makes the propagation process of public opinion more complicated. Considering individual preferences, Wen (2015) proposed an analytical model which is built stochastically from a node level up and the high accuracy of this model is confirmed through extensive simulations [15]. With regard to the emotional evolution analysis for complex interactive text, Bu (2016) proposed an efficient affective computing framework to capture the underlying emotions of Chinese online reviews. Then, the effectiveness and accurateness of this approach are demonstrated through simulation experiments based on large-scaled dataset [16]. The simultaneous spread of negative and positive public opinion cannot be considered as two independent propagation processes, Liu (2017) researched the information propagation of emergency public event (favorable and harmful information) through nonlinear dynamic method [17].

In addition, scholars have also conducted lots of research regarding the influence of public opinion dissemination on various aspects of society. For example, in order to explore the discussion of economic issues in social media (Twitter) during an election, Karami (2018) proposed a computational

public opinion mining approach based on sentiment analysis and topic modeling. The proposed approach has effectively been deployed on millions of tweets to analyze economic concerns of people during the 2012 US presidential election [18]. Considering the growing interests among economists in public opinion towards immigration, Hatton (2017) proposed that preference and salience need to be taken into account when assessing the overall climate of public opinion towards immigration [19]. In order to discuss how public opinion influenced the diffusion of Affordable Care Act policy choices, Pacheco (2017) considered the policy feedback mechanism and tested the public opinion learning mechanism. Their results suggested that scholars and policy makers should consider how shifts in public support influence the spread of ideas across the American states [20].

Through the above analysis, it can be found that scholars have done lots of research on the public opinion propagation process, which has promoted the development of the spreading dynamics and provided rich theoretical basis for this paper. Meanwhile, most researchers focus on the evolution and spreading mechanism of public opinion, and there are relatively few studies on the management and key intervention points of public opinion, which lack guidance for the practical management. Besides, in the current research, most researchers only take negative or positive public opinion as the research object, ignoring the simultaneous existence and dissemination of two kinds of public opinion.

Considering the existence and propagation of positive and negative public opinion, we proposed a tripartite evolutionary game model including netizens, media and the government, analyzed the possible equilibrium strategies and its' stability conditions. Then, the key points of the government intervention in public opinion were determined, and the countermeasures were proposed based on experimental results and analysis. The organization of this paper can be summarized as follows. Section II introduces the main stakeholders involved in public opinion propagation process and their game relationships. Section III constructs a tripartite evolutionary game model and discusses the stability of stakeholders' evolution strategies and equilibrium points theoretically. Then, the simulation results under different scenarios and control strategies based experimental results are presented in Section IV. Finally, conclusions are drawn in Section V.

II. ANALYSIS OF STAKEHOLDERS AND THEIR GAME RELATIONSHIPS

A. DEFINITION OF STAKEHOLDERS IN PUBLIC OPINION SPREADING PROCESS

1) NETIZENS

As individuals engaged in social activities on the Internet, they could express their opinions and spread public opinion through OSN, which together with the public opinion in OSN constitute the network public opinion field. Due to the immediacy, interactivity and anonymity of online public opinion, netizens tend to obtain and propagate information through OSN, which promotes the rapid diffusion and large-scale dissemination of public opinion. Especially when the netizens' conventional interest expression lacks channels, the Internet will become an important way and platform for them to appeal interests, emotional catharsis and even rumor propagation. In addition, as a member of the social network, netizens' viewpoint on social hot issues will inevitably be influenced by group views. During the process of the development of public opinion, there exits a spiral of silence and butterfly effect [21], and netizens' opinion will tend to develop in a certain direction and will be strengthened gradually.

2) MEDIA

As the medium of public opinion propagation, media may influence netizens' cognition of social events, their public opinion propagation behavior, and even the evolution of public opinion during the spreading process of public opinion. Compared with traditional media, modern media has lower information release costs, higher efficiency and can realize the real-time interaction with netizens, which has become one of the main ways of modern news releasing. For instance, Sina, Sohu, NetEase have become main media channels for netizens to obtain information and exchange opinions, and netizens have gained more discourse space.

In the current social media environment, the timeliness and accuracy of media's reports on public opinion events are closely related to netizens' knowing the truth for the first time, which can avoid the emotionalization of netizens and weaken the influence of negative public opinion. While if the media's reports are inconsistent with the truth, it may cause huge public opinion storm in social network.

3) GOVERNMENT

As a manager of social public affairs, the government has the responsibility to guide public opinion and purify cyberspace (reducing the number of negative public opinion in OSN). In the management of public opinion, the government plays many roles, such as public opinion gatekeeper, witnesses, guider, crisis handler, etc [22]. In the field of online public opinion, the government could maintain the openness and transparency of public opinion through setting up official accounts, which may weaken the netizens' extreme emotions, remove the public opinion crisis, and maintain social stability. In a word, the government plays a important role in the formation of public opinion, as well as the its development and propagation process.

B. ANALYSIS OF GAME RELATIONSHIPS AMONG STAKEHOLDERS

From the above description, it is obvious that the main stakeholders involved in the public opinion propagation process include netizens, media and the government. Due to the obvious differences in behavior strategies among netizens, media and the government, while the indistinctive differences in their behavior strategies between netizens, media and the government, so we regard netizens, media and the

government as a group, respectively. And their game relationships are shown as follows.

1) THE GAME RELATIONSHIP BETWEEN NETIZENS AND MEDIA

During the spreading process of public opinion, on the one hand, netizens are the receivers of public opinion, namely, the consumers of information released by the media. Taking advantage of the asymmetry of public opinion to attract more netizens' attention and gain their trust is the basic condition for media to obtain long-term benefit. Therefore, media should report public opinion truthfully and try to restore the truth of hot issues so as to gain the netizens' recognition. On the other hand, netizens are also the publishers and propagators of public opinion, which may provide public opinion material for media and expand the social influence of media.

2) THE GAME RELATIONSHIP BETWEEN NETIZENS AND THE GOVERNMENT

As the manager of public opinion, the government may adopt positive or negative supervision strategy in the face of the propagation of public opinion. For instance, they could prevent the wide diffusion of negative public opinion and purify the network environment through educating or punishing those netizens who propagate negative public opinion. Under the government's different supervision strategies, netizens will choose whether to spread public opinion in OSN through comparing their own gains and losses. For example, in January, 2018, the China national entertainment platform issued a notice to purify the Internet environment, requiring all netizens to resist bad information and communicate in a civilized way. While in February, a celebrity (MC Tianyou) was banned for talking about pornography and other negative information in OSN.

3) THE GAME RELATIONSHIP BETWEEN MEDIA AND THE GOVERNMENT

Faced with different supervision strategies, media will carefully choose whether to report public opinion according to their own benefits. Under the negative supervision strategy, the authenticity of public opinion reported by media cannot be guaranteed, and the government needs to bear the loss of credibility and reputation. While under the positive supervision strategy, the public opinion reported by media will be strictly censored and the media are required to pay more energy to verify the authenticity of public opinion reported. Therefore, media will weight their gains and losses and then choose corresponding strategies under different the government's supervisory strategies.

III. CONSTRUCTION OF TRIPARTITE EVOLUTIONARY GAME MODEL

Based on the above descriptions, during the propagation process of public opinion, we consider netizens, media and the government as three stakeholders, all of which are bounded rational, and they all pursue the goal of maximizing their own interests. The strategy choice of the tripartite game subjects are netizens: {Propagating Positive public opinion (PP), Propagation Negative public opinion (PN), Not Propagating (NP)}; Media: {Reporting Positive public opinion (RP), Reporting Negative public opinion (RN), Not Reporting (NR)}; Government: {Supervision (S), Non-Supervision (NS)}.

A. DEFINITION OF STAKEHOLDERS GAIN AND LOSS

1) NETIZENS

Generally speaking, psychological satisfaction or material gains is the main driving force of individuals' decision-making behavior. While for netizens, the benefits of propagating public opinion is mainly reflected in satisfying their sense of social belonging, gaining recognition, attention, respect and trust from others, which is an important motive force for netizens to participate in the process of public opinion propagation. Therefore, the benefits of netizens choosing to propagate positive and negative public opinion are defined as R_{11} and R_{12} ($R_{12} > R_{11}$), respectively. Meanwhile, they need to pay time, energy and other costs to collect, pay attention to and spread public opinion, which can be defined as C_1. Besides, considering the existence of negative public opinion, when netizens propagate negative public opinion which is harmful to society or economy in OSN, they may be subject to moral or legal punishment, defined as P_1. In particular, when netizens do not spread public opinion in OSN, they will neither benefit nor be punished.

2) MEDIA

For media, the benefits of reporting public opinion are mainly reflected in the increase of click-through rate and attention, as well as the advertising revenue caused by the increase in popularity. The benefits of media choose to report positive and negative public opinion are expressed as R_{21} and R_{22} ($R_{22} > R_{21}$), respectively, and they also need to pay the cost C_2 caused by follow-up report and resource consumption ($C_2 > C_1$). In addition, if the media report negative public opinion, they also may be punished by laws and other aspects, expressed as P_2 ($P_2 > P_1$). When the media does not report public opinion, there is neither benefit nor punishment.

3) GOVERNMENT

For the government, if they choose supervision strategy for the propagation of public opinion in OSN, they need to pay the cost of monitoring and management of public opinion C_3, meanwhile, they will enjoy the improvement of public trust brought by the supervision strategy and the shaping of government image. And netizens can enjoy the extra benefit, such as social stability and cleaning network environment, expressed as U_1. Besides, if the government chooses non-supervision strategy, it needs to bear the risk caused by the wide dissemination of negative public opinion in OSN. At this time, if netizens and media choose to continue

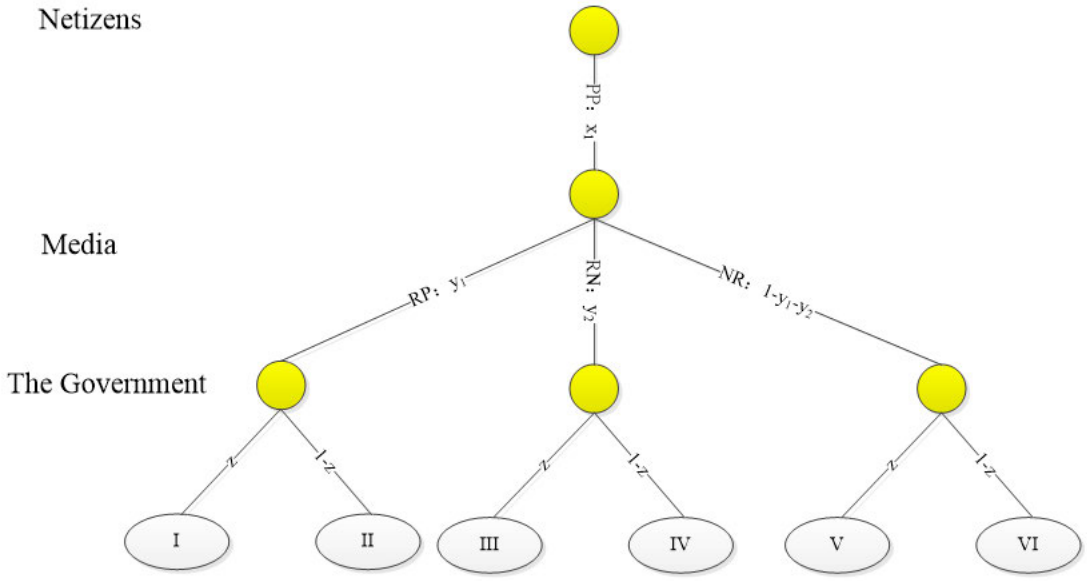

FIGURE 1. Tripartite game model during the spreading process of public opinion (Partial).

disseminating negative public opinion, the additional losses to the society can be expressed as Q_1 and Q_2, respectively.

The probability of netizens choosing *PP*, *PN* and *NP* strategy is defined as x_1, x_2 and $1-x_1-x_2$, respectively. Define the probability of media choosing *RP*, *RN* and *NR* strategy as y_1, y_2 and $1-y_1-y_2$. And the probability of the government choosing *S* and *NS* strategy is z and $1-z$.

Based on the above definition, during the process of public opinion spreading, when netizens choose to propagate positive public opinion, the game strategy and process of media and the government can be shown in Figure 1.

According to the game model shown in Figure 1, we can conclude the payoff matrix of the three parties. When the government choose supervision strategy, the payoff matrix of the netizens, media and the government is shown in Table 1.

TABLE 1. Payoff Matrix of Netizens, Media and Government (When the government choose supervisory strategy).

Media/ Netizens	$PP(x_1)$	$PN(x_2)$	$NP(1-x_1-x_2)$
$RP(y_1)$	$R_{11}+U_1-C_1$ $R_{21}-C_2$ R_3-C_3	$R_{12}+U_1-C_1-P_1$ $-C_2$ $R_3-C_3+P_1$	U_1 $-C_2$ R_3-C_3
$RN(y_2)$	$R_{11}+U_1-C_1$ $-C_2-P_2$ $R_3-C_3+P_2$	$R_{12}+U_1-C_1-P_1$ $R_{22}-C_2-P_2$ $R_3-C_3+P_1+P_2$	U_1 $-C_2-P_2$ $R_3+P_2-C_3$
NR $(1-y_1-y_2)$	$R_{11}+U_1-C_1$ 0 R_3-C_3	$R_{12}+U_1-C_1-P_1$ 0 $R_3-C_3+P_1$	U_1 0 R_3-C_3

When the government choose non-supervision strategy, the payoff matrix of the thee parties is shown in Table 2.

In Table 1 and Table 2, 3 rows in each cell represents the payoff of netizens, media and the government, respectively in some situation. Such as, the first cell in Table 1, 3 rows

TABLE 2. Payoff Matrix of Netizens, Media and Government (When the government choose non-supervisory strategy).

Media/ Netizens	$PP(x_1)$	$PN(x_2)$	$NP(1-x_1-x_2)$
$RP(y_1)$	$R_{11}-C_1$ $R_{21}-C_2$ 0	$R_{12}-C_1$ $-C_2$ $-Q_1$	0 $-C_2$ 0
$RN(y_2)$	$R_{11}-C_1$ $-C_2$ $-Q_2$	$R_{12}-C_1$ $R_{22}-C_2$ $-Q_1-Q_2$	0 $-C_2$ $-Q_2$
NR $(1-y_1-y_2)$	$R_{11}-C_1$ 0 0	$R_{12}-C_1$ 0 $-Q_1$	0 0 0

in the first cell means the payoff of netizens, media and the government equals $R_{11}+U_1-C_1$, $R_{21}-C_2$ and R_3-C_3, respectively, under the scenario when netizens choose to spread positive public opinion, media chooses to report positive public opinion and the government chooses supervisory strategy.

B. EXPECTED REVENUE FUNCTION OF THE THREE PARTIES

Combining the payoff matrix shown in Tables 1-2, we can get the expected revenue of the three parties as follows:

1) NETIZENS

It defines the expected revenue of netizens to choose *PP* strategy as $F_{1(PP)}$, *PN* strategy as $F_{1(PN)}$ and *NP* strategy as $F_{1(NP)}$, respectively. Then the average revenue of netizens ($\overline{F_1}$) can be expressed as:

$$\overline{F_1} = x_1 * F_{1(PP)} + x_2 * F_{1(PN)} + (1-x_1-x_2) * F_{1(NP)} \quad (1)$$

Of which, $F_{1(PP)} = R_{11} - C_1 + zU_1$; $F_{1(PN)} = R_{12} - C_1 + z(U_1 - P_1)$; $F_{1(NP)} = zU_1$.

2) MEDIA

Define the expected revenue of media choosing *RP* strategy as $F_{2(RP)}$, *RN* strategy as $F_{2(RN)}$, and *NR* strategy as $F_{2(NR)}$, respectively. Then the average revenue of media ($\overline{F_2}$) can be expressed as:

$$\overline{F_2} = y_1 * F_{1(RP)} + y_2 * F_{2(RN)} + (1 - y_1 - y_2) * F_{2(NR)} \tag{2}$$

Of which, $F_{2(RP)} = x_1R_{21} - C_2$, $F_{2(RN)} = x_2R_{22} - C_2 - zP_2$, $F_{2(NR)} = 0$.

3) GOVERNMENT

Define the expected revenue of the government choosing *S* strategy as $F_{3(S)}$, and *NS* strategy as $F_{3(NS)}$, respectively. Then the average revenue of the government ($\overline{F_3}$) can be expressed as:

$$\overline{F_3} = z * F_{3(S)} + (1 - z) * F_{3(NS)} \tag{3}$$

Of which, $F_{3(S)} = R_3 - C_3 + x_2P_1 + y_2P_2$, $F_{3(NS)} = -x_1Q_1 - x_2Q_2$.

C. REPLICATOR DYNAMICS EQUATION IN TRIPARTITE GAME MODEL

On the basis of the above payoff function and Malthusian equation [23], we can get the replicator dynamics equation of netizens choosing to propagate positive and negative public opinion strategy, which as be expressed as follows:

$$\begin{aligned} H(x_1) &= \frac{dx_1}{dt} = x_1(1 - x_1) * \frac{\partial \overline{F}_1}{\partial x_1} \\ &= x_1(1 - x_1) * (R_{11} - C_1) \end{aligned} \tag{4}$$

$$\begin{aligned} H(x_2) &= \frac{dx_2}{dt} = x_2(1 - x_2) * \frac{\partial \overline{F}_1}{\partial x_2} \\ &= x_2(1 - x_2) * (R_{12} - C_1 - zP_1) \end{aligned} \tag{5}$$

The replicator dynamics equation of media choosing report positive and negative public opinion strategy can be expressed as follows:

$$\begin{aligned} H(y_1) &= \frac{dy_1}{dt} = y_1(1 - y_1) * \frac{\partial \overline{F}_2}{\partial y_1} \\ &= y_1(1 - y_1) * (x_1R_{21} - C_2) \end{aligned} \tag{6}$$

$$\begin{aligned} H(y_2) &= \frac{dy_2}{dt} = y_2(1 - y_2) * \frac{\partial \overline{F}_2}{\partial y_2} \\ &= y_2(1 - y_2) * (x_2R_{22} - C_2 - zP_2) \end{aligned} \tag{7}$$

Similarly, the replicator dynamics equation of the government choosing supervisory strategy is as follows:

$$\begin{aligned} H(z) = \frac{dz}{dt} &= z(1 - z) * \frac{\partial \overline{F}_3}{\partial z} = z(1 - z) \\ &* [R_3 - C_3 + x_2(P_1 + Q_1) + y_2(P_2 + Q_2)] \end{aligned} \tag{8}$$

D. STABILITY ANALYSIS OF EVOLUTIONARY STRATEGY

Due to the significant impact of negative public opinion on society, we specially focus on the negative public opinion spreading behavior of netizens and the negative public opinion reporting behavior of media. Therefore, the gradual stability of the netizens' *PN* strategy, the medias' *RN* strategy and the government's supervisory strategy will be analyzed respectively.

1) ANALYSIS OF THE GRADUAL STABILITY OF NETIZENS' *PN* STRATEGY

When $H(x_2) = 0$, then, $x_2^* = 0$, $x_2^* = 1$, $z^* = \frac{R_{12} - C_1}{P_1}$. At the same time, $\frac{\partial H(x_2)}{\partial x_2} = (1 - 2x_2) * (R_{12} - C_1 - zP_1)$. According to the stability theorem and evolutionary stability strategy of replicated dynamic differential equation [24], [25], when $H(x_2^*) = 0$ and $\frac{\partial H(x_2)}{\partial x_2}|_{x_2^*} < 0$, x_2^* is evolutionary stability strategy. Therefore, the discussion is as follows:

i) When $z = \frac{R_{12} - C_1}{P_1}$, $H(x_2) \equiv 0$, $\frac{\partial H(x_2)}{\partial x_2} \equiv 0$, indicating that all strategies are stable states. At this time, the strategy selection probability of netizens does not change with time.

ii) When $R_{12} - C_1 < 0$, obviously, $z > \frac{R_{12} - C_1}{P_1}$, therefore, $x_2^* = 0$ and $x_2^* = 1$ are two stable points for netizens to choose the *PN* strategy. Right now, $\frac{\partial H(x_2)}{\partial x_2}|_{x_2^*=0} < 0$, $\frac{\partial H(x_2)}{\partial x_2}|_{x_2^*=1} > 0$, so $x_2^* = 0$ is the equilibrium point. The result shows that when the benefit of propagating negative public opinion is less than the cost, netizens prefer not to spread negative public opinion for avoiding risk.

iii) When the above two conditions are not satisfied, that is $R_{12} - C_1 > 0$ and $z \neq \frac{R_{12} - C_1}{P_1}$, we can discuss the stability from the following two situations. If $z > \frac{R_{12} - C_1}{P_1}$, then, $\frac{\partial H(x_2)}{\partial x_2}|_{x_2^*=0} < 0$, $\frac{\partial H(x_2)}{\partial x_2}|_{x_2^*=1} > 0$, so $x_2^* = 0$ is the equilibrium point. If $z < \frac{R_{12} - C_1}{P_1}$, then, $\frac{\partial H(x_2)}{\partial x_2}|_{x_2^*=0} > 0$, $\frac{\partial H(x_2)}{\partial x_2}|_{x_2^*=1} < 0$, so $x_2^* = 1$ is the equilibrium point. Under this situation, the benefits of netizens choosing propagating negative public opinion are greater than the sum of costs and punishment. From the perspective of maximizing interest, netizens prefer to propagate negative public opinion. The duplicate dynamic phase diagram of netizens' strategy is shown in Figure 2.

2) ANALYSIS OF THE GRADUAL STABILITY OF MEDIAS' *RN* STRATEGY

Let $H(y_2) = 0$, then, $y_2^* = 0$, $y_2^* = 1$, $x_2^* = \frac{zP_2 + C_2}{R_{22}}$, and $\frac{\partial H(y_2)}{\partial y_2} = (1 - 2y_2) * (x_2R_{22} - C_2 - zP_2)$. Therefore, the discussions are as follows:

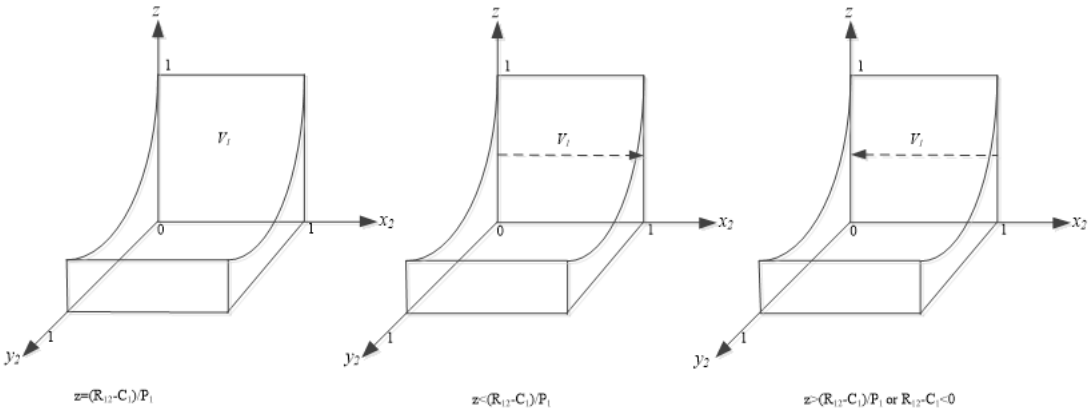

FIGURE 2. The duplicate dynamic phase diagram of netizens' *PN* strategy.

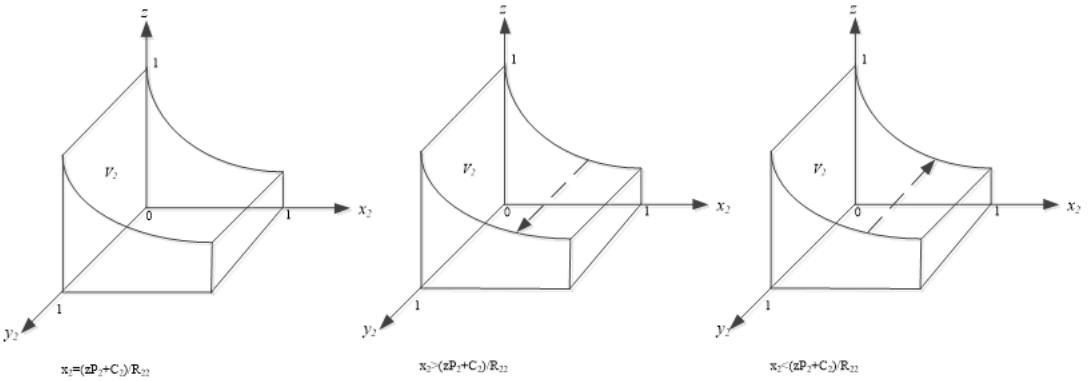

FIGURE 3. The duplicate dynamic phase diagram of medias' *RN* strategy.

i) When $x_2^* = \frac{zP_2 + C_2}{R_{22}}$, $H(y_2) \equiv 0$, $\frac{\partial H(y_2)}{\partial y_2} \equiv 0$, indicating that all strategies are stable states. And the proportion of media's strategy choice does not change over time.

ii) When $x_2^* \neq \frac{zP_2 + C_2}{R_{22}}$, it is easy to solve that $y_2^* = 0$ and $y_2^* = 1$ are two stable points. If $x_2^* > \frac{zP_2 + C_2}{R_{22}}$, $\frac{\partial H(y_2)}{\partial y_2}|_{y_2^*=0} > 0$, $\frac{\partial H(y_2)}{\partial y_2}|_{y_2^*=1} < 0$, so $y_2^* = 1$ is the equilibrium point. The results show that when the benefits of media reporting negative public opinion are greater than the sum of punishment and cost, media will report negative public opinion in OSN.

iii) If $x_2^* < \frac{zP_2 + C_2}{R_{22}}$, $\frac{\partial H(y_2)}{\partial y_2}|_{y_2^*=0} < 0$, $\frac{\partial H(y_2)}{\partial y_2}|_{y_2^*=1} > 0$, so $y_2^* = 0$ is the equilibrium point. Here, the benefits of media reporting negative public opinion are less than the sum of punishment and cost. From the perspective of bounded rationality, media is more inclined not to spread negative public opinion. The duplicate dynamic phase diagram of media' strategy is shown in Figure 3.

3) ANALYSIS OF THE GRADUAL STABILITY OF GOVERNMENT'S SUPERVISORY STRATEGY

Similarly, let $H(z) = 0$, then, $z^* = 0$, $z^* = 1$, $y_2^* = \frac{C_3 - R_3 - x_2 * (P_1 + Q_1)}{P_2 + Q_2}$, and $\frac{\partial H(z)}{\partial z} = (1 - 2z) * [R_3 - C_3 + x_2 * (P_1 + Q_1) + y_2 * (P_2 + Q_2)]$. Therefore, the discussions are as follows:

i) When $y_2^* = \frac{C_3 - R_3 - x_2 * (P_1 + Q_1)}{P_2 + Q_2}$, $H(z) \equiv 0$, $\frac{\partial H(z)}{\partial z} \equiv 0$, indicating that all strategies are stabile. At this time, the strategy selection probability of government does not change over time.

ii) When $x_2 * (P_1 + Q_1) + R_3 > C_3$, obviously, $y_2 > \frac{C_3 - R_3 - x_2 * (P_1 + Q_1)}{P_2 + Q_2}$ is constant. It is easy to find that $z^* = 0$ and $z^* = 1$ are two stable points for government to choose supervision strategy for public opinion propagation. Right now, $\frac{\partial H(z)}{\partial z}|_{z^*=0} > 0$, $\frac{\partial H(z)}{\partial z}|_{z^*=1} < 0$, so $z^* = 1$ is the equilibrium point. The result shows that when the benefits of choosing supervisory strategy are greater than the cost, the government prefers to choose the supervision strategy for maximizing the benefits.

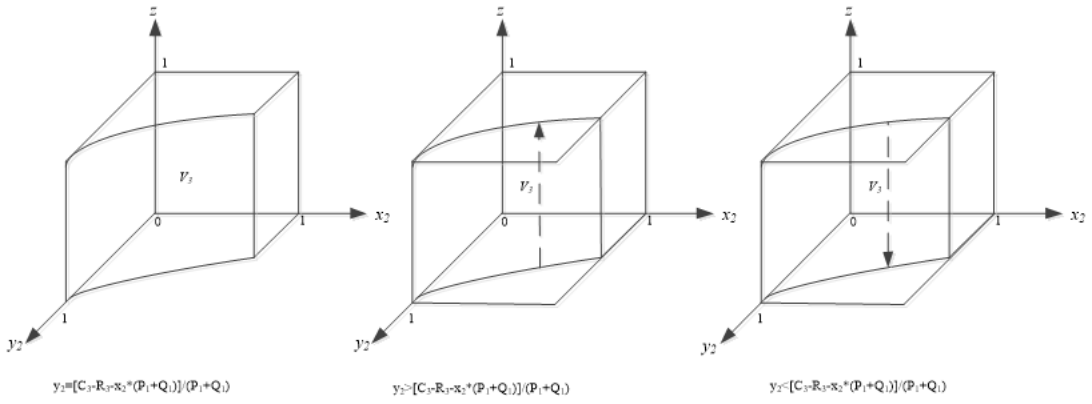

FIGURE 4. The duplicate dynamic phase diagram of government's supervisory strategy.

iii) When the above two conditions are not satisfied, that is $x_2 * (P_1 + Q_1) + R_3 < C_3$ and $y_2 \neq \frac{C_3 - R_3 - x_2 * (P_1 + Q_1)}{P_2 + Q_2}$, we can discuss the stability from the following two situations. Firstly, if $y_2 > \frac{C_3 - R_3 - x_2 * (P_1 + Q_1)}{P_2 + Q_2}$, then, $\frac{\partial H(z)}{\partial z}|_{z^*=0} > 0$, $\frac{\partial H(z)}{\partial z}|_{z^*=1} < 0$, so $z^* = 1$ is the equilibrium point. While, if $y_2 < \frac{C_3 - R_3 - x_2 * (P_1 + Q_1)}{P_2 + Q_2}$, then, $\frac{\partial H(z)}{\partial z}|_{z^*=0} < 0$, $\frac{\partial H(z)}{\partial z}|_{z^*=1} > 0$, $z^* = 0$ is the equilibrium point. Under this situation, the costs of the government choosing supervising public opinion propagation are greater than the sum of benefits and penalty from netizens and media. Therefore, the government will tend to choose non-supervisory strategy. The duplicate dynamic phase diagram of government' supervisory strategy is shown in Figure 4.

E. STABILITY ANALYSIS OF EQUILIBRIUM POINT

In Section 3.4, we analyzed the stability of evolutionary strategy of netizens, media and the government, respectively, while for the whole dynamic system, which equilibrium point it evolves to during the dynamics process cannot be directly judged. According to Cao' research [26], if the trajectory starting from any small neighborhood of a certain equilibrium point eventually tends to the point, we can call it as the evolution equilibrium point of the system. During the process of public opinion propagation, the replication dynamic system involving netizens, media and the government is shown in the following Formula.

$$\begin{cases} (a): H(x_1) = x_1(1 - x_1) * (R_{11} - C_1) \\ (b): H(x_2) = x_2(1 - x_2) * (R_{12} - C_1 - zP_1) \\ (c): H(y_1) = y_1(1 - y_1) * (x_1R_{21} - C_2) \\ (d): H(y_2) = y_2(1 - y_2) * (x_2R_{22} - C_2 - zP_2) \\ (e): H(z) = z(1 - z) * [R_3 - C_3 \\ \quad + x_2(P_1 + Q_1) + y_2(P_2 + Q_2)], \end{cases} \tag{9}$$

Due to we focus on the negative public opinion propagation behavior of netizens and the negative public opinion reporting behavior of media, and it does not include x_2, y_2, z in formula (9-a) and (9-c). For facilitating the solution, the above dynamic system can be rewritten as:

$$\begin{cases} H(x_2) = x_2(1 - x_2) * (R_{12} - C_1 - zP_1) \\ H(y_2) = y_2(1 - y_2) * (x_2R_{22} - C_2 - zP_2) \\ H(z) = z(1 - z) * [R_3 - C_3 + x_2(P_1 + Q_1) \\ \quad + y_2(P_2 + Q_2)] \end{cases} \tag{10}$$

In order to solve the equilibrium point of tripartite evolutionary game, let $H(x_2) = H(y_2) = H(z) = 0$. It is obvious that the dynamic system (10) have eight pure strategy equilibrium points $\{T_1(0, 0, 0), T_2(0, 1, 0), T_3(0, 0, 1), T_4(0, 1, 1), T_5(1, 0, 0), T_6(1, 1, 0), T_7(1, 0, 1), T_8(1, 1, 1)\}$ and a mixed strategy equilibrium point $T_9(x_2^*, y_2^*, z^*)$ in the definition domain $\Omega = \{0 \leq x_2 \leq 1, 0 \leq y_2 \leq 1, 0 \leq z \leq 1\}$. Of which,

$$\begin{cases} x_2^* = \dfrac{P_2(R_{12} - C_1) + P_1C_2}{P_1R_{22}} \\ y_2^* = \dfrac{C_3 - R_3}{P_2 + Q_2} - \dfrac{(P_1 + Q_1) * (P_2R_{12} - C_1P_2 + P_1C_2)}{P_1R_{22}(P_2 + Q_2)} \\ z^* = \dfrac{R_{12} - C_1}{P_1} \end{cases} \tag{11}$$

In Friedman's [23] study, he stated that if $\lim_{t \to \infty}(x(t), y(t), z(t)) = (x_0, y_0, z_0)$, the point (x_0, y_0, z_0) can be called the evolution equilibrium point. And the stability of the evolutionary equilibrium point can be judged by the eigenvalues of the Jacobian matrix corresponding to the dynamic system. If all eigenvalues of the corresponding matrix of an equilibrium point are negative real numbers, then the equilibrium point can be called the local asymptotically stable equilibrium point of the dynamic system. So the Jacobian matrix corresponding

TABLE 3. Stability analysis of equilibrium points in evolutionary game.

No.	Equilibrium point	Eigenvalue sign of Jacobian matrix	Stability
1	$T_1(0,0,0)$	If $R_{12} < C_1, R_3 < C_3$ $\lambda_i < 0 (i = 1,2,3)$	Asymptotically stable point
2	$T_2(0,1,0)$	$\lambda_2 > 0$	Unstable point
3	$T_3(0,0,1)$	If $R_{12} < C_1 + P_1, R_3 > C_3$, $\lambda_i < 0 (i = 1,2,3)$	Asymptotically stable point
4	$T_4(0,1,1)$	$\lambda_2 > 0$	Unstable point
5	$T_5(1,0,0)$	If $C_1 < R_{12}, C_2 > R_{22}$, $C_3 > R_3 + P_1 + Q_1$, $\lambda_i < 0 (i = 1,2,3)$	Asymptotically stable point
6	$T_6(1,1,0)$	If $C_1 < R_{12}, C_2 < R_{22}$, $R_3 + P_1 + Q_1 + P_2 + Q_2 < C_3$, $\lambda_i < 0 (i = 1,2,3)$	Asymptotically stable point
7	$T_7(1,0,1)$	If $C_1 + P_1 < R_{12}, C_2 + P_2 > R_{22}$, $R_3 + P_1 + Q_1 > C_3$, $\lambda_i < 0 (i = 1,2,3)$	Asymptotically stable point
8	$T_8(1,1,1)$	If $C_1 + P_1 < R_{12}, C_2 + P_2 > R_{22}$, $R_3 + P_1 + Q_1 + P_2 + Q_2 > C_3$, $\lambda_i < 0 (i = 1,2,3)$	Asymptotically stable point
9	$T(x_2^*, y_2^*, z^*)$	$\lambda_2 > 0, \lambda_3 > 0$	Unstable point

to the replication dynamic system (10) is shown as:

$$J = \begin{bmatrix} \frac{\partial H(x_2)}{\partial x_2} & \frac{\partial H(x_2)}{\partial y_2} & \frac{\partial H(x_2)}{\partial z} \\ \frac{\partial H(y_2)}{\partial x_2} & \frac{\partial H(y_2)}{\partial y_2} & \frac{\partial H(y_2)}{\partial z} \\ \frac{\partial H(z)}{\partial x_2} & \frac{\partial H(z)}{\partial y_2} & \frac{\partial H(z)}{\partial z} \end{bmatrix} \tag{12}$$

From the above analysis, we can conclude that there may be nine equilibrium points in the dynamic system. Taking point $T_1(0, 0, 0)$ as an example, we will discuss the condition that the system satisfies the asymptotic stability. Therefore, the Jacobian matrix of the dynamic system (10) at point $T_1(0, 0, 0)$ can be expressed as:

$$J_{T_1} = \begin{bmatrix} R_{12} - C_1 & 0 & 0 \\ 0 & -C_2 & 0 \\ 0 & 0 & R_3 - C_3 \end{bmatrix} \tag{13}$$

Obviously, the eigenvalues of matrix J_{T_1} are $\lambda_1 = R_{12} - C_1$, $\lambda_2 = -C_2$ and $\lambda_3 = R_3 - C_3$. If the parameters satisfy the conditions: $R_{12} < C_1, R_3 < C_3$, then all three eigenvalues are negative, and the point $T_1(0, 0, 0)$ is asymptotic stable locally. Under this condition, the strategies of netizens, media and the government are not to propagative negative public opinion, not to report negative public opinion and not to supervise, respectively. Similarly, the locally asymptotic stability and corresponding conditions of all equilibrium points are shown in Table 3.

In Table 3, according to theoretical analysis, in the tripartite game system including netizens, media and the government, there may exist six evolutionary equilibrium points, i.e., T_1, T_3, T_5, T_6, T_7, T_8. While it is worth noting that if the dynamic system is locally stable at point T_5 or T_6, we can conclude that the cost of the government's supervision strategy is greater than the sum of benefits and the government punishment for netizens and media. In other words, the dynamic system may converge to Pareto equilibrium only when the requirement for parameter are too strict. Considering the actual situation, the above parameter requirement cannot be satisfied, so the situations that T_5 and T_6 become asymptotically stable points are not considered in this paper. Besides, for the point T_1, i.e., netizens choose not to propagate negative public opinion, media choose not to report negative public opinion, and government choose not supervise, which is of no practical significance, this scenario is also not considered in our research. Overall, we specially focus on the three scenarios corresponding to the point T_3, T_7 and T_8.

IV. SIMULATION AND ANALYSIS

In order to further analyze the evolution process of the three stakeholders' strategy during the dynamic game system, we simulated the evolutionary path of behavior strategies of netizens, media and the government. Firstly, the discrete mathematical expression of the behavior strategy selection of the three participant can be concluded as Formula (14) by discretizing the above game model.

$$\begin{cases} \frac{dx_2(t)}{dt} \approx \frac{x_2(t + \Delta t) - x_2(t)}{\Delta t} \\ \frac{dy_2(t)}{dt} \approx \frac{y_2(t + \Delta t) - y_2(t)}{\Delta t} \\ \frac{dz(t)}{dt} \approx \frac{z(t + \Delta t) - z(t)}{\Delta t} \end{cases} \tag{14}$$

A. PARAMETER SETTINGS

During the simulation process, the initial time is 0 and the end time of evolution is 50. And the initial values of the three parties' strategy selection probability are set as: $[x_1, x_2, y_1, y_2, z] = [0.3, 0.4, 0.3, 0.4, 0.5]$. Besides, due to the complexity of this problem, it is difficult to obtain the relevant actual data directly, so the experimental parameters in the game model are determined mainly by the following three ways. Firstly, the actual survey data during the public opinion management process in Ref. [27], [28] and the quantitative analysis of relevant indicators of public opinion

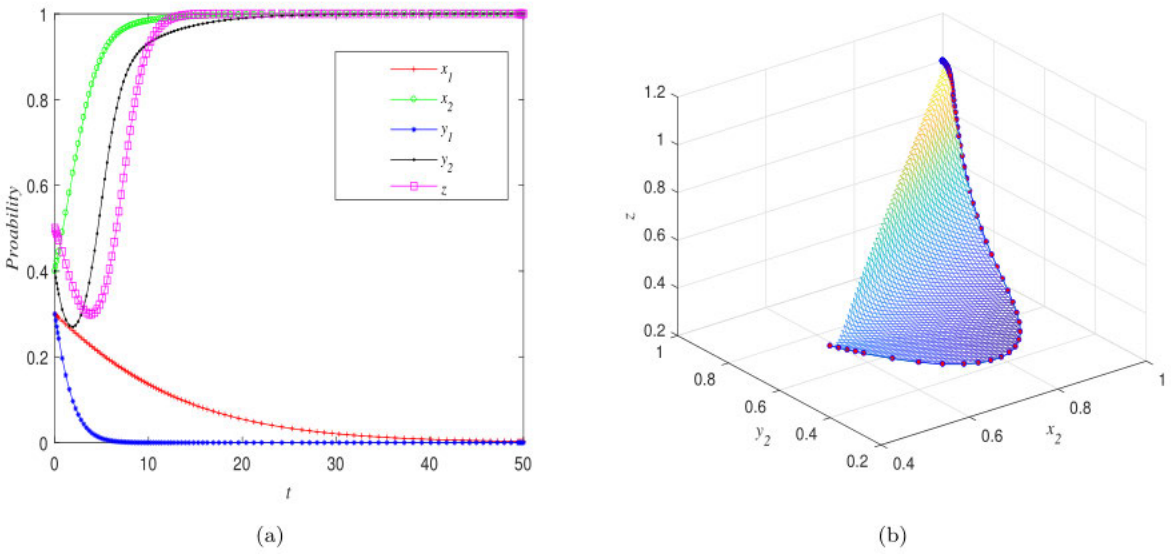

FIGURE 5. Scenario I: The trend diagram of tripartite game strategy evolution (Stable at Point $T_8(1, 1, 1)$).

evaluation in Ref. [29], [30] are referred. Then, in order to ensure the reliability and validity of the research conclusions, the relative quantitative relationships among the variables are consulted with 10 experts in the field. Lastly, we also consider the definitions and constrain conditions of relevant parameters proposed in Section 3, such as $R_{21} > R_{11}$, $R_{22} > R_{12}$, $C_2 > C_1$, etc. Above all, the main experimental parameters are set as:

$$\begin{aligned} R_{11} &= 0.4, \quad R_{12} = 1.2, \; C_1 = 0.5, \; P_1 = 0.5 \\ R_{21} &= 1.0, \quad R_{22} = 2.2, \; C_2 = 1.0, \; P_2 = 1.0 \\ R_3 &= 2.0, \quad C_3 = 1.5, \; Q_1 = 0.1, \; Q_2 = 0.3 \end{aligned} \tag{15}$$

B. SUPPRESSION OF NEGATIVE PUBLIC OPINION PROPAGATION

1) SCENARIO I

Under the experimental parameters set as Formula (15), the simulation results are shown in Figure 5. Figure 5(a) shows the changing trend of five probabilities (x_1, x_2, y_1, y_2, z) over time. As can be seen from Figure 5(a), as time goes on, the probability of netizens choosing to propagate positive public opinion tends to 0 ($x_1 \to 0$), and the probability of spreading negative public opinion tends to 1 ($x_2 \to 1$). And, $y_1 \to 0$, $y_2 \to 1$, $z \to 1$. In addition, we focus on the negative public opinion spreading behavior of netizens and the negative public opinion reporting behavior of media, therefore, Figure 5(b) reflects the motion trajectory of point (x_2, y_2, z) in three-dimensional space. It can be seen that the point (x_2, y_2, z) gradually tends to the point $(1, 1, 1)$ in three-dimensional space from the Figure 5(b).

In Formula (15), for netizens, the benefits of spreading positive public opinion are less than the cost ($R_{11} < C_1$), while the benefits of spreading negative public opinion are more than the sum of cost and punishment ($R_{12} > C_1 + P_1$). And for media, the benefits of reporting positive public opinion are not greater than the cost ($R_{21} = C_2$), while the benefits of reporting negative are more than the sum of cost and punishment ($R_{22} > C_2 + P_2$). While for the government, the benefits of choosing supervisory strategy are greater than the cost ($R_3 + P_1 + P_2 + Q_1 + Q_2 > C_3$). Therefore, during the process of the evolution of game strategy, the strategy choice of the tripartite game subject tends to the point $T_8(1, 1, 1)$ gradually.

For netizens and media, even though they may be punished by the government for spreading (reporting) negative public opinion, they are still more inclined to choose to propagate (report) negative public opinion when faced with hot social events with greater attraction due to the relatively low punishment intensity. Under this scenario, the government should adhere to the public opinion supervision strategy and strengthen the supervision of public opinion, especially for the negative public events with great social influence. In addition, more punishment should be imposed on netizens and media who spread (report) negative public opinion to further suppress their negative public opinion spreading (reporting) behavior.

2) SCENARIO II

From Formula (9-d), $\dfrac{\partial H(y_2)}{\partial P_2} < 0$, that is, as P_2 increases, $H(y_2)$ will gradually decreases, so does y_2 for $H(y_2) < 0$. In theory, with the increase of punishment for reporting negative public opinion by the government, the probability of media choosing to report negative public opinion gradually decreases. Therefore, on the basis of Formula (15), update $P_2 = 1.5$ and the other parameters remain unchanged. And the simulation results are shown in Figure 6.

As time goes on, $x_1 \to 0$, $x_2 \to 1$, $y_1 \to 0$, $y_2 \to 0$ and $z \to 1$, which are shown in Figure 6(a), and the point

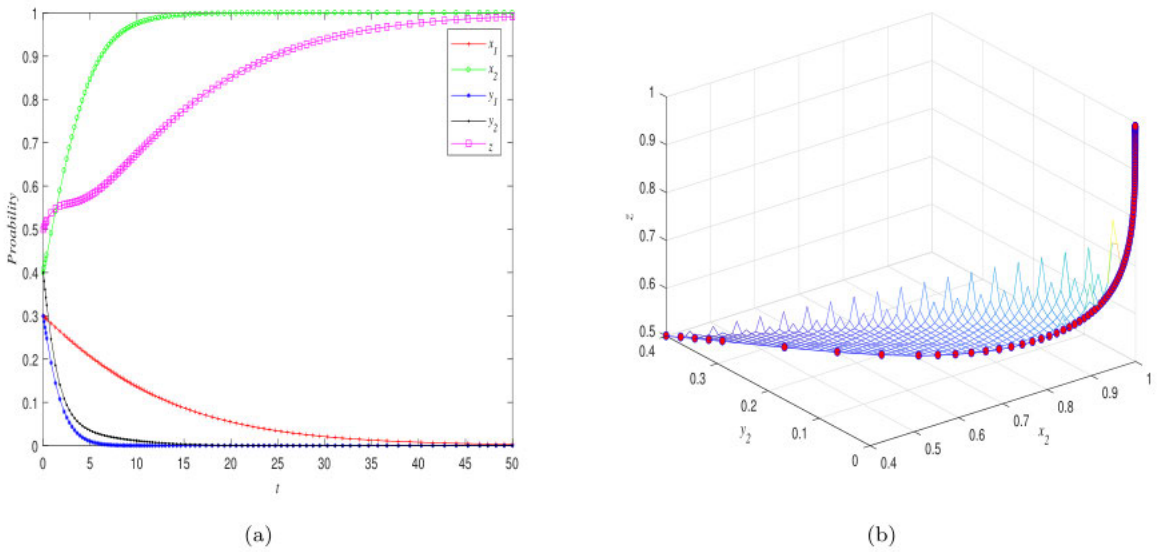

FIGURE 6. Scenario II: The trend diagram of tripartite game strategy evolution (Stable at Point $T_7(1, 0, 1)$).

(x_2, y_2, z) gradually tends to the point $(1, 0, 1)$ from the initial point shown in Figure 6(b).

At this moment, for media, the benefits of reporting negative public opinion are less than the sum of its cost and punishment ($R_{22} < C_2 + P_2$), therefore, they will not choose the strategy of reporting negative public opinion. Meanwhile, $R_{21} = C_2$, nor will they choose to report positive public opinion. Under this situation, even if media has to bear the loss of opportunity cost caused by failing to grasp the hot social events, they will still choose the "silence strategy" from the perspective of profit maximization. That is, they neither choose reporting positive public opinion, but also do not choose reporting negative public opinion. In addition, the strategy choice of netizens and the government is the same as that of Scenario I, which is no longer analyzed in detail. During this evolutionary game process, the strategy choice of netizens, media and the government gradually stabilizes at point $T_7(1, 0, 1)$, that is, compared with Scenario I, the government's control strategy for the propagation of negative public opinion is gradually playing a role.

3) SCENARIO III

According to Formula (9-b), $\frac{\partial H(x_2)}{\partial P_1} < 0$. Therefore, with the increasing of the punishment (P_1), the probability of netizens choosing to spread negative public opinion (x_2) gradually decreases for $H(x_2) < 0$. Then, on the basis of the above experiments (Scenario II), update $P_1 = 1.0$, and the other parameters remain unchanged. The simulation results are shown in Figure 7.

Obviously, as time goes on, both netizens and media will choose the strategy of not spreading (reporting) public opinion $(x_1 \to 0, x_2 \to 0, y_1 \to 0, y_2 \to 0)$, while the government still insists on the supervision strategy $(z \to 1)$, which is shown in Figure 7(a). And the point (x_2, y_2, z) gradually tends to the point $T_3(0, 0, 1)$ from the initial point in three-dimensional space.

Based on the above experiments, for netizens, the benefits of spreading negative public opinion will be less than the sum of costs and punishment if the government further increases the punishment for the propagation of negative public opinion to netizens ($R_{12} < C_1 + P_1$). Therefore, netizens will not choose to spread negative public opinion from the perspective of rational people. At this time, for the propagation of negative public opinion in OSN, the tripartite game system including netizens, media and government, has reached a more ideal state, that is, the point (x_2, y_2, z) gradually tends to the point $T_3(0, 0, 1)$. Meanwhile, under this scenario, owning to $R_{11} < C_1$, netizens will not choose to spread positive public opinion, that is, $x_1 \to 0$.

From the above analysis, it can be concluded that the government could restrain the wide spread of negative public opinion in OSN through regulating the punishment intensity on netizens and media for their negative public opinion spreading (reporting) behavior, so as to achieve the purpose of purifying the network space. It is worth noting that in the above two scenarios, although the governments' control strategy inhibits the negative public opinion spreading behavior of netizens and media, while their "silence strategy" should also attract our attention. Social media in particular, their "silence strategy" means a waste of public resources and a loss to society. So on the basis of suppressing the negative public opinion reporting behavior, how to promote their positive public opinion spreading behavior? That is the key question will be discussed in the next section.

C. PROMOTION OF POSITIVE PUBLIC OPINION PROPAGATION

1) SCENARIO IV

As can be seen in Formula (9-a), $\frac{\partial H(x_1)}{\partial R_{11}} > 0$, $\frac{\partial H(x_1)}{\partial C_1} < 0$. In other words, we can promote netizens' positive public opinion spreading behavior through increasing their benefits

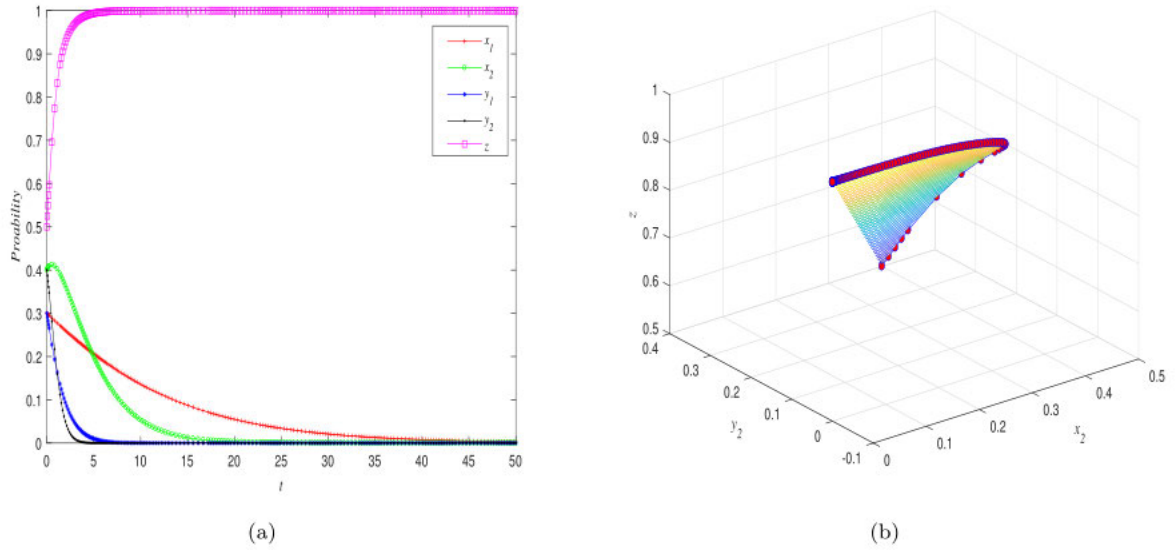

FIGURE 7. Scenario III: The trend diagram of tripartite game strategy evolution (Stable at Point $T_3(0, 0, 1)$).

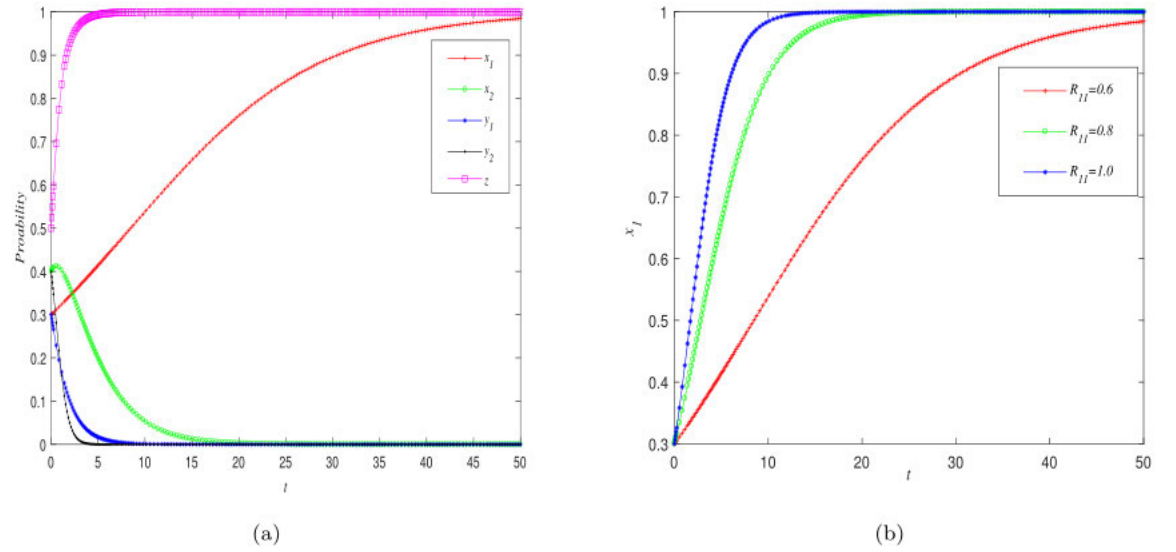

FIGURE 8. Scenario IV: The trend diagram of tripartite game strategy evolution.

(R_{11}) or reducing the cost (C_1). While, through the above analysis, it is found that the cost (C_1) affects both positive and negative public opinion spreading behavior of netizens. Therefore, in order to better control the netizens' public opinion spreading behavior, update $R_{11} = 0.6$ on the basis of Scenario III, and the other parameters remain unchanged. The simulation results are shown in Figure 8.

Different from Scenario III, under this situation, the probability of netizens choosing to spread positive public opinion gradually increases and stabilizes at 1, i.e., $x_1 \to 1$, which is shown in Figure 8. Right now, for netizens, the benefits of spreading positive public opinion are greater than their cost ($R_{11} > C_1$), and the benefits of spreading negative public opinion are less than the sum of cost and punishment ($R_{12} < C_1 + P_1$). Therefore, it promotes the netizens' positive public opinion spreading behavior, at the same time suppresses their negative public opinion spreading behavior effectively.

Besides, as can be seen in Figure 8-b, the larger R_{11} is, the faster the probability of netizens choosing to spreading positive public opinion stabilizes at 1. When other factors remain unchanged, compared with the netizens' cost of spreading public opinion, the higher the benefits of spreading positive public opinion, the stronger their willingness to spread positive public opinion.

2) SCENARIO V

As can be seen in Formula (9-c), in addition to their own benefits and cost of reporting positive public opinion, the media's positive public opinion reporting strategy will

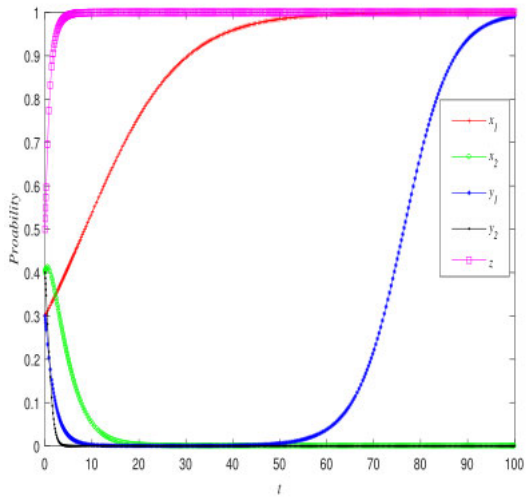

FIGURE 9. Scenario V: The trend diagram of tripartite game strategy evolution.

also be influenced by the netizens' positive public opinion spreading behavior, i.e., $\frac{\partial H(y_1)}{\partial x_1} > 0$. Similar to Scenario VI, as the cost affects both the media's positive and negative public opinion reporting strategy, update $R_{21} = 1.2$ based on Scenario IV, and the other parameters remain unchanged. The simulation results are shown in Figure 9.

As can be seen in Figure 9, the probability of media choosing to report positive public opinion (y_1) decreases at first ($t \leq 10$), and lasts for a period of time in $y_1 = 0$ ($10 < t \leq 50$), then increases over time ($60 < t \leq 100$) and finally stabilizes at 1 ($t > 100$). The above phenomenon can be explained from the following two aspects.

On one hand, from Formula (9-c): $H(y_1) = \frac{dy_1}{dt} = y_1 * (1 - y_1) * (x_1 R_{21} - C_1)$, it can be seen that when x_1 is small, there may be $H(y_1) < 0$ for $x_1 R_{21} - C_1 < 0$ even $R_{21} > C_1$, that is y_1 decreases over time. It should be noted that since $y_1 \geq 0$, so $y_1 = 0$ will last for a period time unless $H(y_1) > 0$ is guaranteed. Then, as x_1 increases, $H(y_1)$ is also increasing, and then $\frac{dy_1}{dt} > 0$, resulting in the improvement of y_1 over time and then tends to 1.

On the other hand, in practice, the benefits of media reporting public opinion are mainly from the advertising revenue brought by the netizens' subscription, reading, participation and propagation. That is to say, the media's benefits are closely related to the netizens' public opinion spreading behavior. When the probability of netizens spreading positive public opinion is small, the benefits of media are also small, which explains why, when x_1 is small, y_1 decreases and lasts $y_1 = 0$ for a period of time.

Under this situation, although the benefits of media reporting positive public opinion are greater then its cost ($R_{21} > C_2$), while in the early stage of the evolution of public opinion spreading, the probability of media choosing report positive public opinion decreases gradually, and the media even chooses "silence strategy" for a period of time ($y_1 = y_2 = 0$) as the probability of netizens spreading positive public opinion (x_1) is small.

In addition, in order to verify the above viewpoints, a set of comparative experiments are carried out in this section. On the basis of the scenario I, the experimental parameters are adjusted to $R_{11} > C_1, R_{21} < C_2$, and another set of parameters are set as $R_{11} < C_{11}, R_{21} > C_2$. The simulation results are shown in Figure 10-(a) and 10-(b), respectively.

As can be seen from Figure 10-(a), when the benefits of netizens spreading positive public opinion is greater than its cost ($R_{11} > C_1$), the probability of them choosing to spread positive public opinion tends to 1 ($x_1 \to 1$) gradually. While the benefits of media reporting positive public opinion is less than its cost ($R_{21} < C_2$), so the media will not continue to choose the strategy of reporting positive public opinion ($y_1 \to 0$), which is trivial.

Whereas, from the Figure 10-(b), if the benefits of netizens spreading positive public opinion are less than the cost ($R_{11} < C_1$), they will not spread positive public opinion any more in OSN ($x_1 \to 0$), from the perspective of rational person. But at this time, although the benefits of media reposting positive public opinion are more than the cost ($R_{21} > C_2$), the media will still choose the "silence strategy" ($y_1 \to 0$) as a result of the fact that the netizens do not spread public opinion in OSN.

From the above analysis, it can be concluded that the probability of media reporting positive public opinion is mainly affected by R_{21}, C_2 and x_1. Due to the complex impact mechanism of cost on media's behavior, in order to increase the probability of media reporting positive public opinion, we will analyze from the benefits of media reporting positive public opinion and the benefits of netizens spreading positive public opinion. Based on Scenario V, set $R_{21} = \{1.2, 1.4, 1.6\}$, $R_{11} = \{0.6, 0.8, 1.0\}$, respectively, while the remaining parameters remain unchanged. The simulation results are shown in Figure 11.

In Figure 11, on the whole, the probability of media reporting positive public opinion (y_1) tends to 1 at a faster speed through increasing the benefits of media reporting positive public opinion as well as the benefits of netizens spreading positive public opinion (R_{12} and R_{21}), which can effectively promote the positive public opinion reporting behavior of media. When $R_{12} > C_1$ and $R_{22} > C_2$, for media, the greater the benefits of reporting public opinion, the stronger their willingness to choose to report public opinion (Figure 11-a). Besides, the larger R_{11}, the stronger the will of netizens to spread positive public opinion, and then the media will choose reporting public opinion strategy more actively (Figure 11-b).

Besides, although the above two strategies can promote media's behavior of reporting positive public opinion significantly, while there are still some differences in the effects. In Figure 11-a, with the increase of R_{21}, y_1 tends to 1 at a faster speed, while there is no significant change in the minimum value of y_1 for $min(y_1) = 0$. That is to say, the media will still choose "silence strategy" for a period

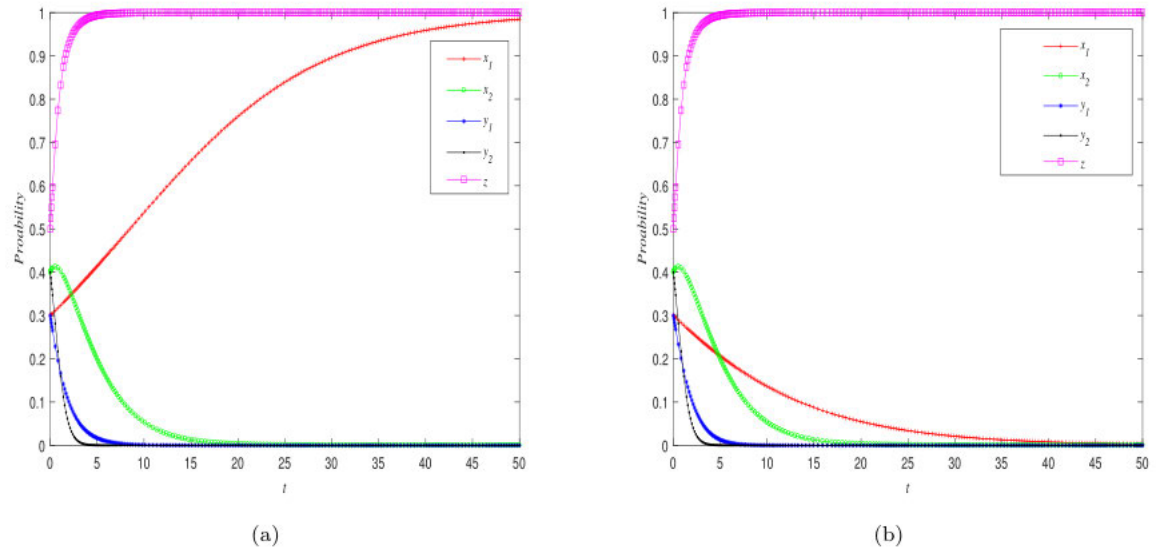

FIGURE 10. Comparative experiments results: (a) $R_{11} > C_1, R_{21} < C_2$; (b): $R_{11} < C_{11}, R_{21} > C_2$.

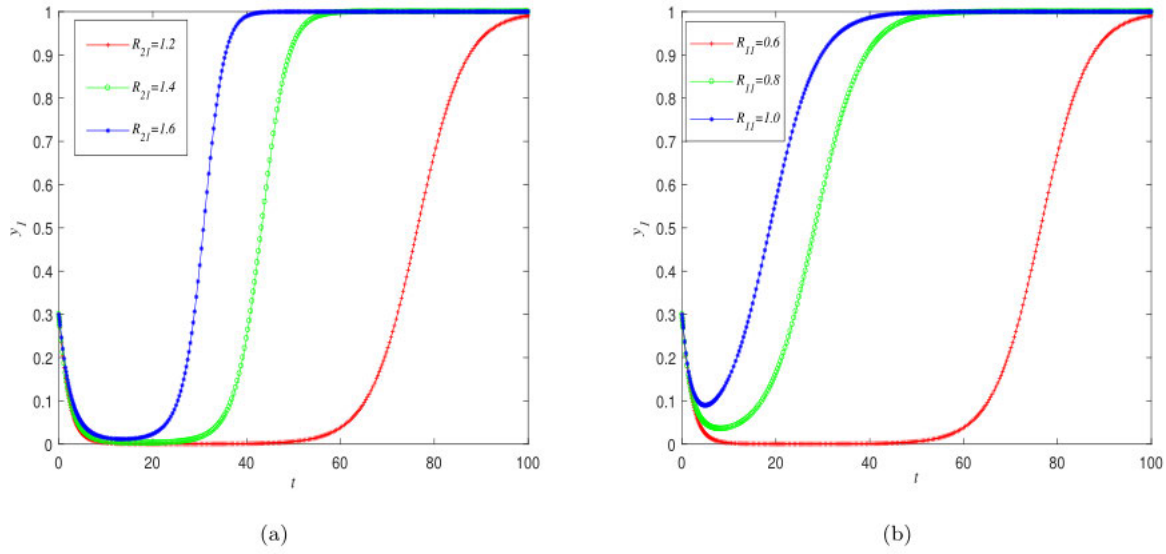

FIGURE 11. The effect of R_{21} (a) and R_{11} (b) on the probability of media reporting positive public opinion.

of time. While in Figure 11-b, with the increase of R_{11}, not only y_1 tends to 1 faster, but also the minimum value of y_1 is also increasing, which means that the media no longer choose the ''silence strategy''. From this experimental result, we can conclude that promoting the netizens' behavior of spreading positive public opinion is a more effective way to increase the probability of media reporting positive public opinion, under the condition that the benefits of media reporting public opinion are greater than their cost.

D. ANALYSIS OF PUBLIC OPINION CONTROL STRATEGY

Since the propagation process of public opinion involves many different stakeholders, from the above experimental results and analysis, it can be concluded that the key to manage and control public opinion in OSN lies in realizing the balance of interests among all stakeholders. In reality, the management and control of public opinion, that is, restricting the diffusion of negative public opinion, and then promoting the propagation of positive public opinion, should take the government as the main driving force, the media as the main body, and meet the needs of netizens. In addition, obviously, the main factors (variables) that influence the propagation of public opinion are the benefits and losses of netizens, media and the government. Then, regarding to the management and control of public opinion in OSN, we can start from the following aspects.

For netizens, when the benefits of spreading negative public opinion are greater than the sum of cost and punishment, netizens will choose to spread negative public opinion out of the need of social belonging. Therefore, on the one hand, the government should increase the punishment on netizens for their negative public opinion spreading behavior, especially the users with certain influence in the network. Once they are found to spread negative public opinion, delete their comments or log off their social accounts. Besides, the users who caused serious social consequences will be investigated for criminal responsibility according to law. On the other hand, for the positive public opinion, the government should encourage netizens to propagate them in OSN, and even can cooperate with social network platforms to push the positive public opinion to netizens for reducing their cost of collecting public opinion, or to give material rewards to users who actively spread the positive public opinion.

As a kind of commercial organization, the media tends to pay more attention to the reading amount of report information, the number of subscribers and other indicators under the stimulation of huge commercial profits, but pay less attention to the authenticity and the objectivity of the report information. In addition, due to information asymmetry, media's report will significantly affect the trend of public opinion in the whole society. Therefore, for the media's public opinion reporting behavior, on the one hand, the government should strengthen the monitoring of the media's reporting content, especially the authoritative media with powerful social influence. Once the negative public opinion reporting behavior is found, they will be penalized heavily, and the above actions should be supplemented by legal support. On the other hand, in terms of the promotion of positive public opinion, the government could provide necessary information sources to media, reduce the cost of collecting and tracking information, and promote their positive public opinion reporting behavior.

Lastly, as the main driving force of network public opinion management, in addition to the above means, the government should monitor the network public opinion at all times by combining big data and relevant technical means. Besides, the government could divide negative public opinion information into different levels according to the urgency of the event, and processed in priority order.

V. CONCLUSION

In the new media environment, the propagation of public opinion in OSN has attracted great concern by the government sector and academic community for its remarkable influence on social stability. Considering the existence of both positive and negative public opinion, we mainly analyzed the strategy selection of netizens, media and the government during the propagation process of public opinion, and a tripartite evolutionary game model was proposed based on evolutionary game theory. Then, the strategy selection conditions of the three stakeholders and the existence and stability of the equilibrium point of the whole game system were discussed respectively. In order to suppress the spread of negative public opinion, while promoting the propagation of positive public opinion, numerical simulations are introduced to discuss the key points of the government intervention and control of public opinion propagation. Finally, based on the experimental results and analysis, we put forward that the key to manage and control public opinion is to meet the benefit balance conditions of all stakeholders, and propose the management and control strategy of the government to deal with the propagation of public opinion in OSN from two key directions: benefits and punishment.

Actually, public opinion propagation in OSN is a very complex process, and there are many factors which influence the strategy selection of all stakeholders, such as the complexity of network structure, the diversity of netizens' attributes, the differences of propagation mechanisms and the disturbance of external environment. While, the tripartite evolutionary game model in this paper is still simplified to some extent, without considering all the factors. Besides, due to the limitations of survey data and experimental conditions, the setting of experimental parameters can only reflect part of the actual situation, and the experimental results lack the support of actual data, which will be the focus of follow-up research.

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