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Research on the Emergence of Herd Behavior of Tradable Green Certificate Transaction Subjects based on system dynamics

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ABSTRACT

The Tradable Green Certificate (TGC) system scientifically guides renewable energy investment by internalising the positive externalities of renewable electricity. With the promotion of energy transition, the demand for TGC has increased significantly, and the scale of market players has gradually expanded. Market players will imitate other players' trading strategies for reasons such as herd mentality, which is manifested as herd behaviour. If TGC market players ignore high-quality information and blindly imitate the behaviour of other players, it will limit the diffusion of effective information in the market and reduce the pricing efficiency of the market. Therefore, this paper explores the emergence law of herd behaviour in the TGC market based on a hybrid system dynamic model, with a view to providing theoretical and methodological support for the immediate identification of market risk. This paper portrays the emergence process of herd behaviour of TGC trading subjects, and analyses the emergence law through multi-scenario computational experiments. The results show that (1) herd behavior will emerge from all kinds of strategy subjects and there is a positive feedback relationship between the emergence speed and the return difference between subjects. (2) The emergence of herd behaviour of fundamental strategy subjects has scale and structural effects, and only when the initial imitation scale of such subjects reaches 40% or the market share is less than 50%, will the emergence of herd behaviour, and the depth of its emergence shows an 'S' type growth. (3) The herd mentality and the weakening of cognitive bias of TGC trading subjects will reduce the emergence speed of herd behaviour, but have almost no effect on the depth of emergence.

Keywords: Renewable energy, Tradable Green Certificate, herd behavior, system dynamics

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1. Introduction

Tradable green certificate (TGC) system is a market-based system in which a country or region mandates the market share of renewable energy generation in the form of policies and regulations [1]. TGCs are issued by a government-appointed issuer to eligible renewable energy power producers (RE producers) based on the amount of renewable energy feed-in electricity. The distribution companies (Discos) purchase TGCs in accordance with the quota targets and submit them to the regulator to fulfil their quota obligations. With the advancement of energy transition, the demand for TGCs has increased significantly, and the scale of market players has gradually expanded. Market players will imitate other players' trading strategies for reasons such as herd mentality, which is manifested as herd behavior [2-3]. In the TGC market, large vendors with resource advantages often have high-quality information to support their decisions, while small and medium-sized vendors will imitate the trading strategies of large vendors in order to save the cost of searching for information, thus contributing to the emergence of herd behavior [4]. If market players abandon fundamental information and blindly imitate the behavior of other players, it will hinder the diffusion of effective information in the market and reduce the pricing efficiency of the market. In order to avoid the emergence of irrational herd behavior, this paper studies the emergence law of herd behavior of TGC trading subjects based on system dynamics, with a view to providing theoretical and methodological support for regulators to scientifically guide the emergence of herd behavior and identify market risks [5].

Scholars believes that individuals are bonded rationality, and the formation of herd behavior is influenced by both rational and irrational factors [6-7]. Among them, rational factors include information asymmetry, reputation and remuneration [8-10], and irrational factors include herd mentality and cognitive bias [11-12]. In terms of information asymmetry, investors at information disadvantage will imitate other investors' decisions in order to save information search costs, which leads to herd behavior [13-15]. Based on this, Avery et al. and Cipriani et al. explored the asymmetry of information in the financial market from multiple dimensions and improved the herd learning model of the stock market accordingly to study the herd behavior of investors more specifically [16-17]. Ayoub and Balawi portrayed herd behavior based on heterogeneous information strategies and dynamic scale-free interpersonal networks, and showed that the lower the information precision, the more significant the level of herd behavior of the subject [18]. Gu et al. found that the emergence of herd behavior is followed by an informational cascade, and proved that imitation learning is an effective strategy in the sequential decision-making process [19]. In terms of reputation, subjects tend to mimic the behavior of more reputable subjects for cost-benefit reasons in order to reduce decision risk. Leece and White found that opaque information environments are more conducive for analysts to engage in reputational herd behavior, where more competent analysts take action first while less competent analysts choose to follow [20]. An et al. showed that if a credit rating agency's credit rating in the previous period diverges from other agencies, the agency tends to adjust to a rating that converges with other agencies for reputational reasons [21]. Shao et al. show that firms formulating information security management strategies mimic those of reputable firms for the cost-effectiveness of the program [22]. In terms of compensation structure, the compensation structure linked to benchmark returns tends to trigger herd behavior. Tian et al. argued that this compensation structure weakens incentives for institutional investors to give up private information and avoid making investment decisions that are different from others so as not to lag behind their peers in terms of performance [23]. Cheng Tianxiao et al. find that foreign institutional investors imitate domestic institutional investors based on reputation or incentives [24]. Yang et al.'s experimental results suggest that following the majority choice and giving up contrary private information reduces deviation from benchmarks and produces better rankings under conditions of limited information [25].

As far as irrational factors are concerned, the herd mentality inherent in bonded rational individuals motivates them to imitate and follow the decisions and choices of others [26-28]. Chen et al.'s survey study showed that under conditions of incomplete information about the product and the seller of the house, the herd mentality motivates buyers to produce herd behaviors in order to reduce the risk of the transaction. Cognitive bias is the phenomenon that when people perceive themselves, others or the external environment, the results of perception are often distorted due to their own or situational reasons [29]. Kienzler argues that the limited cognitive resources of an individual lead to the adoption of an investment strategy that is consistent with the behaviors of others in order to save the cost of information collection and processing [30]. Battaglio et al.'s study shows that when certain salient information attracts attention, market participants ignore other information or even private information, which manifests itself as consistency in investment decisions when forming expectations and generating behavioral choices [31]. Most of the above literature proves the correlation between relevant factors and herd behavior through empirical evidence or research, and lacks a quantitative and in-depth exploration of the driving mechanism. Therefore, this paper explores the formation mechanism of herd behavior of TGC trading subjects by combining the generation mechanism of herd behavior with the characteristics of the behavior of TGC market trading subjects. In view of this, this paper makes the following innovations:

1) At present, there are few studies on the emergence of herd behavior of TGC trading subjects, and the emergence studies in other fields are also based on qualitative analysis, lacking in-depth quantitative analysis. This paper innovatively applies system dynamics to the study of herd behavior of TGC trading subjects, quantitatively researches the emergence law of herd behavior, expands the application field of system theory, and also provides theoretical support for market regulators to take measures to avoid market risks.

2) This paper innovatively proposes a multi-stage herd behavior emergence paradigm of “individual behavior generation - group behavior generation - herd behavior emergence”, and constructs a fusion model of herd behavior emergence of TGC trading subjects with multi-layer nested relationships, expanding the methodology for studying the causes of herd behavior formation in complexed system. The model provides a practical basis for the government to grasp the behavioral dynamics of trading entities according to the market environment and take timely measures to guide the behavior of market entities.

2. The emergence mechanism of TGC trading subjects’ herd behavior

The emergence of herd behavior of TGC trading subjects is the process of transforming the TGC market, a complex adaptive system, from chaos to order, and the trading subjects form orderly behavioral rules and social networks by imitating each other's self-organized behavior, as shown in Figure 1. This paper divides the emergence process of herd behavior into three stages: individual behavior generation, group behavior generation and herd behavior emergence. System science research has shown that emergence is generated when the system parameters are at a critical point and stochastic events are reinforced under the positive feedback mechanism of the system [32]. Therefore, the conditions for the emergence of herd behavior in the TGC market include system parameters at critical values, stochastic events, and positive feedback mechanisms caused by nonlinear relationships, which gradually drive the emergence of herd behavior.

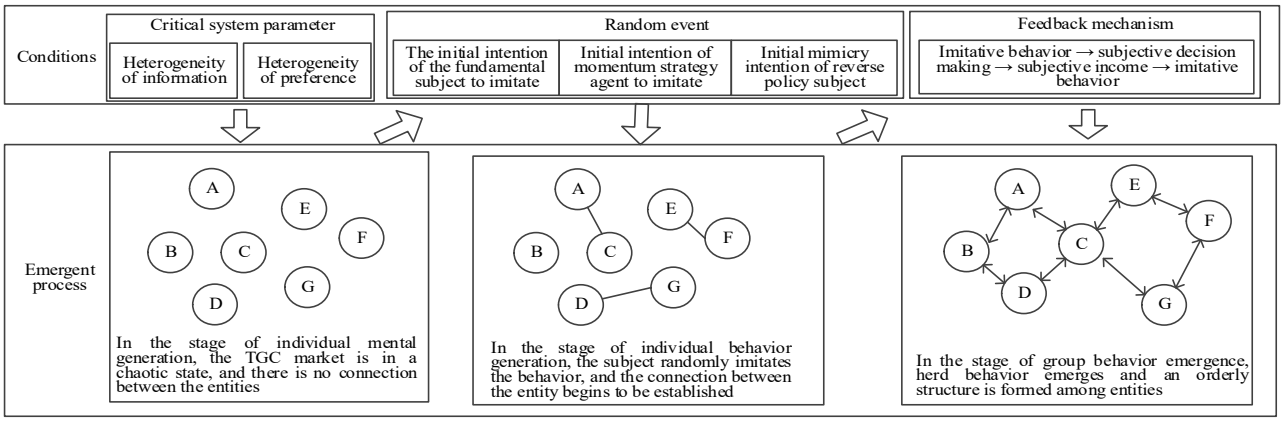


Fig. 1. Emergence mechanism of herding behavior of green certificate trading subjects

In the stage of individual behavior generation, the TGC market is in the early stage of operation, the market is in a chaotic state, and the trading subjects are still unconnected with each other as independent individuals. Due to incomplete information, the subject of the transaction is unfamiliar with the trading rules of TGCs, and gradually understands and learns the market rules to form its own mind. The mind of the subject of TGC trading consists of four parts: storage element, knowledge element, matter element and adaptive element [33], the individual behavior is subject to the constraints and incentives of the TGC trading system, the system is internalized into the individual's mind, and the adaptive adjustment of the mind is externalized into the rules. TGC trading system as the input rules of the mental model, internalized into the subject's cognition through the knowledge element and the storage element, generating the matter element containing imitation or non-imitation, the adaptive subject out of the criterion of maximizing the benefits through the appropriate element and other subjects interact with the learning, and continuously adjusted through the adaptive behavior. At the stage of group behavior generation, the initial imitation willingness of transactional subjects is a key system parameter that influences the emergence of herd behavior. Moreover, since the benefit gap caused by heterogeneous information and beliefs will lead to the reinforcement of the subject's willingness to imitate, the heterogeneity of information and beliefs is also a key system parameter affecting the emergence of herd behavior [34]. As a result, when the initial proportion of TGC trading subjects adopting imitation behavior and the heterogeneity of information and beliefs are in a critical state, it will lead to the enhancement or decline of the earnings of the subjects adopting imitation behavior, thus forming a feedback mechanism of imitation behavior and earnings. At the stage of emergence of herd behavior, the herd behavior of TGC trading subjects under institutional constraints is driven by the feedback mechanism of “imitation behavior - subject decision-making - market supply and demand - TGC price - subject gain - imitation behavior”. Under the influence of herd mentality and cognitive bias, the subject in information disadvantage obtains high-quality information by communicating with the subject with information advantage. With the accumulation of knowledge and experience, the subject self-organization generates imitation behavior, so that the system macro emerges herd behavior, TGC market from chaos gradually transformed into order [35].

3. Methodology

3.1. Model description and assumptions

TGC trading subjects include RE producers on the supply side of market and Discos on the demand side, and both supply and demand sides have herd behavior. Due to the similarity of the decision-making mechanism between the two sides, this paper takes the behavior of Discos in the TGC market as the object of research to explore the emergence law of herd behavior of trading subjects [36]. In the stage of individual behavior generation, exogenous factors and endogenous factors jointly influence

the subject's mind and produce individual behaviors of imitation or non-imitation. In the group behavior generation stage, individuals who make imitation behaviors learn from each other and imitate trading strategies. In each round of trading, Discos make behavioral decisions based on public information, private information, and neighbor (two interacting subjects are each other's neighbors) information [37]. In the emergence stage of herd behavior, group imitation behavior becomes a relatively stable behavioral choice of the group and spreads in the group. There will be a certain proportion of individuals in the group to choose imitation behavior, but as the transaction is carried out, all kinds of strategic subjects of the revenue gap is gradually reflected, the proportion of subjects in the group to take imitation behavior will change.

In order to construct the herd behavior model of TGC market, this paper makes the following assumptions:

1) This paper assumes that the herd behavior of trading subjects is a bonded rationality herd behavior, and individuals imitate the strategic behavior of other subjects out of revenue externality to enhance their own benefits.

2) It is assumed that green power is homogeneous, and the difference in the number of TGCs exchanged for heterogeneous renewable energy generation is not considered.

3) Assume that the validity period of TGCs is infinitely long. In the early stage of the establishment of the TGC market, not setting a deadline for TGCs is conducive to incentivizing Discos and green power manufacturers to adopt the strategy of trading TGCs, thus promoting the establishment of the TGC market.

3.2. Herd behavior's emergence model in TGC market

In this paper, we comprehensively use the mental model, the Constrained Generating Procedure Model (CGP) and the system dynamics model to construct a model for the emergence of herd behavior in the TGC market, as shown in Figure 2 below.

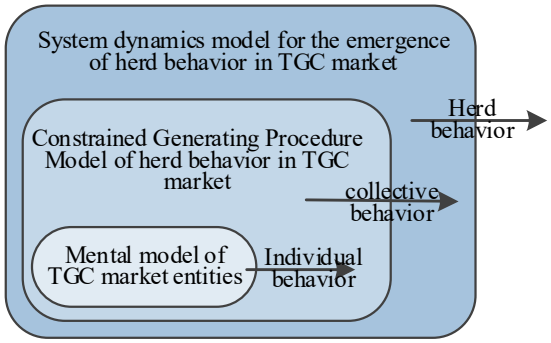


Fig. 2. Herd behavior emergence model structure of TGC market

1) Individual Behavior Generation. Mental model is an internally conceptualized representation of an external system, where social structures are embodied as opportunities or constraints that motivate individuals to act, or constrain them from acting. Individual actions internalize social structures into cognitive and decision-making rules. The TGC trading system, as the input rules of the mental model, is internalized into the subject's cognition through the knowledge and storage elements, and generates the matter elements containing imitation or non-imitation, and the adaptive subject learns through the interaction with other subjects through the appropriate elements out of the criterion of maximizing interests, and continuously adjusts through adaptive behaviors, and externalizes into the mandatory constraints and informal rules of the TGC trading system, as shown in Figure 3.

This paper constructs a mental model of TGC market subjects based on McComb's three-stage mental model [38], which contains three stages of orientation, differentiation and integration, as described below.

(1) Orientation stage: In this stage, the subjects search and store the fundamental information from macro to micro such as the arrangement of the TGC trading system, ijithe development of the renewable energy industry, and the trading rules of the TGC market through the storage element, and communicate with each other. This process is the induction process of the subsequent group imitative behavior, i.e., herd behavior, in which information in the form of beliefs, knowledge, and strategies is spread among all members. The inputs to the mental model of TGC trading subjects are TGC trading institutional arrangements, TGC market information, individual beliefs and memory periods, so that the set of inputs of the first subject is shown in Equation (1).

$$I_j = \left\{ i_{j1}, i_{j2}, i_{j3}, \cdots \right\} \tag{1}$$

where $i_{jh} - j$ may take values in the h th input.

Then, the inputs to the mental model can be defined as the Cartesian product of the individual inputs:

$$I = I_1 \times I_2 \times \cdots \times I_k \tag{2}$$

where k - the number of input parameters of the mental model.

(2) Differentiation stage: in this stage, the subject of TGC trading synthesizes personal information and information from others to form the individual's mental model that governs its behavior. The subject processes the information collected in the orientation stage, and the core mechanism for the subject to process the information is the subject's beliefs, i.e., the subject converts the information into a mental model of the expectation of the price of TGCs, Chiarella et al. [39] argued that the investor has a mixture of beliefs, including: fundamentals, technicals, and noise, and that the formation of the final expectation is determined by a combination of the three beliefs. Subjects realize the differences in information acquisition with other subjects through interaction and decide whether to imitate or not, which in turn form their own expectations of the price of TGCs and make trading decisions. The subject's output of imitating or not imitating is the individual's state, as shown in Equation (3).

$$S = \left\{ s_1, s_2 \right\} \left(s_1 = 1, s_2 = 0 \right) \tag{3}$$

where s_1 -- Imitative behavior is practiced;

s_2 -- non-imitation behavior.

(3) Integration stage: this stage of the subject of the differences in mental interaction, through the “appropriate meta” adaptive learning other subjects' strategies and adjust their own behavior (imitation or non-imitation). TGC trading subject according to the previous stage of the decision-making results of the comparison between the subject of the benefit gap, if the subject of the previous stage of the “non-imitation” behavior led to its benefit is lower than the subject of the imitation behavior, then this stage of the subject's behavior to imitate the probability will increase, and vice versa. This stage is the conversion process of individual modification of their own mental model, through mutual imitation to realize the sharing of information in the group, then the conversion function of the subject's state can be defined as formula (4).

$$f : I \times S \to S \tag{4}$$

$$\begin{aligned} S(t+1) &= f(I_1(t), I_2(t), \cdots, I_k(t), S(t)) \\ &= \begin{cases} s_1, \text{if } \mathrm{R}_{im} > \mathrm{R}_{un} \\ s_2, \text{if } \mathrm{R}_{im} < \mathrm{R}_{un} \end{cases} \end{aligned} \tag{5}$$

$$\mathrm{R}_{im} = P_{TGC} \left[(1 - \varepsilon_L) Q_O + \varepsilon_L Q_N \right] \tag{6}$$

where f -- state transition function;

P_{TGC} -- TGC price;

ε_L -- mimicry probability;

Q_O -- TGC trading subject's own decision;

Q_N -- Decision-making of other subjects;

R_{im} -- Benefits of adopting imitation behavior.

2) Group Behavior Generation. In this paper, we use Constrained Generating Procedure Model (CGP model) to extend the above mental model, and portray the process of group imitation behavior at the level of group behavior. A TGC trading individual observes the behavior of other subjects in the neighborhood, and if it imitates the decisions of other subjects, it means that the decisions of other subjects are the "input" variables of the individual's mental model, which influences the individual's decisions. Mimicry creates connections between subjects to form a network. Let be a small set of individual minds in the individual domain, defined by the transition function, then extend the dimensions of the input set and state set in Eqs. (7) and (8). Since there are multiple heterogeneous subjects in the market for TGCs, the inputs from neighbors to individual minds can be viewed as mixed strategies containing the strategies of heterogeneous subjects in the market, then

$$I_h = I_{h1} \times I_{h2} \times \cdots \times I_{hk(h)} \tag{7}$$

where I_h - the set of inputs to the individual mental model;

$k(h)$ - the number of inputs to the mechanism.

$$S_h = \{s_{h1}, s_{h2}, s_{h3}, \cdots\} \tag{8}$$

where S_h - the set of states of the population within F.

After the extension, the transformation function of an individual can be expressed as:

$$f_h : I_h \times S_h \to S_h \tag{9}$$

In this way, subject h to-subject l mimicry relationships can be defined by correlation function:

$$g_{lj} : S \to I_{lj} \tag{10}$$

That is, at any moment, if individual h adopts imitation behavior that makes its earnings increase, then the probability that individual l adopts imitation behavior will also increase after observing this information, so the connection relationship between individual h and the first input of individual l can be expressed as follows:

$$\begin{aligned} I_{lj}(t) &= g_{lj}(S_h(t)) \\ &= \begin{cases} (1+\chi) I_{lj}(t) \text{ if } \mathrm{R}_h(S_h(t)) > \mathrm{R}_h(S_h(t-1)) \\ (1-\chi) I_{lj}(t) \text{ if } \mathrm{R}_h(S_h(t)) < \mathrm{R}_h(S_h(t-1)) \end{cases} \end{aligned} \tag{11}$$

where χ - the unit value of the increase in the probability of an individual imitating;

$\mathrm{R}_h(S_h(t))$ - the gain of an individual whose state at the moment is.

The imitation behavior of individuals forms high-level herd behavior through the combination of interacting minds (mechanisms). Assuming that the main body of the TGC transaction consists of n individuals, the state set consists of the Cartesian product of the individual state of mind, as shown in Equation (12), and the proportion of 'imitation' state in the state set is the depth of the emergence of herd behavior, as shown in Equation (13).

$$S_c = \prod_j S_j = S_1 \times S_2 \times \cdots \times S_n \tag{12}$$

$$HD_c = D(S_c) = \sum S / n \tag{13}$$

where HD_c - depth of emergence of herd behavior;

C - the subject of the colour certificate transaction.

The input set of a mechanism is the concatenation of the input sets of all individual minds, and for one of these mechanisms, its input set can consist of two parts, i.e., the set of free inputs $I_{x,free}$ and the set of inputs associated with the minds of other individuals $I_{x,com}$ in the mechanism. However, for the input set I_c, since the elements in $I_{x,com}$ are associated with several of the individual minds, their values depend on the states of the other individual minds, which are part of the global set of states, the elements in $I_{x,com}$ can be determined by a function representing the information obtained by the trading individual from observing the states of the other subjects.

$$g_x : S_c \to I_{x,com} \tag{14}$$

For the mind of an individual belonging to C, the transformation function is

$$f_x : I_{x,free} \times I_{x,com} \times S_x \to S_x \tag{15}$$

Since S_x is a component of S_c. it follows that there exists a function (15) that expresses the transformation function of an individual's mind.

$$f_x' : I_{x,free} \times S_c \to S_c \tag{16}$$

From the above analysis, it can be concluded that the set of C's inputs is composed only of the set of free inputs $I_{x,free}$, the set of inputs to the pairs can be defined as

$$I_c = I_{1,free} \times I_{2,free} \times \cdots \times I_{n,free} \tag{17}$$

On the basis of the above analysis, the transformation function for macro emergent herd behavior is defined as:

$$f_c : I_c \times S_c \to S_c \tag{18}$$

Then the depth of emergence of herd behavior is shown in Equation (19).

$$\begin{aligned} S_c(t+1) &= f_c(I_c(t), S_c(t)) \\ &= \left[f_1'(I_{1,free}(t), S_c(t)), f_2'(I_{2,free}(t), S_c(t)), \cdots, f_n'(I_{n,free}(t), S_c(t)) \right] \\ &= S_C(0) + \int \delta \cdot \Delta R_C \cdot dt \end{aligned} \tag{19}$$

where C - the heterogeneous group in the TGC market containing fundamental, momentum and contrarian strategy subjects;

ΔR_C - the difference between the returns of subjects in group C who take imitation behavior and those who take no imitation behavior;

δ - the coefficient of adjustment for the level of herd behavior.

3) Emergence of herd behavior. The emergence of herd behavior is an interactive process between the subject and the environment. Therefore, this paper explores the emergence law of herd behavior by constructing a system dynamics model of the emergence of herd behavior of TGC trading subjects, portraying the feedback mechanism between herd behavior and the environment at the macro level, and embedding the process of generating herd behavior portrayed by CGP. According to Chiarella et al.'s delineation of trading subjects' beliefs [39], Discos contain fundamental strategy groups (hereafter denoted by F groups), momentum strategy groups (hereafter denoted by M groups) and contrarian strategy groups (hereafter denoted by C groups), and FH and FN respectively represent the

fundamental strategy subjects that imitate and do not imitate neighbor decisions, and MH, MN, CH and CN are the same. The causal loop diagram of their herd behaviors is shown in Figure 3.

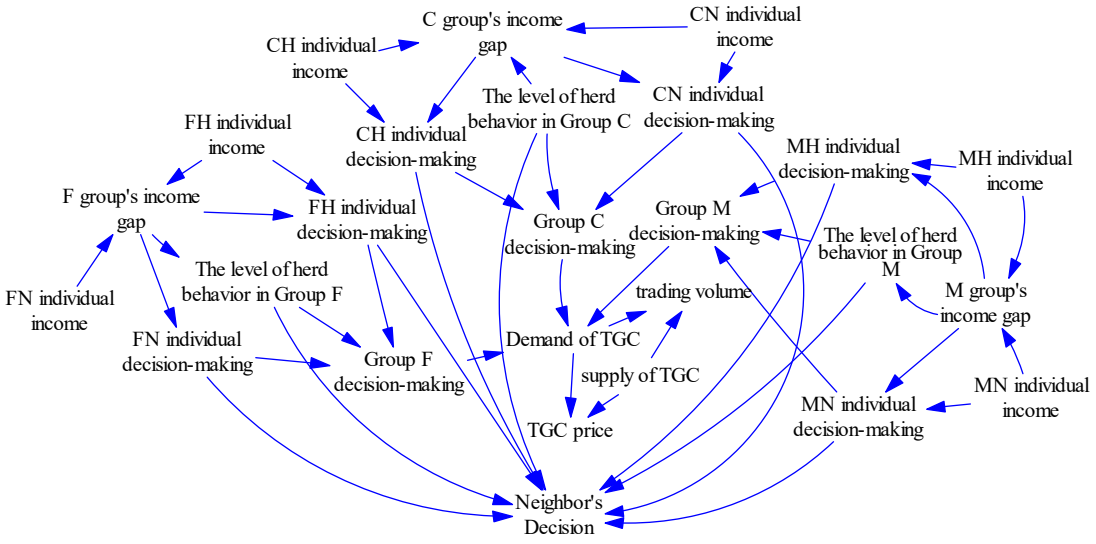


Fig. 3. Causal loop diagram considering the effect of strategic preference on herd behavior

Through their own information searching channels, TGC trading subjects grasp market information affecting the value of TGCs, and judge the value and price trend of TGCs accordingly. As the demand side of TGCs, the quota subject does not necessarily have accurate information about the production cost and consumption cost of renewable energy related to the value of TGCs, and its bonded rationality will also drive it to exchange the information with other subjects and imitate the strategies of other subjects. However, if the accuracy of the information held by some trading subjects is not as accurate as their own information, then after imitating the strategies of other subjects, their returns will decrease, and the subject will not adopt the imitation strategy in the next period. It can be seen that the Discos face the behavioral choice of {imitation, not imitation}, when the proportion of subjects choosing "imitation" behavior increases, the herd behavior gradually emerges. The value of TGCs is represented by the environmental premium of green electricity, which gradually decreases with the progress of renewable energy technology. The price of TGCs is determined by supply and demand, and after each round of market clearing, a uniform trading price and trading volume are generated, and the Discos measure their respective revenues according to the actual trading volume. In the next round of trading, the subjects update their strategies based on the returns from the previous round, and the proportion of subjects adopting imitation strategies in the quota group of low-quality and high-quality information varies according to the difference in returns between subjects adopting imitation strategies and subjects not adopting imitation strategies. Some of the core formulas and variable explanations in this model are shown in Equations (20)-(28).

$$Q_{FH} = (1-\varepsilon_F)\cdot Q_{Ben}\cdot\left[(V-P_{TGC})\cdot\alpha+1\right]+\varepsilon_F\cdot Q_N \tag{20}$$

$$Q_{FN} = Q_{Ben}\cdot\left[(V-P_{TGC})\cdot\alpha+1\right] \tag{21}$$

$$F_P = F_0+\int\delta\cdot\Delta R_F\cdot dt \tag{22}$$

$$q_s = \frac{p_{TGC}}{p_0}\cdot q_{rh} \tag{23}$$

$$q_{rh} = \int\left(q_{iss}-q_{TGC}\right)dt \tag{24}$$

$$q_{ch} = \int \left(q_{TGC} - q_{tur} \right) dt \tag{25}$$

$$q_{tur} = MIN(q^a, q_{TGC} + q_{ch}) \tag{26}$$

$$p_{TGC} = p_0 + \int q_{flu} \cdot dt \tag{27}$$

$$\mathrm{p}_{flu} = q_{od} \cdot p_{TGC} / t_{adj} \cdot h \tag{28}$$

where Q_{FH} -- the expected purchase volume of the subject of the fundamental strategy who chooses to imitate the behavior;

Q_{FN} -- the expected purchase volume of the subjects of fundamental strategies that choose not to imitate the behavior;

ε_F -- the imitation coefficient of the quota subject of the fundamental strategy;

α -- sensitivity coefficient of the subject of the quota for the fundamental strategy;

V -- Value of TGCs;

F_P -- Depth of emergence of herd behavior of Discos of fundamental strategies;

F_0 -- Initial percentage of herd behavior of Discos of fundamental strategies;

ΔR_F -- Return differential between FH subjects and FN subjects;

δ --Factor for adjusting the level of herd behavior.

q_{iss} -- TGCs issued by the government to green power manufacturers;

q_{rh} -- TGCs held by green power manufacturers;

q_{tur} -- TGCs surrendered by Discos;

q_s , q_d -- Supply and demand of TGCs;

q_{od} -- Excess demand for TGCs;

t_{adj} -- Timing of TGC price adjustments;

p_{flu} -- TGC price volatility;

k , h - economic parameters.

4. Simulation and Results

4.1. Experimental design

Based on the constructed system dynamics model of herd behavior emergence, this paper designs multi-scenario computational experiments, and explores the emergence law of herd behavior of various subjects by simulating the emergence process of herd behavior under multiple scenarios in Vensim software. In this paper, the data of China's renewable energy industry development is selected to simulate the emergence process of herd behavior at the early stage of TGC trading, and the initial values and sources of each parameter are shown in Table 1. We firstly design a baseline scenario to analyze the dynamics of the emergence of herd behavior of various TGC trading subjects; then we adjust the system parameters to analyze the scale and structural effects of the emergence in terms of the initial imitation scale of the trading subjects and the heterogeneity of their beliefs (the parameter settings are shown in Table 2 and Table 3); and finally, we explore the effects of the herd mentality, the value information coefficient and the price trend sensitivity coefficient on the herd behavior through sensitivity analyses. Finally, through sensitivity analysis, we investigate the influence of herd mentality, value information coefficient and price trend sensitivity coefficient on the emergence process of herd behavior (the parameter settings are shown in Table 4 and Table 5).

Table 1. Initial value of each parameter

Parameters	Value	Unit	Source

RPS Quota Monthly Growth Rate	0.005697	%	China Energy Outlook 2030
Monthly growth rate of electricity demand	0.0022	%	China Energy Outlook 2030
Renewable energy generation in the base period	2.04×10^9	MWh	China Statistical Yearbook 2019
Monthly growth rate of renewable energy generation	0.0079	%	China Energy Outlook 2030
Penalty	100	yuan	Ref. [40]
Adjustment time for TGC price fluctuations	2	day	Ref. [41]

Table 2. The initial imitation intention of three types of strategic subjects

Scenario	Fundamental strategy	Momentum strategy	Contrarian strategy
Benchmark	0.5	0.5	0.5
1	0.3	0.5	0.5
2	0.5	0.5	0.3
3	0.5	0.3	0.5
4	0.4	0.5	0.5

Table 3. Ratio of the number of three types of strategic subjects

Scenario	F:M:C
Benchmark	1:1:1
5	2:1:1
6	1:2:1
7	1:1:2

Table 4. Imitation coefficients of three types of strategic in the context of information asymmetry

Scenario	Fundamental strategy	Momentum strategy	Contrarian strategy
Benchmark	0.5	0.5	0.5
8	0.3	0.5	0.5
9	0.5	0.3	0.5
10	0.5	0.5	0.3

Table 5. The information sensitivity coefficient of three types of subjects

Scenario	Price trend sensitivity factor
Benchmark	1
11	1.5
12	0.5

4.2. Results

1) Validity test. In this paper, the validity of the model is firstly verified based on the results of the benchmark scenario. According to the Werker-Brenner method [42] for validation of computational experimental model validity, this paper takes China's TGC market as an example, and verifies the validity of the model through the comparison of the computational experimental results with the actual worth. According to the transaction data of China's green power certificate subscription trading platform, the price of parity TGCs is RMB 33-50/MWh, and the actual and simulated values of the TGC price are shown in Figure 4, which shows that the deviation between the simulated value and the actual value is less than 5%, and the validity of the model can be verified.

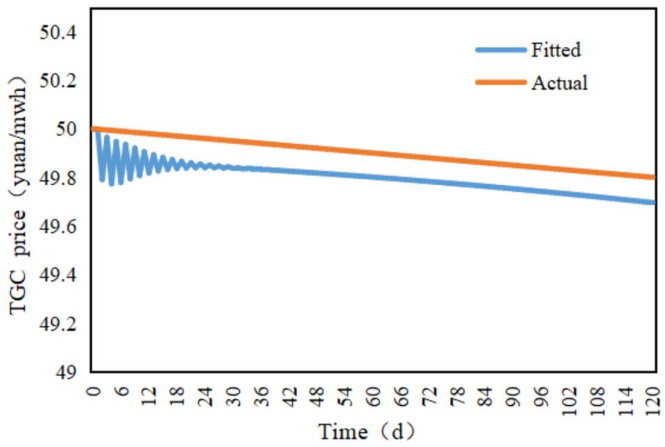
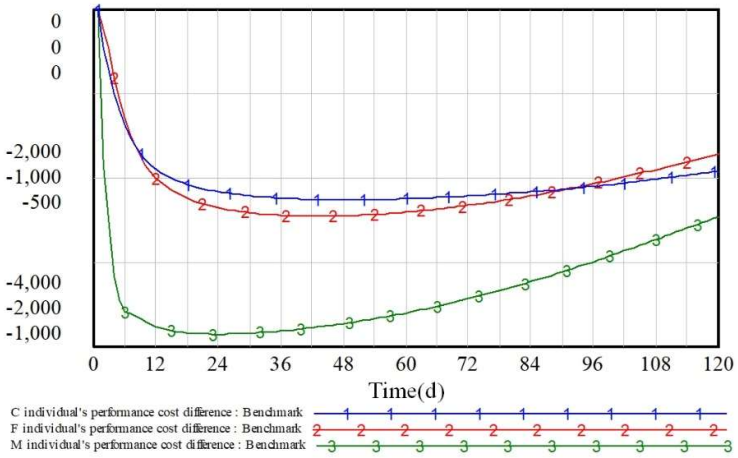


Fig. 4. Comparison between simulated value and actual value of TGC price

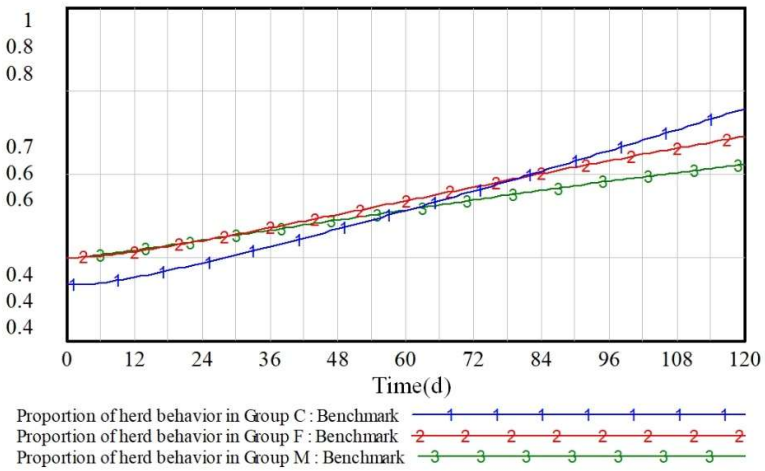
2) Dynamic Characteristics of Herd Behavior Emergence. Under the baseline scenario, the depth of emergence of herd behavior emergence (the proportion of subjects adopting imitation behavior), the

cost of compliance, and the market price of TGCs for each type of subject emergence are shown in Figures 5. Due to the herd mentality, trading subjects will imitate the strategies of others to a certain extent in the initial state, therefore, this paper assesses the level of emergent herd behavior based on the value of the proportion of herd behavior relative to the initial state.

As can be seen in Figure 5, the subjects of fundamental strategies, momentum strategies and contrarian strategies all exhibit herd behavior, and do so at a similar rate. The performance cost of subjects adopting imitation strategies is lower than that of subjects adopting non-imitation strategies, and all three types of subjects can reduce the performance cost through imitation strategies, so it can be seen that their strategies can be further optimised through the emergence of herd behavior. Subjects adopting imitation behavior have more accurate price expectations, so they buy fewer certificates when the actual price is higher and more certificates when the actual price is lower, so the average compliance cost is lower than that of subjects who do not adopt imitation behavior, which leads to the further spread of imitation behavior in the group, and this positive feedback mechanism drives the emergence of herd behavior.



(a) Return difference in each group

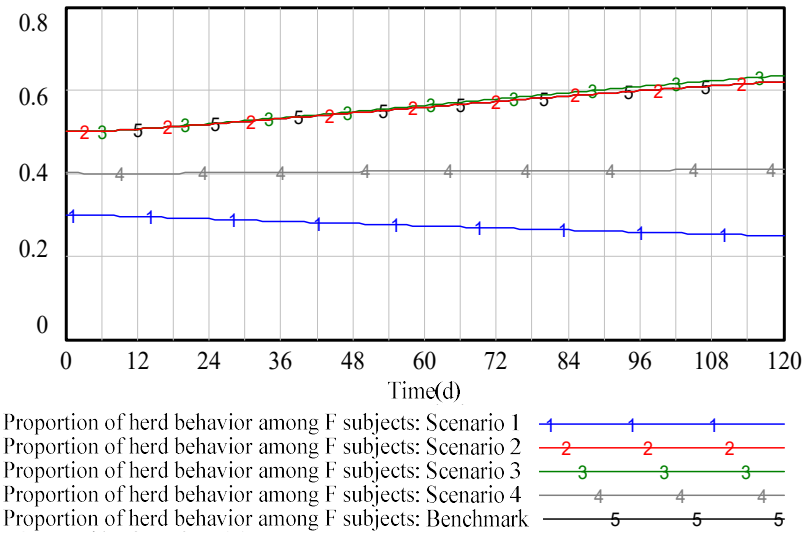


(b) The emergence level of herd behavior of subjects

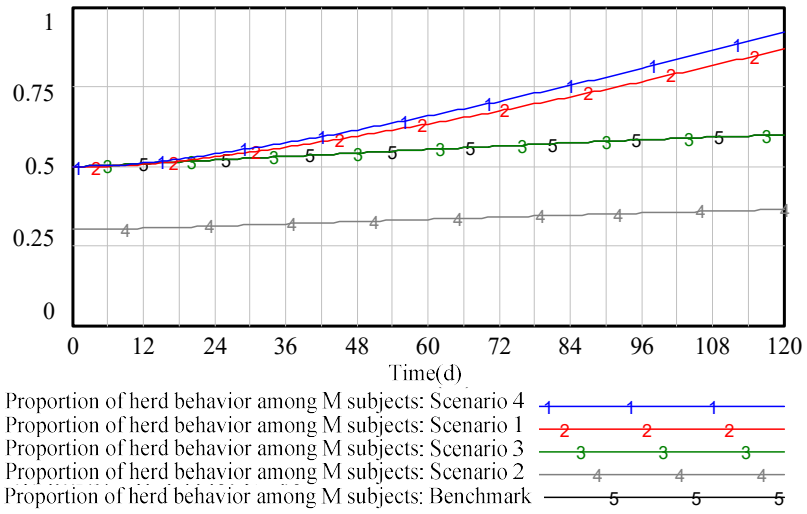
Fig. 5. Results of benchmark scenario

3) The scale effect of the emergence of herd behavior. The scale effect refers to the size of the subject in the system affects the emergence of the system as a whole. In this paper, for the fundamental strategy,

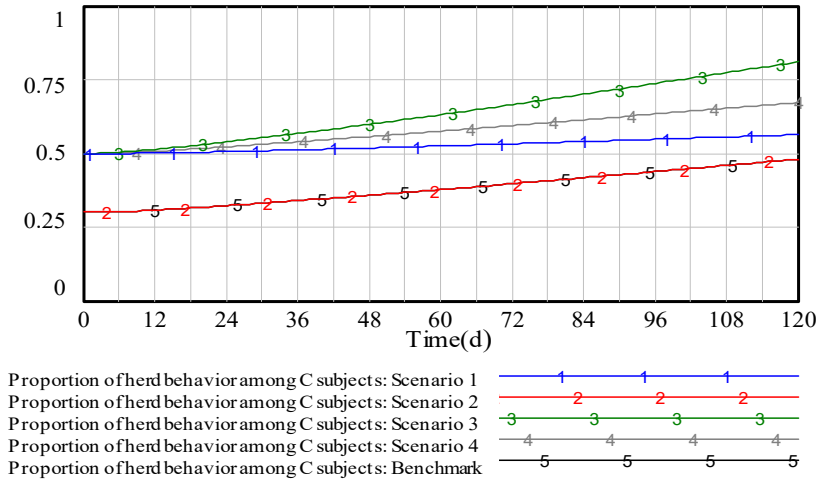
momentum strategy and reverse strategy were set up different imitation strategy initial value, in order to explore the various types of strategy subject of the initial imitation scale exists to cause the emergence of the critical value of the herd behavior, the results are shown in Figure 6.



(a) Proportion of herding behavior of Discos with fundamental strategy



(b) Proportion of herding behavior of Discos with momentum strategy

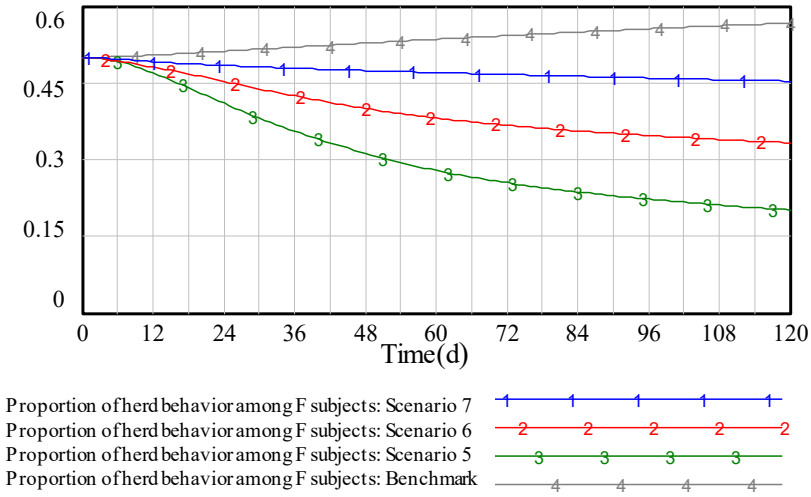


(c) Proportion of herding behavior of Discos with contrarian strategy

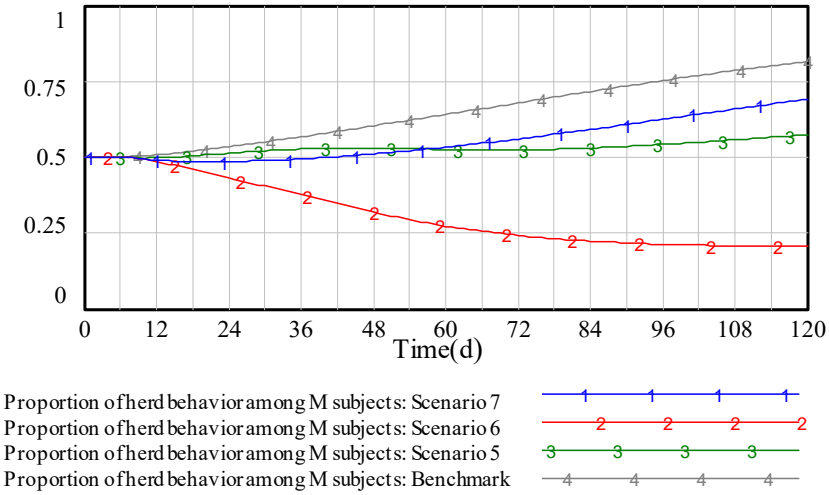
Fig. 6. Critical point analysis of heterogeneity strategy subjects' initial intention to imitate

From Figure 6, it can be seen that the initial imitation ratio of fundamental strategy subjects is less than 0.4 will not emerge from the herd behavior, while the momentum strategy and contrarian strategy subjects will always emerge from the herd behavior, but the emergence rate is negatively correlated with the structure of the proportion. This is because when the initial imitation scale of fundamental strategy subjects is strong, such subjects ignore their own fundamental information and take price trend information into account when making decisions. When the initial proportion of subjects adopting imitation behavior exceeds a critical value, the price trend information diffused in the market interferes with the return of prices to their values and increases price volatility, leading to more fundamental strategy subjects to improve their prediction accuracy of prices by imitating momentum and contrarian strategies, which in turn inhibits the diffusion of fundamental strategies in the market and reduces pricing efficiency. Figures 6 shows that it is difficult for a single momentum strategy and contrarian strategy to accurately predict the price of TGCs because the momentum strategy expects the price to continue to fall, so it hoards more TGCs than the number of TGCs corresponding to the quota, which increases the cost of compliance; whereas, the subject of the contrarian strategy expects that the price will rise, which leads to the fact that it does not buy enough certificates to cover the quota, and it needs to pay penalties, which also increases the cost of compliance. increases the compliance cost. Therefore, both types of subjects improve the accuracy of predicted prices by mimicking the behavior of other subjects, thus reducing compliance costs.

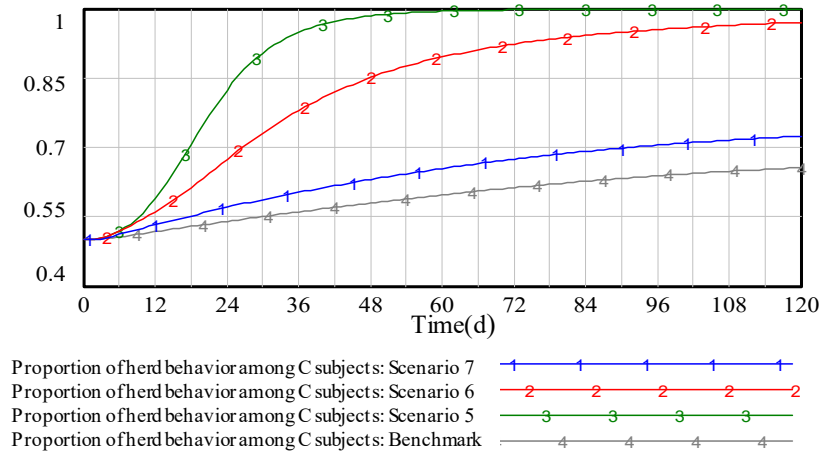
4) Structural Effects of Emerging Herd Behavior. The benefit gap caused by beliefs leads to the reinforcement of subjects' imitation scale, so the heterogeneity of strategies is a key system parameter affecting the emergence of herd behavior, and the results are shown in Figure 7.



(a) Proportion of herding behavior of Discos with fundamental strategy



(b) Proportion of herding behavior of Discos with momentum strategy



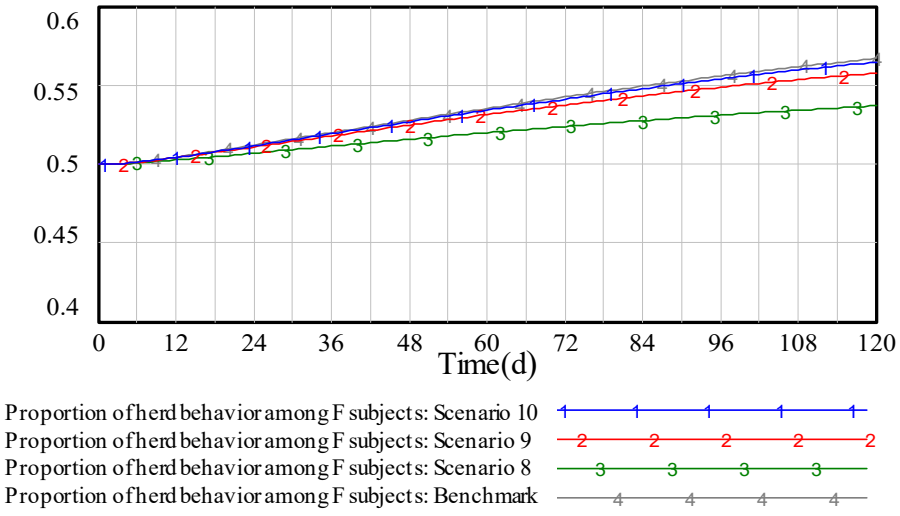
(c) Proportion of herding behavior of Discos with contrarian strategy

Fig. 7. Simulation results of scenario 5-7

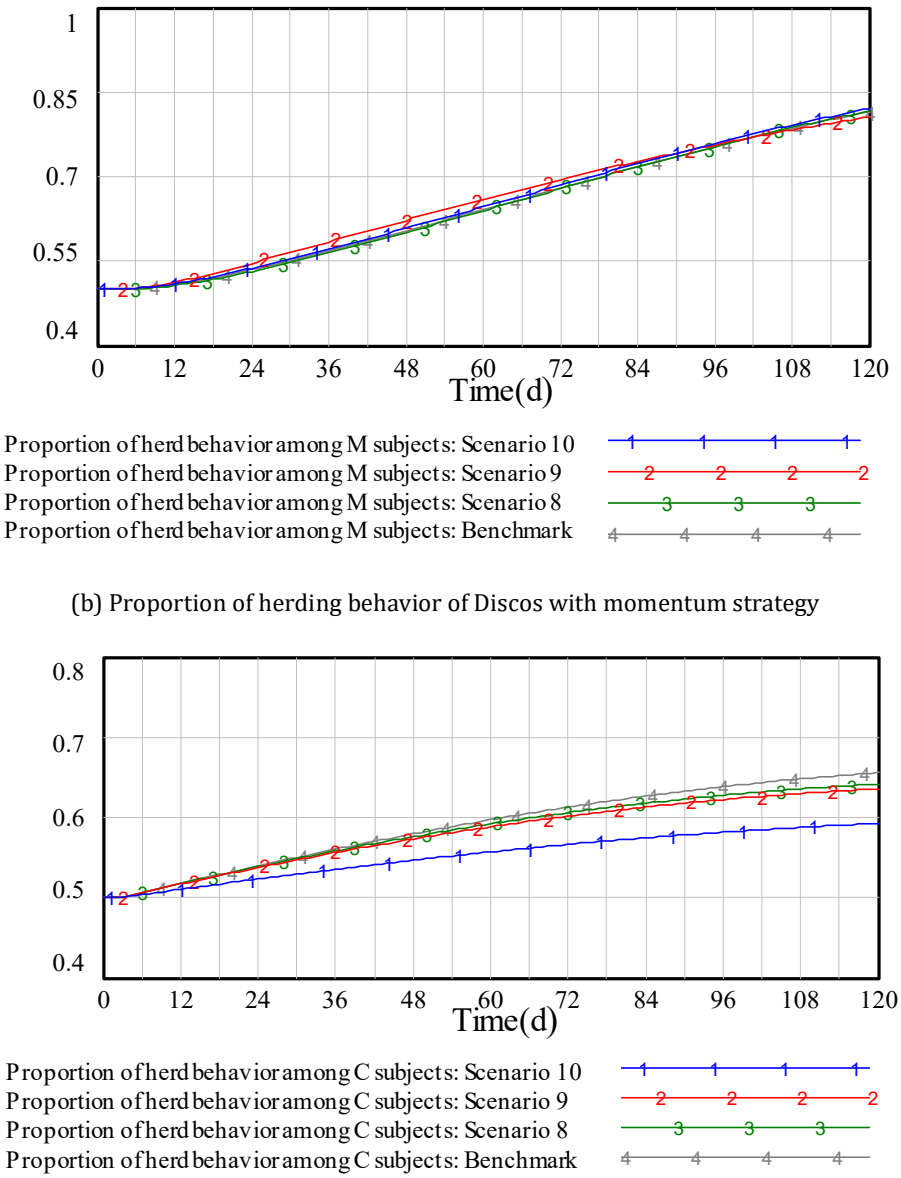
As can be seen in Figure 7, when the fundamental and momentum strategy subjects are in the majority, the level of emergent herd behavior is low, whereas the contrarian strategy subjects consistently emerge with herd behavior. This is because when fundamental strategy subjects account for the majority, the market price is relatively stable, and the fundamental subjects do not need to communicate with other subjects to improve the accuracy of price prediction, but in the baseline scenario, the number of fundamental subjects does not dominate, and the price is influenced by the technical analysis strategy, which makes the fundamental subjects integrate the momentum and contrarian strategy to improve the prediction of price volatility. When momentum strategy subjects are in a higher percentage, their level of herd behavior also decreases, this is because a large number of momentum strategy subjects incorporate their volatility prediction of price into the price, and the alignment of the price with the expectation strengthens the momentum strategy, so their level of herd behavior decreases. From the above analysis, it can be seen that when the proportion of fundamental strategy subjects is more than 50%, the level of their emergent herd behavior decreases and attracts other subjects to adopt fundamental strategies as well. And when the proportion of momentum strategy subjects exceeds 50%, it will drive other subjects to adopt momentum strategy, which is not conducive to the stability of the market.

4.3. Sensitivity Analysis

1) Herd mentality. Bonded rational subject due to unfamiliar with the rules of TGC trading or lack of confidence in their own mastery of decision-making ability, will tend to adopt the decisions of other subjects, through the follow strategy to reduce the risk of return. In the early stage of TGC trading, the market uncertainty is high, the trading individual and other subjects of the decision-making to maintain consistency can reduce the threat of market risk generated by the subject, and to adopt the imitation of the 'hitchhiking' behavior can enhance the subject's sense of belonging. In this experiment, the herd mentality is expressed in the degree of imitation of other subjects' decisions, and the results of the experiment under different herd mentality scenarios are shown in Figure 8.



(a) Proportion of herding behavior of Discos with fundamental strategy



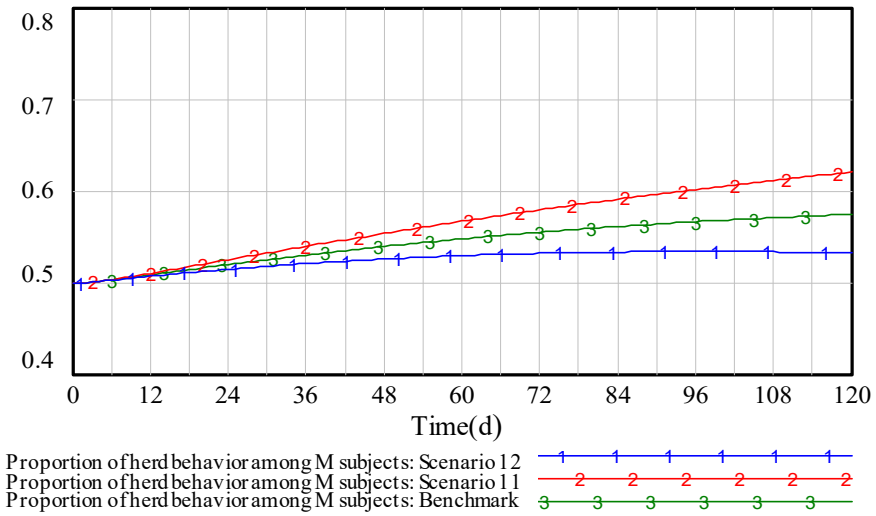
(b) Proportion of herding behavior of Discos with momentum strategy

(c) Proportion of herding behavior of Discos with contrarian strategy

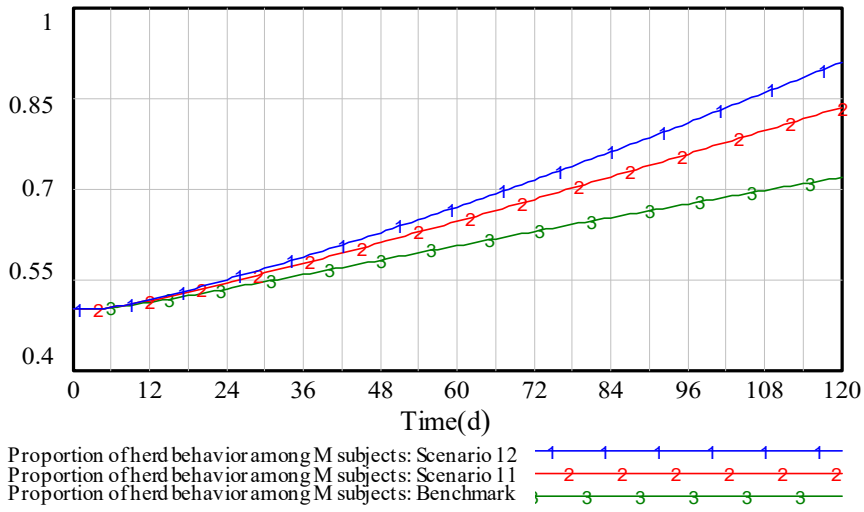
Fig. 8. The effect of herd mentality on the emergence of herd behavior

The results in Figure 8 indicate that a weakening of the herd mentality reduces the speed of emergence of herd behavior, but does not reduce the depth of emergence of the final herd behavior. Changes in the herd mentality do not significantly affect the positive feedback mechanism of the emergence of the subject's herd behavior, and therefore can only slow down the emergence of the subject's herd behavior of the fundamental strategy. The emergence of herd behavior of bonded rational market subjects is mainly driven by earnings, irrational herd mentality will affect the speed of emergence to some extent, but will not change the positive feedback mechanism of earnings and imitation behavior. Even if the herd mentality is low, the revenue gap will drive subjects to adopt imitation behavior. Herd mentality is an irrational psychological factor for bonded rationality market subjects to pursue group identity. The above analysis shows that the reduction of herd mentality by fundamental strategy subjects with information superiority will slow down the level of emergence of herd behavior, which in turn will inhibit the proliferation of low-quality information and technical analysis strategies in the market.

2) Cognitive Bias. According to Kahneman's explanation of herd behavior based on irrational factors, the cognitive bias of TGC trading subjects refers to the fact that the subject's cognitive attention is a scarce resource and has a limited ability to process and handle market information, and therefore cannot process all information systems in the TGC market. In addition, due to the trading subject's cognition, beliefs and habits, he or she is selective in the information collection process, which is manifested in excessive attention to some information and neglect of obscure information. Therefore, this paper makes a sensitivity analysis of the trading subject's cognition of value information and price information to explore the influence of cognitive bias on the emergence of herd behavior, and the results are shown in Figure 9.



(a) Proportion of herding behavior of Discos with momentum strategy



(b) Proportion of herding behavior of Discos with contrarian strategy

Fig. 9. The effect of cognitive bias on emergence of herd behavior

The diminution of cognitive bias also slows down the rate of emergence of herd behaviors in the subjects of momentum strategy and reverse strategy. In Figure 9, the speed of the emergence of herd behavior of both momentum strategy and reverse strategy subjects decreases with the narrowing of cognitive bias. Momentum strategy is the trading subject's insufficient response to market information [43], such subjects believe that the price will continue the historical trend, and the reduction of

cognitive bias indicates that the subject collects timely information and updates the strategy, which improves the prediction accuracy of the price, and therefore the speed of the emergence of herd behavior decreases. The reverse strategy is a manifestation of the subject's overreaction to the price. The subject believes that the proliferation of information about the previous price trend makes the historical trend of the price continue, but the price is about to return to the value, so the trend of the price change is opposite to the recent trend. Similarly, the reduction in the cognitive bias of the subjects of the reverse strategy indicates that the degree of overreaction to information by these subjects has slowed down, and they believe that prices will gradually converge to value, similar to the fundamental strategy, which improves the accuracy of price expectations and slows down the emergence of herd behaviors. The above analysis shows that the reduction of cognitive bias indicates the subject's ability to recognise market, local and private information, reduces the subject's irrationality in interfering with prices, and improves the market's pricing efficiency. Fundamental strategy subjects, momentum strategy subjects and contrarian strategy subjects will emerge herd behavior, the level of herd behavior of fundamental strategy subjects is lower than that of the other two strategy subjects [44-45]; the increase of trading subjects' sensitivity to information will accelerate the emergence of herd behavior of fundamental strategy subjects and momentum strategy subjects.

5. Conclusions

In this paper, the emergence of herd behavior in the TGC market has been studied, focusing on answering the question of the formation conditions of the herd behavior of trading entities and how it emerges. This paper firstly puts forward the research paradigm of 'individual behavior generation - group behavior generation - emergence of herd behavior'. Then, it constructs a herd behavior emergence model with multi-layer nested relationships for TGC trading subjects. Finally, the law of emergence of herd behavior is analyzed through computational experiments. The research results show that:

1) There is herd behavior in China's TGC market, open information exchange channels, positive feedback relationship between subjects, the subject's expectation of pursuing profit maximization, and large-scale vendors with high-quality information are the basic conditions for the emergence of herd behavior, and the trading subjects establish interactive relationships around large-scale vendors, and generate aggregation by imitating each other's trading strategies under the effect of convergence, which leads to the emergence of high-level herd behavior.

2) Fundamental strategy subjects, momentum strategy and contrarian strategy subjects will emerge herd behavior, the speed of emergence of herd behavior and inter-subjective return differentials have a positive feedback relationship. Fundamental strategy subjects with high-quality information have scale and structural effects on the emergence of herd behavior, only when the initial imitation scale of such subjects reaches 40% or less than 50% of the market share, the emergence of herd behavior, and its emergence of the depth of the 'S' type of growth; while the depth of the emergence of herd behavior of the other subjects is not affected by the heterogeneity of information and beliefs. The depth of emergence of other subjects is not affected by heterogeneous information and beliefs, and the speed of emergence is positively correlated with the initial imitation scale and negatively correlated with the market share.

3) The herd mentality and the weakening of cognitive bias of TGC trading subjects will reduce the emergence speed of herd behavior, but have almost no effect on the depth of emergence. The weakening of herd mentality of fundamental strategy subjects with information advantage slows down the emergence of herd behavior, which in turn inhibits the dissemination of low-quality information in the market. The reduction of cognitive bias indicates that subjects' ability to identify market information, local information, and private information is enhanced, subjects' irrational factors interfere with prices less, and the pricing efficiency of the market is improved.

Based on the existing research, the policy recommendations are as follows:

1) Improve the information disclosure mechanism of the TGC market, expand information disclosure channels, and guarantee the accuracy of information. The market should further improve the system of TGC certification, issuance, trading, and clearance, improve the effective information dissemination mechanism, and regularly release key information such as the price, quantity, and time nodes of TGC trading.

2) Encourage market participants to trade based on fundamental information, and enhance the confidence of fundamental strategy participants who possess high-quality information. The government should encourage large market players with information advantages in the TGC market to participate in transactions based on the information they have, and enhance the confidence of market players with good information channels.

3) Strengthen the education of market players and enhance their cognitive ability of information. There are differences in the rationality level, knowledge structure, information analysis ability and financial strength of market players, and market players at an information disadvantage have limited knowledge of the certification mechanism, trading mechanism and settlement mechanism of TGCs, and are easily affected by market noise. The government should strengthen the education of the main body of the TGC transaction, broaden the main body's information exchange channels, and improve the market main body's ability to analyse and judge the information.

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