How do Spillover Effects Affect Food Safety Management of Companies? Searching New Orientation of Regulations for Food Safety

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Abstract

The food safety strategies of companies are a key point in the reduction of food safety risks. In order to encourage the evolution of food safety strategies of companies from food fraud to safety investment, this study builds an evolutionary game model, taking large and small companies as participants, to reveal the dynamic process of spillover effects influencing the choice of food safety strategies of companies. The study shows that (1) the food safety strategies of companies change from safety investment to food fraud, along with the increasing opportunity costs of safety investment. (2) The costs structure of small companies mainly determines whether the industry reaches the equilibrium of safety investment, while the costs structure of large companies mainly determines whether the industry reaches the equilibrium of food fraud. (3) Both competition effects and contagion effects encourage companies to choose safety investment. The more obvious spillover effects of incidents on food safety are, the more likely it is that companies will choose safety investments. (4) Increasing the costs to companies for incidents on food safety and reducing the opportunity cost of safety investment motivates companies to choose safety investment. Consequently, a new orientation of regulations for food safety is formed: the government should allocate different regulatory resources to counteract food fraud behaviors or technologies with a different benefit, should increase the technical costs and costs incurred from committing acts of food fraud, and should expand spillover effects of incidents on food safety.

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Introduction

In recent years, governments around the world have been committed to reducing food safety risks (Yi, 2019). However, the regulatory system did not provide confidence to consumers (Kendall et al., 2019), and governments' efforts have not reduced food safety risks from the root cause. In China, from September 2019 to November 2019, the government investigated and managed 78,000 cases of food safety violations (State Administration for Market Regulation of China, 2019). In Table 1, even under the premise of the continuous improvement of policies and regulations, continuous strengthening of supervision and law enforcement, and participation of the public in co-governance, old problems remain and new problems are emerging. The same phenomenon has occurred in the United States. Major food safety regulations have not significantly reduced the outbreak of foodborne diseases (Yasuda, 2012), and an average of 76 million cases of foodborne illness still occur each year (Fielding et al., 2011). Even under the highly anticipated certification system, production still cannot be developed to increase food safety (Ding et al., 2019).

Existing policies and regulations are unable to reduce food safety risks from the root cause probably because these policies and regulations are rarely designed based on consideration of the companies' food safety management. For example, the Chinese government revised "the Food Safety Law" and "the Regulations on the Implementation of the Food Safety Law" in 2018 and 2019 and only focusing on monitoring and evaluating food safety hazards in advance, strengthening inspections during the process, and increasing penalties on companies after the incident. For a long time, in theoretical analysis and policy design, the essence of the content of policies and regulations remains based on two basic control variables of food safety: the probability of discovery and the intensity of the punishment (Cadieux et al., 2019; Pham, & Dinh, 2020). Notably, the company is the first responsible entity for food safety and has the final decision and execution power regarding food safety management. Therefore, the key to reducing food safety risk is to focus on companies' food safety management, and the selection of companies' safety investment or food fraud management strategy directly affects the level of food safety.

Theoretically, companies are also victims of food safety incidents. Food production is the foundation upon which a company depends, and food safety is the lifeline of a company.

Reducing food safety risks and safety investment should be the priority of most companies. There should be only a few companies taking opportunistic actions to engage in food fraud. However, in the "melamine" incident of Chinese dairy products, as many as 20 out of 154 companies were guilty (People's Daily Overseas Edition, 2008). In China, less than 3% of food companies adopt HACCP systems, and most companies are unmotivated to prevent risks (National Certification and Accreditation Administration of China, 2015). Similar food safety incidents occur frequently in China in the same industry, and companies often continue to apply the same food safety management strategies. All of these factors lead to the conclusion that there is a connection between companies' food safety management strategies.

Recent research has gradually begun focusing on the huge impact of food safety incidents on the entire industry and finding spillover effects of food safety incidents (Toledo, & Villas-Boas, 2019). Spillover effects are more likely to occur in companies in the same industry (Roehm, & Tybout, 2006; Dahlen, & Lange, 2006). In real life, the industry spillover effects of food safety incidents can be divided into two forms the competition effect and contagion effect, and these two types of effects often exist simultaneously (Ngo et al., 2020). In some major trust product markets, the contagion effect dominates (Romley, & Shih, 2017). After a food safety incident, the performance of the company is affected (Soon et al., 2019). The existence of spillover effects from food safety incidents could explain the aforementioned connection.

Thus, how do spillover effects affect the choice of management strategies for a company's? Do the competition effect and the contagion effect under spillover effects have the same direction on the impact of a company's food safety management? How can a rational system be designed based on spillover effects to guide companies to choose safety investment and abandon food fraud? By analyzing the spillover effects of food safety incidents, is it possible to form incentive-compatible mechanisms to reduce food safety risks without changing other systems and only changing the allocation of regulatory resources? The literature on spillover effects of food safety incidents has not conducted analyzes from the perspective of the impact of spillover effects on a company's decisions. As a result, today's research often proposes policy recommendations from the industry perspective that encourage governments or companies to take a multifaceted approach to reduce the impact of spillover effects from food safety incidents (Liu, & Ma, 2016). If based on the basic principles of

"Safety First" or "Consumer First" should governments design policies to reduce the impact of spillover effects from food safety incidents? At present, there are no clear answers to these questions.

This article attempts to provide satisfactory answers to the aforementioned questions, expand the research focus to strategic interaction between companies, and promote the evolution of the company's food safety management tow to safety investment. Based on the theory of spillover effects, combined with the opportunity cost of food safety management, this article first statically analyzes the factors that affect the decision of food safety management in companies. Next, an evolutionary game model with large and small companies as participants is constructed to reveal the dynamic process of food safety management in food companies. Finally, the article discusses the practical application of the conclusions on government food safety management.

Theoretical framework

In a food supply system, food generally must proceed through the steps of, for example, agricultural product production, primary processing, deep processing, distribution and sales, storage, consumption, and catering to achieve the final value (Parfitt et al., 2010). This article defines the main participants who are directly involved in food production and consumption and have a direct relationship with food safety risks as internal participants. The participants indirectly involved in food production and consumption, and indirectly related to food safety risks, are defined as external participants. In every part of food supply system, every action of an internal participant can lead to contamination of the food. Nobody in the supply system can manage the increasingly complex food safety-related risks alone. As external participants, governments affect the food supply system from the formulation of policies and regulations at the macrolevel to the sampling inspection and information release at the microlevel. When market failures and government failures occur, other external participants, for example, media, inspection agencies, certification agencies, industry organizations, and capital markets, also participate in and cooperate with the government to supervise. These two types of external participants complement each other in information, technology, and other aspects; therefore, both in theory and reality, the risk of food safety is reduced to a great extent. Thus, what could be considered the level of food safety risk is the result of the behavior of internal and external participants, and it is essential to analyze the strategic interactions between participants.

The relationship between food safety risks, food safety management, and food safety issues

Food has always been exposed to physical, chemical, and microbiological aspects, which constitutes a natural risk to food safety. In recent years, the artificial risks posed by food fraud have gradually become the leading risks to food safety. The purpose of companies committing food fraud is to produce food with a certain surface value at a lower cost, resulting in higher profits than if they followed the regulations. The company aims to maximize profits and thus has a strong motivation to commit food fraud.

In Figure 1, the cost-benefit analysis determines whether the company engages in food fraud or safety investment, and the choice of the company directly affects the level of food safety risk. Due to the strong asymmetry of food production information, the cost-benefit analysis of a company must consider not only the actual costs and benefits of food safety management but also the opportunity cost of choosing the safety investment rather than food fraud.

In a food supply chain, food safety risks are triggered by a certain probability, which causes food safety problems (Bachev, 2013). It is difficult for consumers to directly observe the food safety issues and production behavior of companies; thus, some companies are driven by the benefits of committing food fraud to reduce costs (Starbird, 2005). This type of moral hazard caused by information asymmetry has long been a concern of researchers (Akerlof, 1970). Based on the theoretical analysis, the most serious information asymmetry occurs in the asymmetry of risk information among internal and external participants and in the asymmetry of information on the behavior of companies to reduce or increase food safety risks. However, even if there is asymmetry in the information on risk information and food safety control behaviors, internal and external participants can still attribute food safety issues by observing and judging them.

Behavioral logic of the company’s food safety management

In a food supply system, there are several large-scale food production companies and small-scale food production companies (Figure 2). During period T, large and small companies decide on actions of food fraud or safety investment through cost-benefit analysis, which also determines the food safety risk level of food produced by large and small companies and forms the food safety risk level of the whole industry. Correspondingly, large companies, small companies, and the entire industry have food safety issues with a certain probability. Strategic interaction exists between companies (Fehr, & Gachter, 2002; Santos, 2008) because of the indirect and network reciprocal relationships between large companies and small companies (Nowak, 2006).

During period T, internal participants and external participants jointly observe food safety issues through a variety of methods. An interpretation is that the food safety incidents are the objective of the existence of the external performance of food safety risk. Thus, the essence of food safety incidents is the observation of participants of food safety issues, and food safety incidents produce two main results: (1) participants use these incidents as a basis to identify whether the company chose safety investment or food fraud; and (2) due to spillover effects of food safety events, if the participants attribute the event to the behavior of the company, there will be a competitive effect, that is, the participants deny the company that perpetrated the event and affirm other companies in the same industry. Conversely, if participants attribute the event to the industry, a contagious effect occurs, that is, the participant denies the entire industry (Gao et al., 2013).

Affected by food safety incidents, the purchase, investment, supervision, and other behaviors of internal and external participants change (Roy et al., 2018). For example, when consumers observe food safety incidents, they may adopt consumption substitution behaviors; when the capital market observes food safety incidents, investors may reduce their investment behavior; and when the government observes food safety incidents, they may impose penalties. The purchase, investment, supervision, and other behaviors of internal and external participants determine the cost and benefit of food safety management for large and small companies in period T+1, and their choice of food fraud or safety investment. Due to the industry spillover effects of the aforementioned food safety incidents, the actions taken by large and small companies are interdependent. Table 2 presents the costs and benefits of a company’s food safety management.

Methods and models

The analysis of food safety involves government, companies, consumers, and other subjects therefore, evolutionary game analysis based on the behavior of participants has become one of the main tools of its research. The research from the perspective of the evolutionary game between the two sides has mainly included the games between a government and companies (Song et al., 2018), and between food suppliers and manufacturers (Song et al., 2019); the research from the perspective of tripartite evolutionary games has mainly included games of companies, consumers, and governments (Luo et al., 2018).

The research has not considered evolutionary games among heterogeneous companies from the industry perspective. Therefore, it is impossible to answer the question of food safety management choices of heterogeneous companies in the face of different costs and benefits. Evolutionary game theory focuses on how cooperation can be generated and spread in disordered groups (Santos, & Pacheco, 2005; Perc, & Szolnoki, 2009), and expanded the traditional game by, for example, relaxing the rational hypothesis, refining the Nash equilibrium, and investigating the dynamic adjustment process. The objects studied in this article satisfy the basic assumptions of evolutionary games, and the number of game groups at large. Game participants can continuously adjust their strategies based on imitation, trial, error, and learning behavior (Smith, 1976). Therefore, this article can reasonably construct and analyze the evolutionary game model with large companies and small companies as participants.

Model Assumptions

Assumption 1: Only two types of game groups in the game: large companies (T) and small companies (S) of the same food industry. Individuals in both groups are limited rational people, their strategy choices are based on the actual utility of the strategy, and both sides of the game choose the strategy simultaneously. The game return matrix can be viewed as conforming to the expectation theory, that is, satisfying the form of $U = \sum_i p_i w_i$. Among them, p_i is the objective probability of a food safety incident i, and w_i is the actual benefit of participants after the food safety incident i.

Assumption 2: To simplify the analysis, an assumption is that food safety management of large and small companies are divided into two situations: safety investment and food fraud. That is, a company's food safety management strategy is discrete. There are only two strategies: safety investment (H) and food fraud (L). In large companies, the ratio of choosing safety investment strategies is *x*, and the ratio of choosing food fraud strategies is 1-*x*; in small companies, the ratio of choosing safety investment strategies is *y*, and the ratio of choosing food fraud strategies is 1-*y*. The game process is to repeatedly draw a member randomly from two types of infinite groups for a paired game. The learning and strategy imitation of game participants is limited to the group. In this case, it is possible to analyze the replication dynamics and evolutionary stability strategies of the two groups.

Assumption 3: The difference in food safety risk is only related to the food safety management of the company. The food produced by the safety investment strategy fulfills the requirements of the controllable risks. By contrast, the food produced by the food fraud strategy does not fulfill or fall below the requirements of controllable risks. The rationality among many participants is complementary, that is, participants are fully rational in observing food safety incidents and use this to identify a company's behaviors and attributes regarding food safety incidents. d means all the negative impacts of the food fraud strategy on all companies in the industry after being identified by the participants. This negative impact from the industry is significantly different for large and small companies because large companies often pursue both their own interests and the interests of society. An assumption is that the two types of negative impacts are linearly related, that is, if the negative impacts on large companies are D_T, the negative impacts on small companies are $D_S = \alpha D_T$, where α is the discount coefficients for this influence.

Assumption 4: The strategic choices of the two players in the game have complementary effects. When a large company and a small company adopt the strategy (T_H, S_H), the industry has the lowest food safety risks and the lowest probability of food safety issues, participants identify large and small companies' choice of safety investment measures. When one player adopts food fraud strategies (T_H, S_L) or (T_L, S_H), the industry's food safety risks increase, and the probability of food safety issues increases; then, participants observe the food safety issues and identify and attribute them. When large and small companies adopt the strategy (T_L, S_L), the industry has the highest food safety risks and the highest probability of food safety issues, and participants identify that large and small companies committed food fraud. To simplify the model, without affecting the conclusion of the game, an assumption is that when large and small companies choose safety investment strategies, the benefits obtained from the improvement of their food safety levels are consistent, and the impact on production costs is consistent, and when choosing a food fraud strategy, the impact on production costs is consistent.

Based on the aforementioned assumptions, this article first builds a food safety management benefit matrix (Table 3). For large and small companies, the final result of evolutionary games is to find the Nash equilibrium with mixed strategies.

The meaning of each parameter is as follows:

V represents the gains from the reduction of food safety risks because of competition effects when companies choose safety investment strategies. That is, after a company chooses the safety investment strategy, it benefits from the participants' all positive evaluations of the company. Such positive evaluations are from the different strategy choices of the company, resulting in the difference in food safety risks, where $V \in (0, +\infty)$. Ensuring food safety is the basic responsibility of a company. It is rare for a single company to obtain participants' positive evaluation of the company for choosing a safety investment strategy.

C_H represents the increased production cost when a company chooses a safety investment strategy, that is, the cost that the company pays to reduce risk, where $C_H \in (0, +\infty)$.

C_L represents the reduced production cost when a company chooses a food fraud strategy, that is, the cost saved by the company because of food fraud, where $C_L \in (0, +\infty)$.

ΔC indicates the difference in production costs caused by a company's choice of the safety investment strategy and food fraud strategy, that is, the opportunity cost of a company's choice of safety investment strategy, where $\Delta C = C_H + C_L$.

D indicates that because of contagion effects, after participants observe food safety incidents, the full negative impact of all companies in the industry on a large company is the cost of a large company affected by industry losses, where $D \in (0, +\infty)$.

α indicates that because of contagious effects, after participants observe food safety incidents, the proportion of the negative impact of all companies in the industry on small companies is the discount coefficient of a small company relative to a large company affected by the industry loss, where $0 < \alpha \leq 1$.

L represents the cost of the company after the participants observe a food safety incident and the food fraud strategy is identified by the participants. This loss is mainly divided into two parts: the loss caused by the punishment from the government, and the reduced willingness of consumers to pay. This cost is different for a large and small company: L_1 and L_2 are used to represent these two costs，where $L_1 \,\&\, L_2 \in (0, +\infty)$ and $L_1 > L_2 > D > \alpha D$.

r indicates the probability of food safety incidents when a large company chooses a safety investment strategy and a small company chooses a food fraud strategy, where $r \in (0,1)$.

K indicates the probability of food safety incidents when a large company chooses a food fraud strategy and a small company chooses a safety investment strategy, where $k \in (0,1)$ and $k > r$. The behavior of large companies is generally believed to have a greater impact on the industry. If large companies adopt strategies to increase risk, food safety incidents are more likely to occur in the industry.

Model Construction

The following is an evolutionary game model based on replication dynamics.

For large companies, the expected return safety investment strategy is $U_{TH} = -y\Delta C + (1-y)(V - \Delta C - rD)$, the expected return of food fraud strategy is $U_{TL} = y(-kL_1 - kD) + (1-y)(-L_1 - D)$, and the average return for large companies is $U_T = xU_{TH} + (1-x)U_{TL} = x[-y\Delta C + (1-y)(V - \Delta C - rD)] + (1-x)[y(-kL_1 - kD) + (1-y)(-L_1 - D)]$.

A conclusion is that the replication dynamic equation of large companies is

$$F(x) = \frac{dx}{dt} = x(U_{TH} - U_T) = x(1-x)(U_{TH} - U_{TL}) = x(1-x)[V - \Delta C + L_1 + (1-r)D - y(V + (1-k)L_1 + (1-r-k)D)] \quad (1)$$

Equation 1 shows that only if $x = 0,1$ or $y_0 = \frac{V - \Delta C + L_1 + (1-r)D}{V + (1-k)L_1 + (1-r-k)D}$, the proportion of corresponding strategies of large companies is the stationary point of the game.

For small companies, the expected return of safety investment strategy is $U_{SH} = -x\Delta C + (1-x)(V - \Delta C - \alpha kD)$, the expected return of food fraud strategy is $U_{SL} = x(-rL_2 - \alpha rD) + (1-x)(-L_2 - \alpha D)$，and the average return for small companies is $U_S =$

$yU_{SH}+(1-y)U_{SL}=y[-x\Delta C+(1-x)(V-\Delta C-\ \alpha kD)]+(1-y)[x(-rL_2-\alpha rD)+(1-x)(-L_2-\alpha D)]$.

A conclusion is that the replication dynamic equation of small companies is

$$F(y)=\frac{dy}{ds}=y(U_{SH}-U_{SL})=y(1-y)(U_{SH}-U_{SL})=y(1-y)[V-\Delta C+L_2+(1-k)\alpha D-x(V+(1-r)L_2+(1-r-k)\alpha D)]\ (2)$$

Equation 2 shows that only if $y=0,1$ or $x_0=\frac{V-\Delta C+L_2+(1-k)\alpha D}{V+(1-r)L_2+(1-r-k)\alpha D}$, the proportion of the corresponding strategies of small companies is the stationary point of the game.

The evolutionary dynamic system composed of formulas (1) and (2) has five stationary points: $\mathrm{E}_1(0,0)$, $\mathrm{E}_2(1,0)$, $\mathrm{E}_3(0,1)$, $\mathrm{E}_4(1,1)$, and $\mathrm{E}_5(x_0,y_0)$. Friedman (1998) proposed that for a group dynamic described by a differential equation system, the stability of its equilibrium point can be obtained from the local stability analysis of the Jacobian matrix (*J*) of the system. First, according to the system composed of formula (1) and formula (2), find its Jacobian matrix (*J*), and calculate its determinant (*det J*) and the trace (*tr J*) of the matrix at the aforementioned five stationary points, respectively. Then, determine the sign of *det J* and *tr J* and determine the local stability of the point by the combination of the signs.

$$\text{For } J=\begin{bmatrix}\frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y}\\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y}\end{bmatrix}=\begin{bmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{bmatrix}\ (3)$$

In this formula

$$a_{11}=(1-2x)\,[V-\Delta C+L_1+(1-r)D-y(V+(1-k)L_1+(1-r-k)D)]$$

$$a_{12}=\ -x(1-x)[V+(1-k)L_1+(1-r-k)D]$$

$$a_{21}=-y(1-y)[(V+(1-r)L_2+(1-r-k)\alpha D)]$$

$$a_{22}=(1-2y)[V-\Delta C+L_2+(1-k)\alpha D-x(V+(1-r)L_2+(1-r-k)\alpha D)]$$

If the following conditions are met

① $a_{11}+a_{22}<0$ (Trace condition)

② $\begin{vmatrix}a_{11} & a_{12}\\ a_{21} & a_{22}\end{vmatrix}=a_{11}a_{22}-a_{12}a_{21}>0$ (Determinant condition)

Then the equilibrium point of the replication dynamic equation is asymptotically stable, and this equilibrium point is the evolutionary stability strategy (ESS).

Make $b_1 = V - \Delta C + L_1 + (1-r)D$, $b_2 = V - \Delta C + L_2 + (1-k)\alpha D$, $b_3 = V + (1-k)L_1 + (1-r-k)D$, $b_4 = V + (1-r)L_2 + (1-r-k)\alpha D$. Then, formula (3) can be simplified as

$$J = \begin{bmatrix} (1-2x)(b_1 - yb_3) & -x(1-x)b_3 \\ -y(1-y)b_4 & (1-2y)(b_2 - xb_4) \end{bmatrix} \quad (4)$$

When judging the nature of symbols, an inference is mainly made based on economic principles and some assumptions set by this model. Obviously, $k < \frac{1}{2} < 1 - r$, $r < \frac{1}{2} < 1 - k$. According to the sign of b_1、b_2、$b_1 - b_3$、$b_2 - b_4$, 16 conditions of dynamic system replication can be obtained. In Table 4, Condition 1 has 5 equilibrium points, $E_1(0,0)$ and $E_4(1,1)$ are ESS; Condition 2 has 4 equilibrium points, $E_4(1,1)$ is ESS; and Condition 3 has 4 equilibrium points, $E_1(0,0)$ is ESS. Conditions 4 to 16 are not specifically listed. In these conditions, some conditions use (0,1) or (1,0) as the ESS, large and small companies have evolutionary stabilization strategies, and the result of evolutionary stabilization strategies is the strategic differentiation between large and small companies. In some conditions, because $V + L_1 + (1-r)D > k(L_1 - D)$, $V + L_2 + (1-k)\alpha D > r(L_2 - \alpha D)$, $V + L_1 + (1-r)D > V + L_2 + (1-k)\alpha D$, $k(L_1 + D) > r(L_2 + \alpha D)$, inequality cannot hold, and evolutionary stabilization strategies for large and small companies do not exist. In these 16 conditions, this article focuses more on evolutionary stabilization strategies (T_H, S_H) and (T_L, S_L) because (T_H, S_H) is the most ideal corporate behavior in reality and (T_L, S_L) is the corporate behavior that needs to be avoided most.

Results and discussion

Opportunity costs of the company's risk management and food safety management equilibrium

Proposition 1: As long as the opportunity cost ΔC of safety investment is less than the product of the probability of food safety incidents r and the loss of small companies choosing food fraud, both large companies and small companies will choose safety investment.

Proof: In condition 2, when $b_1 > 0$, $b_2 > 0$, $b_1 - b_3 = k(L_1 + D) - \Delta C > 0$, $b_2 - b_4 = r(L_2 + \alpha D) - \Delta C > 0$. There exists an ESS, that is, large companies and small companies choose safety investment strategies, and companies that choose food fraud strategies will disappear because of evolution. Condition 2 is equivalent to $\begin{cases} \Delta C < V + L_1 + (1-r)D \\ \Delta C < V + L_2 + (1-k)\alpha D \\ \Delta C < k(L_1 + D) \\ \Delta C < r(L_2 + \alpha D) \end{cases}$, because $V + L_2 + (1-k)\alpha D > r(L_2 + \alpha D)$, $V + L_1 + (1-r)D > k(L_1 + D) > r(L_2 + \alpha D)$, only if $\Delta C < r(L_2 + \alpha D)$, the inequality holds, and both large and small companies with evolutionary stability strategies will choose safety investment strategies. L_2 and αD are part of the cost of small companies, where Result 1 can be drawn.

Lemmas 1 follows Proposition 1. For a certain safety investment behavior or technology, whether large companies and small companies choose this behavior or technology simultaneously depends on the cost structure of small companies.

Proposition 2: When the opportunity cost ΔC of safety investment lies between the following two items, both large and small companies choose safety investment or both choose food fraud. The first item is the product of the probability of food safety incident k and the loss of the large company choosing food fraud. The second item is the sum of the following three items: the benefit V that the company obtains from the reduction of food safety risks, the cost paid by the small company L_2 , and the product of the probability that the food safety incident does not occur $1 - k$ and the impact of industry losses on a small company αD.

Proof: In condition 1, when $b_1 < 0$、$b_2 < 0$ and $b_1 - b_3 = k(L_1 + D) - \Delta C > 0$, $b_2 - b_4 = r(L_2 + \alpha D) - \Delta C > 0$, there are two evolutionary stable strategies: Both large companies and small companies choose food fraud strategies or both choose safety investment strategies. No matter which strategy the evolution results belong to, companies that choose another strategy will disappear in the process of evolution. Condition 1 is equivalent to $\begin{cases} \Delta C < V + L_1 + (1-r)D \\ \Delta C < V + L_2 + (1-k)\alpha D \\ \Delta C > k(L_1 + D) \\ \Delta C > r(L_2 + \alpha D) \end{cases}$, because $V + L_1 + (1-r)D > V + L_2 +$

$(1-k)\alpha D$, $k(L_1+D) > r(L_2+\alpha D)$, only if $k(L_1+D) < \Delta C < V + L_2 + (1-k)\alpha D$, the inequality holds, and both large and small companies with evolutionary stability strategies will choose safety investment or food fraud strategies.

Lemmas 2 follows **Proposition 2**. Whether large and small companies choose safety investment or food fraud behaviors or technologies simultaneously, depends on their cost structure.

Proposition 3: As long as the opportunity cost of safety investment ΔC is greater than the sum of the following three, large and small companies choose food fraud. The first is the benefit V that the company obtains from the reduction of food safety risks. The second is the cost L_1 paid by the large company. The third is the product of the probability that a food safety incident does not occur $1-r$ and the impact of industry losses on large company D.

Proof：In condition 3, when $b_1 < 0$, $b_2 < 0$, $b_1 - b_3 = k(L_1+D) - \Delta C < 0$ and $b_2 - b_4 = r(L_2+\alpha D) - \Delta C < 0$, there is an ESS, that is, both large and small companies choose food fraud strategies, and companies that choose safety investment strategies will disappear in the evolution. Condition 3 is equivalent to $\begin{cases} \Delta C > V + L_1 + (1-r)D \\ \Delta C > V + L_2 + (1-k)\alpha D \\ \Delta C > k(L_1+D) \\ \Delta C > r(L_2+\alpha D) \end{cases}$, because $V + L_1 + (1-r)D > V + L_2 + (1-k)\alpha D$, $V + L_1 + (1-r)D > k(L_1+D) > r(L_2+\alpha D)$, only if $\Delta C > V + L_1 + (1-r)D$, the inequality holds, and both large and small companies with evolutionary stability strategies choose food fraud strategies. L_1 and D are part of the cost of large companies, where Conclusion 3 can be drawn.

Lemmas 3 follows **Proposition 3**. For a certain food fraud behavior or technology, whether large and small companies adopt this behavior or technology simultaneously depends on the cost structure of large companies. This explains that large-scale companies take the lead in food fraud, and large and small companies commit food fraud together, forming the "Industry Crisis" and "Regulatory Captives."

Proposition 4 follows **Lemmas 1–3**. For a certain safety investment behavior or technology, as the opportunity cost of this behavior or this technology increases, the food safety management of large and small companies changes from safety investment to food fraud. Whether companies choose safety investment is mainly affected by the cost structure of small companies, and whether they choose food fraud is mainly affected by the cost structure of large companies.

Policy Corollary 1 follows **Proposition 4**. The cost of food safety management should be the focus of policy analysis. The government should allocate different regulatory resources to food safety management activities or technologies with different costs and should focus on the supervision of food fraud that causes higher returns to companies. For food fraud that causes lower returns, the government can rely on market mechanisms to achieve regulatory goals, and through evolutionary games among companies, it can eventually achieve the equilibrium outcome of companies choosing to prevent risks or not choosing food fraud.

Conditions for companies to achieve ideal food safety management equilibrium

In Condition 1, there are two evolutionary stability strategies (T_H，S_H) and (T_L，S_L), where (T_H，S_H) is the most ideal corporate behavior in reality, and (T_L，S_L) is the corporate behavior that needs to be avoided most. Further discussion is necessary on conditions that can be used to achieve the strategy of a company's equilibrium in (T_H，S_H). Because $\Delta C > k(L_1 + D) > r(L_2 + \alpha D)$, the benefits of the ESS (T_L，S_L) are significantly greater than (T_H，S_H), that is, the food fraud strategy has become the "Pareto Optimal" of large and small companies. However, the expected direction of the design of policies and regulations is that both large and small companies choose safety investment strategies. Obviously, the optimal company and the optimal policy are completely opposite, which also explains the strong motivation of corporate food fraud. This target deviation causes the target direction to be exactly opposite to the model direction in the process of analyzing how to reach the ideal equilibrium condition. To make policy analysis meaningful, in the following analysis, the (T_H，S_H) strategy is set to $E_1(0,0)$, and the (T_L，S_L) strategy is set to $E_4(1,1)$.

Figure 3 depicts the dynamic evolutionary game process of large companies group T and small companies group S. In the figure, the polyline $E_2E_5E_3$ formed by two unstable points E_2、E_3 and saddle points E_5 is the critical line where the system converges to different strategies. The relative position of the initial state of the system and the saddle points affects the evolution process and stable state of large and small company groups. When the initial state is located in the area to the left of the polyline $E_1E_2E_5E_3$, the system will converge to $E_1(0,0)$, and the stability strategy will gradually evolve toward the "Pareto optimal" direction. Finally, both large and small companies choose safety investment strategies, which is an ideal state. When the initial state is located in the area on the right side of the polyline $E_2E_5E_3E_4$, the system converges $E_4(1,1)$. In the end, both large and small companies choose food fraud strategies. Although it has reached an equilibrium state, food safety risks increase and food safety issues increase, which is an undesirable state. Both of the aforementioned states are evolutionary stable closed states, and in either state, participants who take another behavior will disappear in the evolution.

In Figure 3, the evolution of the system cannot be achieved in one step. Therefore, for a period of time, the system will be in a situation where the two strategies coexist because of the choice of different strategies and different proportions by large and small companies. The long-term equilibrium result of the game between the large company group T and the small company group S may be the choice of safety investment strategy or food fraud strategy. The specific evolution path and stable state are determined by the area $S_{E_1E_2E_5E_3}$ of region $E_1E_2E_5E_3$ and the area $S_{E_2E_5E_3E_4}$ of region $E_2E_5E_3E_4$. If $S_{E_2E_5E_3E_4} > S_{E_1E_2E_5E_3}$, the system will be more likely to evolve along the path E_5E_4 toward food fraud; if $S_{E_2E_5E_3E_4} < S_{E_1E_2E_5E_3}$, the system will be more likely to evolve along the path E_5E_1 toward safety investment; if $S_{E_2E_5E_3E_4} = S_{E_1E_2E_5E_3}$, the probability of choosing safety investment is equal to the probability of choosing food fraud and the direction of system evolution cannot be determined. According to Figure 3, the area of the region $E_1E_2E_5E_3$ is $S_{E_1E_2E_5E_3} = \frac{1}{2}(x_0 + y_0)$. A comparative static analysis method is used to analyze the influence of each parameter on the area. Suppose a parameter variable to be investigated is θ, then the change rate of the area of this parameter is $\frac{\partial S_{E_1E_2E_5E_3}}{\partial \theta} = \frac{\partial S_{E_1E_2E_5E_3}}{\partial x_0} \times \frac{\partial x_0}{\partial \theta} + \frac{\partial S_{E_1E_2E_5E_3}}{\partial y_0} \times \frac{\partial y_0}{\partial \theta} = \frac{1}{2}(\frac{\partial x_0}{\partial \theta} + \frac{\partial y_0}{\partial \theta})$.

Proposition 5: When a company chooses safety investment, because of the competition effect, the higher the profit from the improvement of its food safety level, the more incentive the companies have to choose safety investment.

Proof: According to the X and Y coordinates of point E_5, $\frac{\partial x_0}{\partial V} > 0$ and $\frac{\partial y_0}{\partial V} > 0$.

According to the phase diagram, area formula of $S_{E_1E_2E_5E_3}$, and rate of change formula, $\frac{\partial S_{E_1E_2E_5E_3}}{\partial V} > 0$, and the proposition is proved.

Proposition 6: After a food safety incident, because of the contagion effect, the greater the impact of industry losses on a company, the more incentive the companies have to choose safety investment.

Proof: According to the X and Y coordinates of point E_5, $\frac{\partial x_0}{\partial D} > 0$, $\frac{\partial y_0}{\partial D} > 0$, $\frac{\partial x_0}{\partial \alpha} > 0$, and $\frac{\partial y_0}{\partial \alpha} = 0$. According to the phase diagram, area formula of $S_{E_1E_2E_5E_3}$, and rate of change formula, $\frac{\partial S_{E_1E_2E_5E_3}}{\partial D} > 0$ and $\frac{\partial S_{E_1E_2E_5E_3}}{\partial \alpha} > 0$, and the proposition is proven.

Lemmas 4 follows **Proposition 5** and **6**. Whether the competition effect or the contagion effect, it will increase the probability that the industry produces food toward the direction of safety investment, that is, the more obvious spillover effects of food safety incidents, the more likely for small and large companies in the industry to choose safety investment.

Policy Corollary 2 follows **Lemmas 4**. The government should take various measures to increase spillover effects of food safety incidents, thereby increasing the probability that the industry will choose safety investment.

Proposition 7: After a food safety issue, the higher the cost the companies pay after the food fraud is identified by the participants, the more incentive the companies have to choose safety investment.

Proof: According to the X and Y coordinates of point E_5, $\frac{\partial x_0}{\partial L_1} = 0$, $\frac{\partial y_0}{\partial L_1} > 0$, $\frac{\partial x_0}{\partial L_2} > 0$, and $\frac{\partial y_0}{\partial L_2} = 0$. According to the phase diagram, area formula of $S_{E_1E_2E_5E_3}$, and rate of change formula, $\frac{\partial S_{E_1E_2E_5E_3}}{\partial L_1} > 0$ and $\frac{\partial S_{E_1E_2E_5E_3}}{\partial L_2} > 0$, and the proposition is proven.

Policy corollary 3 follows **Proposition 7**. The government should increase the cost to the company after it is identified as committing food fraud, prompting the industry to choose safety investment.

Proposition 8: The lower the opportunity cost of safety investment, the greater the incentive for the companies to choose safety investment.

Proof: According to the X and Y coordinates of point E_5, $\frac{\partial x_0}{\partial \Delta C} < 0$ and $\frac{\partial y_0}{\partial \Delta C} < 0$. According to the phase diagram, area formula of $S_{E_1E_2E_5E_3}$, and rate of change formula, $\frac{\partial S_{E_1E_2E_5E_3}}{\partial \Delta C} < 0$, and the proposition is proved.

Policy corollary 4 follows **Proposition 8**. The government should increase investment in research and development of technology, reduce the cost of safety investment strategies, or increase the cost of technology and use of food fraud, to prompt the industry to choose safety investment.

Conclusion

A continuous game and interactions between large and small companies form food safety strategies of companies. It is a complex and dynamic process between the two parties in the game. According to the theory of SE and the concept of opportunity cost, this study constructed an evolutionary game model and draws many important conclusions. Firstly, the opportunity cost of safety investment behaviors or technologies influences the food safety strategies of companies. Secondly, regarding whether competition effects or contagion effects will prompt companies to choose safety investment, the more obvious SE of incidents on food safety is, the more likely that companies will choose safety investment. Other conclusions could also be drawn. Both large and small companies choose safety investment that is mainly influenced by the cost structure of small companies, and both choose food fraud that is mainly influenced by the cost structure of large companies. There are positive incentives, increasing the costs that companies pay after food fraud is identified, as well as reducing the opportunity cost of safety investment, both of which incentivize companies to choose safety investment. To realize the goal of reducing food safety risks and to solve the food safety problem, the government should intervene and regulate the market from a new orientation, as a critical external participant.

First, the government should allocate different regulatory resources to different costs of food safety management behaviors or technologies and should focus on monitoring behaviors or technologies of food fraud that provide higher returns to the company. This conclusion is derived from Lemmas 1-3, Proposition 1-4, and Policy Corollary 1. For behaviors or technology of food fraud that provides lower returns, market mechanisms can be used to achieve regulatory goals. In that manner, the cost of food safety management behavior or technology should be the focus of policy research. A wide belief is that economic evaluation of food safety measures is a critical tool for company and government performance evaluation (Zan et al., 2017). However, the conclusion of this article reveals that government should also analyze the cost of food safety management behavior or technology of companies. Food safety management behavior or technology is not only the concern of natural science, but also social science needs to study.

Second, starting with the "Safety First" or "Consumer First" principle, the government should not reduce spillover effects of food safety incidents but should instead increase the spillover effects of food safety incidents, increasing the probability that the industry will choose safety investment. This conclusion is derived from Lemmas 4, Proposition 5-6, and Policy Corollary 2. From the perspective of the industry, food safety incidents are mainly manifested as a "Fall Together" contagious effect, which has a significant negative impact on the industry. From the perspective of the government and consumers, spillover effects of food safety incidents are more similar to a "Collective Punishment Mechanism." Joint responsibilities cause the companies involved monitor each other through contractual relationships, hoping for the result of multiwin rather than multilose. This joint responsibility between companies in the same industry creates the demand for industry associations, which restrict the behavior of companies in the industry through industry norms, to reduce the collective punishment of society for the industry (Zhang, and Deng, 2003). In terms of policy design, the active role of industry associations in food safety governance should be emphasized.

Third, the government should increase the penalties for companies that commit food fraud, to prompt the industry to choose safety investment. This conclusion is derived from Proposition 7 and Policy Corollary 3. This policy has a clear direction: Amplify the various costs that companies must bear after a food safety incident. These costs include penalties from external participants (such as the government) and "vote with your feet" from internal participants (consumers). Notably, this conclusion is based on the assumption that internal and external participants can observe food safety incidents, that is, the degree of information asymmetry of participants regarding food safety incidents is relatively low. This requires more risk communication between internal and external participants, especially on food safety incidents, and the government should play a major role in this and promptly report food safety incidents.

Fourth, the government should increase public investment in technology research and development, reduce the cost of safety investment, or increase the use cost and technology cost of food fraud, to promote the industry to choose safety investment. This conclusion is derived from Proposition 8 and Policy Corollary 4. Food safety has "quasi-public goods" attributes; thus, the increase in the investment in research and development of technologies must be government-led. However, the government's understanding of increasing the cost of food fraud is not comprehensive. Specifically, the government can not only increase the technical cost of food fraud but also increasing the cost of the usage of food fraud. For example, for dairy products, "melamine" is an example, if the technical cost of synthesizing melamine is much higher than the production cost of milk powder, or melamine cannot be easily obtained, a company has no incentive to add melamine to milk powder. The government can refer to the management of dangerous goods and supervise some low-cost food frauds from the source.

The conclusion of this article is mainly aimed at the subdivided food industries with a large number of companies and the government can’t fully supervise, that is, the conclusion of this paper is more suitable for the complete competition market and monopoly competition market. As mentioned above, an important assumption of evolutionary game theory is that there are many participants. In most food industries in developing countries, there are many participants, while in developed countries, the situation is somewhat different.

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Table 1

Examples of the most concerning food safety incidents in China from 2005 to 2020

No.	Incidents	First Report	Recent Report	No.	Incidents	First Report	Recent Report
1	Aquatic product "Malachite Green"	2005	2018	7	Dairy Products "Industrial Gelatin"	2011	2020
2	Livestock Products "Sudan Red"	2006	2013	8	Livestock Products "Saccharin"	2013	2020
3	Dairy Products "Melamine"	2008	2008	9	Livestock Products "Zombie Meat"	2015	2020
4	Edible Oil Product "Ditch oil"	2010	2020	10	Takeaway Products "Unhygienic Production"	2016	2020
5	Livestock and Poultry Products "Clenbuterol"	2011	2020	11	Takeaway Product "Inferior Cooking Bag"	2018	2020
6	Health products, Liquor "Plasticizer"	2011	2020	12	Bee Products "Fake Honey"	2018	2020

Note: The authors sought the data from relevant news and government notices. "First Report" means adverse effects first identified and "Recent Report" means hazards removed from the market.

Table 2

Cost and benefit of the company's food safety management

	Food fraud	Direction of influence	Safety investment	Direction of influence
Cost analysis	Industry losses after participants identify corporate behavior	Rise	Production cost of food	Rise
	Direct corporate losses (e.g., government penalties) after participants identify corporate behavior	Rise		
	Indirect corporate losses (e.g., reduced willingness to pay by consumers) after participants identify corporate behavior	Rise		
Benefit analysis	Production cost of food	Fall	Benefits from fulfilling food safety social responsibility	Rise
			Benefits from product premiums and capital investment after comparison with other companies	Rise

Table 3

Benefit matrix of food safety management for large and small companies

Large companies	Small companies	
	Safety investment (*y*)	Food fraud (*1-y*)
Safety investment (*x*)	$-\Delta C$， $-\Delta C$	$V-\Delta C-rD$， $-rL_2-\alpha rD$
Food fraud (*1-x*)	$-kL_1-kD$， $V-\Delta C-\alpha kD$	$-L_1-D$， $-L_2-\alpha D$

Table 4

Conditions of system of replication dynamics and equilibrium point

	Symbol of b_1	Symbol of b_2	Symbol of b_1-b_3	Symbol of b_2-b_4	Number of Equilibrium Points	ESS
Condition 1	-	-	+	+	5	(0,0)、(1,1)
Condition 2	+	+	+	+	4	(1,1)
Condition 3	-	-	-	-	4	(0,0)

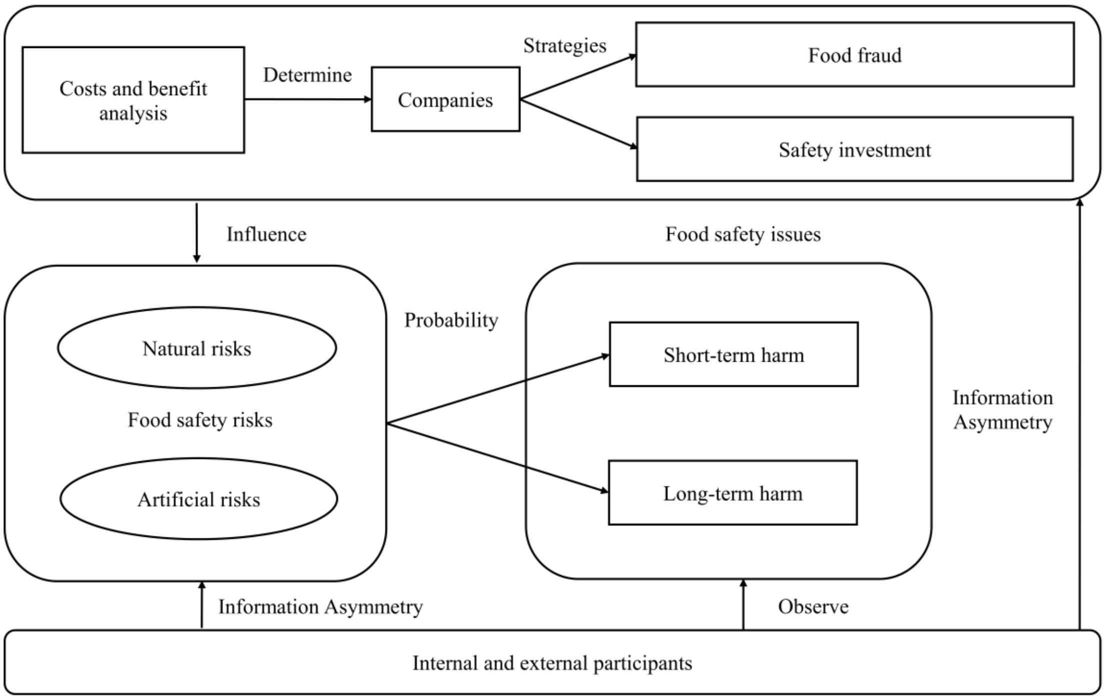

Figure 1

Relationship between food safety risks, food safety management, and food safety issues

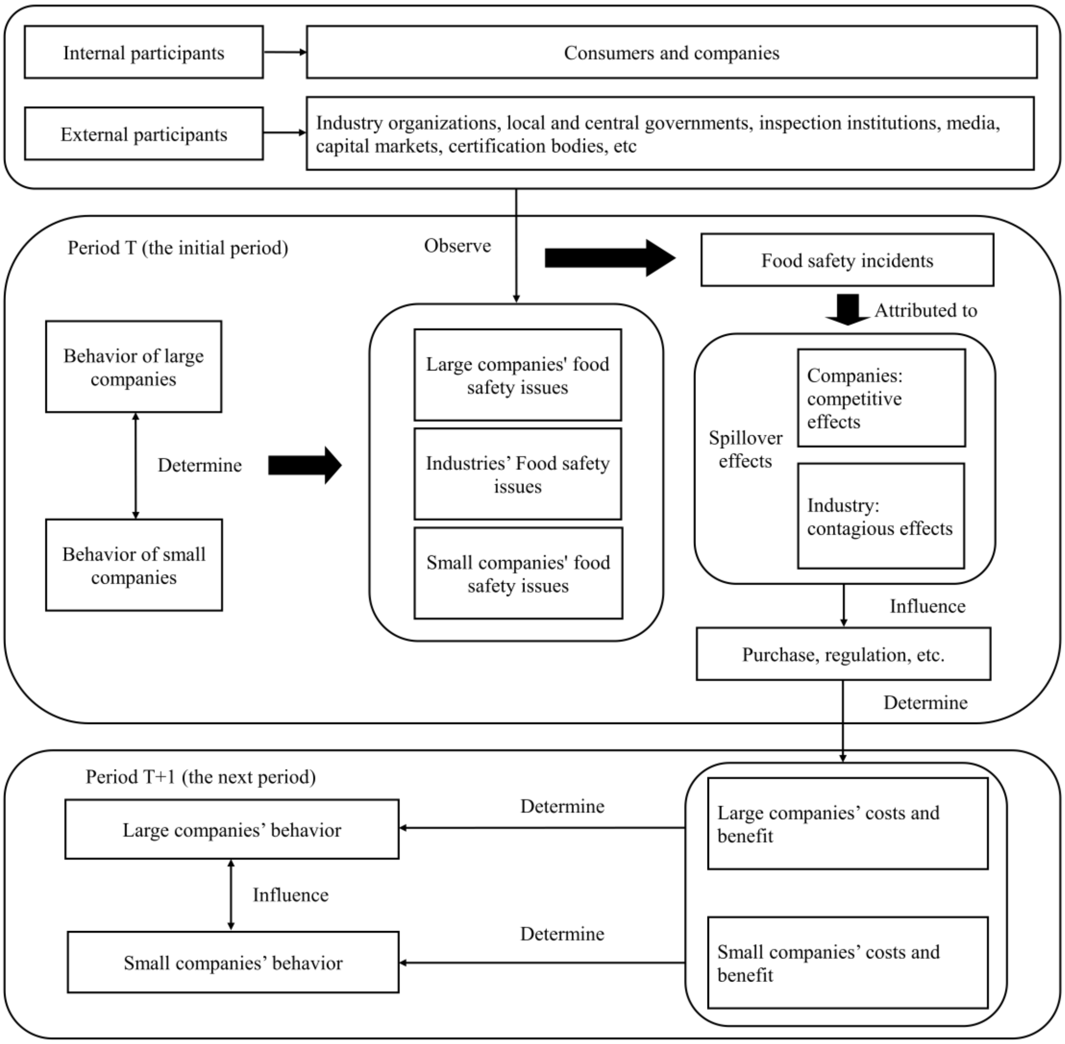

Figure 2

Analysis of the formation mechanism of the company's food safety management

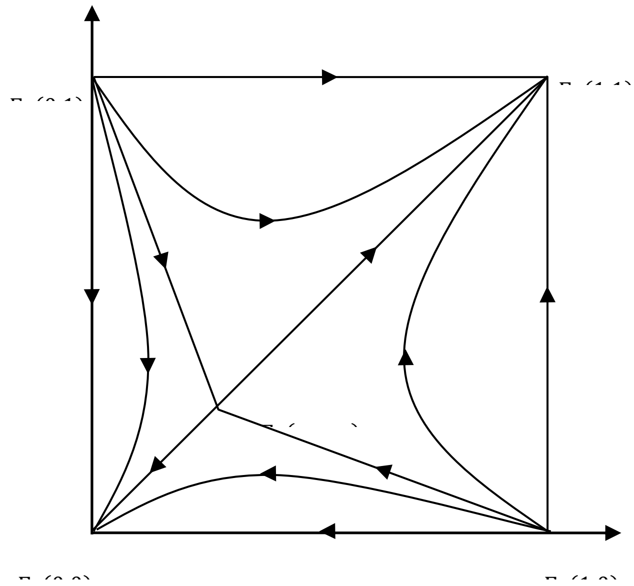

Figure 3

Phase diagram of the dynamic evolution of a five-equilibrium system