Zero Determinant Strategy to Enhance Environmental Protection Cooperation of Enterprises

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Abstract. Industrial enterprises are the main source of environmental pollution in our country, which has caused great damage to the ecological environment. The government has been paying more attention to environmental protection, but previous studies have focused on the one-way influence of the government on industrial enterprises, ignoring the two-way relationship between the government and industrial enterprises, and the interaction between enterprises and enterprises. Enterprise is designed to maximize their own interests, which damages system performance. In this paper, we simulate the interaction between government and enterprises, enterprises and enterprises as a repeated game to guide enterprises in their efforts to reduce pollution. We apply a zero determinant (ZD) strategy for the government and enterprises. No matter what their opponents do, they are able to defend their interests with their ideal values and find the conditions for their best. Numerical results demonstrate the performance of the two zero determinant strategies that are recommended.

Keywords. Zero determinant game; environmental protection; cooperation.

1. Introduction
For a long time, China’s traditional economic development has led to the shortage and depletion of many natural resources, and the contradiction between resources and environment is increasingly acute. The direct cause of energy conservation and emission reduction is the pressure from the resource environment, enterprises generally lack the investment and behavior of energy conservation and emission reduction. The government should encourage enterprises to reduce environmental pollution and implement energy conservation and emission reduction through policies. This paper uses game theory to put forward a zero determinant strategy for the government and enterprises. The government provides financial subsidies, taxes, fines and other factors for enterprises, as well as the profits that enterprises get from environmental protection work, and promotes enterprises to invest in environmental protection work and maximize the benefits.

On the dilemma of environmental pollution, public goods theory and externality theory have made profound explanations: environmental resources usually belong to the category of public goods, thus determining that public and enterprise behaviors (such as water pollution emissions) have significant negative externalities, thus making Nash equilibrium emissions exceed Pareto optimal emissions, resulting in “tragedy of the commons” [1]; The openness of environmental pollution enterprise behavior provides an opportunity for enterprises to demonstrate selfish behavior. For example,
Enterprises can participate in low-quality solutions, namely “free riding” [2], which will harm the overall interests. Thus, environmental governance is not only a technical problem, but also a realistic dilemma under the action of different interest demands and behavior-oriented conflicts of complex stakeholders [3]. Therefore, classical game theory is widely used to reveal the interests and actions of multiple stakeholders. Authors in Ref. [4] discussed the relationship between the responsibility requirements and behaviors of the government, enterprises, villagers and village committees in the process of rural water environment governance by using incomplete information game theory. The research shows that the strategies and behaviors of all parties' interest subjects are mutually restricted. Refs. [5-6] respectively established evolutionary game models of public participation in environmental behavior of enterprises, environmental protection behavior of government and social subjects, and pollution discharge behavior of government and enterprises, and analyze evolutionary phase diagrams and evolutionary stability strategies of two games of public, enterprise and government under different situations. The evolutionary game model of local government and local government, local government and sewage enterprise, local government and central government is constructed in Refs. [7-8], the evolution law of behavior of enterprises and the strategy of evolution stability are analyzed, and the factors influencing the environmental supervision strategy of local government are obtained.

To ensure the high efficiency of pollution control, we face a challenging problem, which is how to encourage cooperation among selfish enterprises [9]. In recent years, researchers have proposed some methods to strengthen business cooperation. One way is to rely on the price mechanism [10]. There are also ways to use the paid auction mechanism to solve tasks that require multiple companies, which makes the requester need to set a large number of rewards to motivate the company [11]. The author in Ref. [12] designed an asymmetric full-pay competition model. The incentive mechanism model takes into account the company’s belief in cooperation, with the goal of maximizing the income generated by cooperation. Another method is based on the reputation mechanism [13], and the company's decision depends on the historical strategies of other companies. In Ref. [14], the binary reputation mechanism is applied so that even if the reputation is updated incorrectly, the best social benefits can be achieved. Both methods have advantages and disadvantages. The pricing method mechanism is simple in design, but it is difficult to implement in practical applications; the reputation strategy is more complicated, which is equivalent to a more complex reputation update, so as to achieve the goal of not relying on the “central bank” to control currency [15].

At the same time, game theory has developed into a widely used mathematical tool for studying the competitive relationship of rational individuals [16-17]. In the field of repeated game research, zero determinant strategy (ZD strategy) is used as a new probability and conditional strategy to deal with the problem of “free rider” [18]. Through the ZD strategy, one participant can unilaterally set the expected return of the other participant, or set the ratio between the expected returns of both parties regardless of the opponent's strategy [19].

In this article, our main goal is to promote companies to participate in environmental protection tasks, that is, to contribute hard behavior in environmental protection work. We establish the interaction between enterprises and enterprises as a non-cooperative repeated game model, and apply ZD strategies to deal with the “free rider” behavior of enterprises. Therefore, the enterprise can unilaterally maintain the interests of the enterprise under the circumstance of the enterprise’s efforts to invest in environmental protection, so that it can reach the expected and stable value.

The rest of this article is arranged as follows: The second part elaborates on corporate environmental protection issues and describes the model. The third part proposes the ZD strategy to strengthen cooperation between enterprises and analyzes the conditions needed to maximize social welfare. In the fourth part, the ZD strategy of environmental protection game is numerically simulated. Finally, the fifth part is the conclusion.

2. Model Description

Suppose a local government and all its polluting enterprises form a game system. Participants in the game include local governments and polluting enterprises. Payoff includes tax relief, environmental protection funds invested by the government in enterprises, and avoidance of punishment (hereinafter collectively referred to as reward). Environmental protection task is that the local government requires polluting enterprises to reach environmental targets, which can be divided into $K$ categories.
according to pollution or enterprise characteristics. When the local government issues pollution control tasks and sets rewards for the tasks, the polluting enterprises get and complete the corresponding tasks. For a certain task \( k \) completed, the local government will allocate the corresponding reward \( r \) to the enterprises that contribute to the task \( k \). In this paper, we focus on a type of task, assuming that the task needs multiple polluting enterprises to complete. We propose a model in which the government allocates the corresponding task types according to the pollution types and capabilities of enterprises.

Therefore, in the aforementioned game system, we define the interaction between enterprises as “competition”. In the course of each competition, we specify the environmental protection tasks to be completed by the enterprises, and each enterprise will solve the corresponding tasks to obtain rewards. Suppose there are two companies X and Y, and they perform tasks in a competitive manner (the method proposed in this article is also applicable to multiple companies). In fact, companies choose strategies rationally in order to maximize their own interests. When an enterprise accepts a task, each enterprise can perform the task with two attitudes of effort \( E \) or no effort \( N \), that is, the enterprise can choose two strategies: \( E \) and \( N \). If both enterprises choose \( E \) or \( N \), and use cost \( c \) or 0 to complete the task accordingly, each enterprise will be rewarded \( 2r \) or 0; When an enterprise chooses \( N \) (the cost of consumption is 0), another enterprise should pay \( c' (c' > 2c) \). The payoff matrix between two enterprises is expressed as table 1.

Table 1. Payoff matrix of enterprises X and Y.

|       | \( X \) | \( E \) | \( N \) |
|-------|--------|--------|--------|
| \( X \) | \( \frac{r}{2} - c, \frac{r}{2} - c \) | \( \frac{r}{2} - c', \frac{r}{2} \) |
| \( E \) | \( \frac{r}{2}, \frac{r}{2} - c' \) | \( 0,0 \) |
| \( N \) | \( \frac{r}{2} - c' \) |

From the above table, we believe that there are two Nash equilibriums in the game, namely \( (E,N) \) and \( (N,E) \). In equilibrium, no enterprise will unilaterally deviate from its current state to obtain higher returns. In this case, both companies only consider their own interests and ignore the other's behavior, resulting in lower overall returns. The overall return of Nash equilibrium is lower than the return of joint efforts. However, if the company repeats the interaction, the situation will change. Repeated gaming means that each company needs to consider its own behavior, whether it will affect the future feedback of other companies. In Ref. [18], Press and Dyson proved that using ZD probabilistic strategies in repeated games can force the expected returns of two companies into a fixed linear relationship. In the next section, we consider the repeated game model and apply the ZD strategy of repeated games to achieve higher overall returns.

3. Game Analysis of Zero Determinant Strategy
Firstly, the ZD game model is regarded as a two-person two-strategy game. When both enterprises choose \( E \) (cooperate), the payoff of each enterprise is \( \frac{r}{2} - c \), when both parties choose \( N \) (betray), the payoff of both are 0. When one party cooperates and the other party chooses to betray, the one who chooses to cooperate gets the reward \( \frac{r}{2} - c' \), while the one who betrays gets the highest payoff \( \frac{r}{2} \). Figure 1 describes the corresponding payoff.
Memory-one game is commonly used in games with repeated zero determinant strategy. Repeated game model refers to two identical enterprises playing multiple rounds of repeated games. Enterprises may be able to infer to a certain extent the strategy that opponents will adopt in the current round from the results of the previous round of games. Compared with short-term memory, long-term memory does not bring any advantages to enterprises. Using one-step memory game, the strategies of the two enterprises in the current iteration only depend on the results of the previous round. In the previous round, according to the choices made by the two enterprises respectively, four output results will be obtained, \( xy \in \{EE, EN, NE, EE\} \), of which the \( E \) and \( N \) represents efforts or not to put into environmental protection work. Correspondingly, the environmental protection utility (payoff) generated by the two enterprises can be expressed as vector \( R_x = \left( \frac{r}{2} - c, \frac{r}{2} - c, \frac{r}{2} - c, 0 \right) \) and \( R_y = \left( \frac{r}{2} - c, \frac{r}{2} - c, \frac{r}{2} - c, 0 \right) \). In the current case, enterprise X’s strategy is expressed in \( p = (p_1, p_2, p_3, p_4) \) as the probability that the current round will choose to collaborate under four different outputs in the previous round. Enterprise Y’s strategy is similar to that of X and is recorded as \( q = (q_1, q_2, q_3, q_4) \). The mixed strategy \( p \) or \( q \) shows the cooperation probability corresponding to the four results \((EE, EN, NE, EE)\). In the current round, the behaviors selected by the two enterprises are represented by the product of probabilities, as shown in table 2.

**Table 2.** One-step memory strategies of two enterprises.

| Y   | E   | N   |
|-----|-----|-----|
| X   |     |     |
| E   | \( p_i q_i \) | \( p_i (1-q_i) \) |
| N   | \( (1-p_i) q_i \) | \( (1-p_i)(1-q_i) \) |

In table 2, X and Y represent the two participating enterprises, \( E \) and \( N \) respectively represent the strategies adopted by enterprises X and Y in the previous round. \( p_i q_i, p_i (1-q_i), (1-p_i) q_i \), and \( (1-p_i)(1-q_i) \) \((i, j \in 1, 2, 3, 4)\) refers to the probability that the current round of selection strategy \( xy \in \{EE, EN, NE, NN\} \) corresponds to the case of the previous step of selecting cooperation. For example, if both enterprise X and Y have chosen \( E \) in the previous step, then in this round, the probability of enterprise X choosing \( E \) is \( p_1 \), and the probability of enterprise Y choosing \( E \) is \( q_1 \). Then the probabilities choosing \( N \) of enterprise X and enterprise Y are \( (1-p_1) \) and \( (1-q_1) \) respectively. Therefore, according to the output result \( EE \) of the previous round, the probabilities of selecting strategies \( \{EE, EN, NE, NN\} \) in this round are \[ [p_i q_i, p_i (1-q_i), (1-p_i) q_i, (1-p_i)(1-q_i)] \] respectively.

According to the principle shown in table 2, this means that there is a Markov matrix composed of \( p \) and \( q \), which contains a stable vector \( v \) and can combine the respective profit matrices to produce an expected result for each enterprise. Equation (1) represents a Markov transition matrix for rows and columns from the previous action to the next action in the order of X.

\[
M = \begin{bmatrix}
p_i q_i & p_i (1-q_i) & (1-p_i) q_i & (1-p_i)(1-q_i) 
p_i q_i & p_i (1-q_i) & (1-p_i) q_i & (1-p_i)(1-q_i) 
p_i q_i & p_i (1-q_i) & (1-p_i) q_i & (1-p_i)(1-q_i) 
p_i q_i & p_i (1-q_i) & (1-p_i) q_i & (1-p_i)(1-q_i)
\end{bmatrix}
\]
Obviously, the sum of each row in the matrix $M'$ is 1, so there is a unit eigenvalue, from which it can be concluded that the matrix $M' = M - I$ is singular. Therefore, the stable vector $\mathbf{v}$ of this Markov matrix, or any vector proportional to it, $\mathbf{v}'M = \mathbf{v}'$ will be satisfied, or $\mathbf{v}'M = 0$.

In addition, using Kramer’s law on the matrix $M'$ can obtain $\text{Adj}(M')M' = \det(M')I = 0$. Where $\text{Adj}(M')$ is the adjoint matrix of the matrix $M'$. Each line of $\text{Adj}(M')$ described in the above formula is proportional to $\mathbf{v}'$. Because $\text{Adj}(M')$ is the adjoint matrix of matrix $M'$, so

$$\text{Adj}(M') = \begin{bmatrix}
d_{11} & d_{21} & d_{31} & d_{41} \\
d_{12} & d_{22} & d_{32} & d_{42} \\
d_{13} & d_{23} & d_{33} & d_{43} \\
d_{14} & d_{24} & d_{34} & d_{44}
\end{bmatrix}$$

Among them $d_{ij} = (-1)^{i+j} \det(M_{ij})$. Selecting the fourth row of the matrix $\text{Adj}(M')$, $[v_1, v_2, v_3, v_4] \propto [d_{14}, d_{24}, d_{34}, d_{44}]$ can be obtained ($\mathbf{v}' = [v_1, v_2, v_3, v_4]$). And if we add the first column of the matrix $M'$ to the second and third columns, the value of the determinant $\det(M_{ij})$ will not change. Because,

$$M' = M - I =$$

$$\begin{bmatrix}
-1+p_1q_1 & p_1(1-q_1) & (1-p_1)q_1 & (1-p_1)(1-q_1) \\
p_1q_2 & p_2(1-q_2)-1 & (1-p_2)q_2 & (1-p_2)(1-q_2) \\
p_1q_3 & p_3(1-q_3) & (1-p_3)q_3 & (1-p_3)(1-q_3) \\
p_1q_4 & p_4(1-q_4) & (1-p_4)q_4 & (1-p_4)(1-q_4)-1
\end{bmatrix}$$

For an arbitrary vector $\mathbf{f} = [f_1, f_2, f_3, f_4]^T$, the point multiplication of the vectors $\mathbf{f}$ and $\mathbf{v}$ is as follows:

$$\mathbf{v} \cdot \mathbf{f} = \mathbf{v}' \mathbf{f} = [v_1, v_2, v_3, v_4] \begin{bmatrix}
f_1 \\
f_2 \\
f_3 \\
f_4
\end{bmatrix}$$

$$= \det\begin{bmatrix}
-1+p_1q_1 & -1+p_1 & -1+q_1 & f_1 \\
p_1q_2 & -1+p_2 & q_2 & f_2 \\
p_1q_3 & p_3 & -1+q_3 & f_3 \\
p_1q_4 & p_4 & q_4 & f_4
\end{bmatrix} = D(p,q,\mathbf{f})$$

It is worth noting that the result of the $\mathbf{v} \cdot \mathbf{f}$ can be expressed by a determinant, in which the second column is $\mathbf{p} = (-1+p_1, -1+p_2, p_3, p_4)$ controlled solely by enterprise X; The third column is $\mathbf{q} = (-1+q_1, q_2, -1+q_3, p_4)$, decided by enterprise Y alone; The fourth column has only vector $\mathbf{f}$.

At the same time, under the order of strategy $xy \in \{EE, EN, NE, NN\}$, the single-round payoff vector of enterprise X is $R_x = \left( \frac{r}{2} - c, \frac{r}{2} - c, \frac{r}{2}, 0 \right)^T$, and the single-round payoff of enterprise Y is $R_y = \left( \frac{r}{2} - c, \frac{r}{2} - c, \frac{r}{2}, 0 \right)^T$. Therefore, in a stable state, the corresponding expected payoff is
where all component in vector $\mathbf{1}$ are 1. The denominator is to ensure that the sum of all components in the vector $\mathbf{v}$ is 1, which is a condition to be satisfied by a stable probability vector.

It is easy to prove that the expected payoff $w_x$ and $w_y$ in equation (5) linearly depend on their corresponding payoff vectors $\mathbf{R}_x$ and $\mathbf{R}_y$. Similarly, any linear combination of these two expected payoff will also satisfy this relationship, so we get

$$aw_x + \beta w_y + \delta = \frac{D(\mathbf{p,q},dR_x + \beta R_y + \delta \mathbf{1})}{D(\mathbf{p,q})}$$

From equation (6), we can see that both enterprises X and Y have a certain chance to choose a strategy that can unilaterally make the determinant on the right 0. More specifically, if the strategy selected by enterprise X is satisfied $\mathbf{p} = \alpha \mathbf{R}_x + \beta \mathbf{R}_y + \delta \mathbf{1}$, or the strategy selected by enterprise Y is satisfied $\mathbf{q} = \alpha \mathbf{R}_x + \beta \mathbf{R}_y + \delta \mathbf{1}$, the determinant value in the right molecule in equation (6) will be 0, and the linear relationship between $w_x$ and $w_y$,

$$\alpha w_x + \beta w_y + \delta = 0$$

This is the zero determinant strategy mentioned earlier [7]. Based on equation (7), when enterprise X adopts ZD strategy, no matter what strategy enterprise Y adopts, the expected returns of enterprise X and Y are linearly related, and $\alpha/\beta \leq 0$. Enterprise X's strategy $\mathbf{p}$ should meet

$$
\begin{bmatrix}
p_1 - 1 \\
p_2 - 1 \\
p_3 \\
p_4 \\
\end{bmatrix} = 
\begin{bmatrix}
\alpha (r/2-c) + \beta (r/2-c) + \delta \\
\alpha (r/2-c) + \beta r/2 + \delta \\
\alpha r/2 + \beta (r/2-c) + \delta \\
\alpha 0 + \beta 0 + \delta \\
\end{bmatrix}
$$

For probability $0 \leq p_i \leq 1(i = 1,2,3,4)$, we can get the following range:

$$
\begin{align*}
0 \leq (\alpha (r/2-c) + \beta (r/2-c) + \delta + 1) & \leq 1 \\
0 \leq (\alpha (r/2-c) + \beta r/2 + \delta + 1) & \leq 1 \\
0 \leq (\alpha r/2 + \beta (r/2-c) + \delta) & \leq 1 \\
0 & \leq \delta \leq 1
\end{align*}
$$

By transforming the above formula, we can get the range of parameters $\alpha$, $\beta$ and $\delta$,

$$
\begin{align*}
-1 & \leq \alpha / \beta \leq 0 \\
\delta & \leq \min\left(-\alpha (r/2-c) - \beta (r/2-c), -\alpha (r/2-c) - \beta r/2\right) \\
\delta & \geq \max\left(-\alpha r/2 - \beta (r/2-c), 0\right)
\end{align*}
$$
According to the conditions of (9), the strategy used by enterprise Y is evolving continuously, and it attempts to maximize its own interests against the behavior of enterprise X adopting ZD strategy. According to the above conditions, it can be concluded that when enterprise X adopts ZD strategy to realize \( \alpha w_x + \beta w_y + \gamma = 0 \), and \( \alpha/\beta < 0 \), enterprise Y wants to maximize its ultimate expected benefits.

In fact, our goal is to make both enterprises make great efforts in environmental protection. When Enterprise X aims to achieve the highest overall payoff, X ZD adopt strategy. X can unilaterally set the long-term payoff of enterprise Y at a fixed value. In order to achieve this goal, only \( \alpha = 0 \) at that time, enterprise X can use ZD strategy to achieve \( w_y = -\delta/\beta \), thus producing \( w_y = -\delta/\beta \).

Substituting \( w_y = -\delta/\beta \) into equation (8), the ZD strategy adopted by enterprise X can be expressed as follows:

\[
\begin{align*}
p_1 &= 1 + \beta \left( \frac{r/2 - c}{w_y} \right) + \delta \\
p_2 &= 1 + \beta \left( \frac{r/2}{w_y} \right) + \delta \\
p_3 &= \beta \left( \frac{r/2 - c}{w_y} \right) + \delta \\
p_4 &= \delta
\end{align*}
\]

When \( r/2 > c > c \), the following two conditions were met:

\[
\begin{align*}
0 \leq \delta &\leq \min \left( \frac{w_y}{r/2 - c - w_y}, \frac{w_y}{r/2 - w_y} \right) \\
&\leq \min \left( \frac{-\delta}{r/2 - c}, \frac{-\delta}{r/2 - c}, \frac{1 - \delta}{r/2 - c} \right)
\end{align*}
\]

After transformation, \( p_1, p_2, p_3, p_4 \) can be used to express \( \beta \) and \( \delta \). In addition, the expected payoff of enterprise Y can be expressed by \( p_1 \) and \( p_4 \) only (HH and NN strategies were adopted in the previous round). The expected payoff is expressed as follows:

\[
w_y = \frac{p_4 (r/2 - c)}{p_4 - p_1 + 1}
\]

In other words, when enterprise X adopts the strategy \( \tilde{p} = p_W + \delta \mathbf{1} \), he can control the payoff of enterprise Y within a certain range. In fact, it can be deduced that enterprise X can unilaterally control the long-term payoff of enterprise Y within the scope \( [r/2 - c, r/2 - c] \).

When enterprise X aims to achieve the highest overall payoff, ZD strategy can be adopted. At this time, enterprise Y obtains the greatest payoff when both parties cooperate with each other and the lowest payoff when both parties betray. Therefore, ZD strategy can promote enterprise cooperation.
and obtain maximum overall benefits. In addition, we consider the game between the government and enterprises according to the same theory. The government can use the above ZD strategy to control the overall payoff and the expected payoff of enterprises.

4. Numerical Simulation

In order to evaluate the social performance of the ZD strategy, we conducted a simulation experiment to compare the ZD probability strategy \([1, 0.987, 0.025, 0.05]\), Tit-for-Tat (TFT) \([1, 0, 1, 0]\), Pavlov \([1, 0, 0, 1]\), and a strategy arbitrarily \([0.4, 0.3, 0.2, 0.1]\). Set \(c = 1, c' = 3, r = 10\) in below simulations.

As shown in figure 1, enterprise X adopts ZD strategy and enterprise Y adopts strategy \(q = [1, 0, 0, 1]\), so that the overall social payoff and enterprise payoff can be stably maintained at a high value. However, in figure 2, when enterprise X uses Tit-for-Tat, enterprise Y adopts Pavlov, and the total payoff and the payoff of enterprise are lower than when X adopts ZD strategy. In figure 3, when enterprise X adopts ZD strategy and enterprise Y adopts strategy \(q = [0.4, 0.3, 0.2, 0.1]\), it shows that the overall social payoff and the utility of the two enterprises can also maintain a relatively high stable state. However, figure 4 shows that when enterprise X applies Pavlov strategy and Y applies \(q = [0.4, 0.3, 0.2, 0.1]\), the overall social benefits will be lower. Finally, in figure 5, when both enterprises X and Y adopt ZD strategy, the expected payoff of the two enterprises is the same. Compared with other situations, the overall social payoff reaches the highest value at this time.

![Figure 1: Enterprise X adopts ZD strategy, Enterprise Y adopts Pavlov strategy.](image1)

![Figure 2: Enterprise X uses TFT, Enterprise Y adopts Pavlov strategy.](image2)

![Figure 3: Enterprise X adopts ZD strategy, enterprise Y adopts \(q = [0.4, 0.3, 0.2, 0.1]\).](image3)

![Figure 4: Enterprise X adopts Pavlov strategy, enterprise Y adopts \(q = [0.4, 0.3, 0.2, 0.1]\).](image4)
5. Conclusion
In this paper, we consider the cooperation of environmental pollution enterprises and apply ZD strategy to analyze the process of enterprise cooperation. Among them, enterprises adopting ZD strategy can set the payoff of their opponents regardless of their behaviors, keep the overall payoff at the expected value, and find the conditions to achieve the maximum overall payoff. The theory can also be used in the game between the government and enterprises. The government can use ZD strategy to control the expected payoff and the overall payoff of enterprises. In addition, we carry out numerical simulation and analysis on the probability strategy. Experiments show that the adoption of ZD strategy can promote the cooperation between enterprises and maximize the overall social benefits.

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