The Applicable Conditions of Incentive Contract for Knowledge Sharing in Industrial Construction Supply Chain Based on Evolutionary Game Theory

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Abstract. Knowledge sharing is fundamental for improving knowledge system of industrial construction, and incentive contract is considered important means to promote knowledge sharing. This study aims to analyze the applicable conditions of incentive contract for knowledge sharing and provide guidance for core enterprises to formulate incentive contracts to promote knowledge sharing between member enterprises. Based on evolutionary game theory, an incentive model of knowledge sharing is developed. By solving the model, it is shown that the preconditions for applying incentive contract in industrial construction supply chain are that output capacity of knowledge sharing is higher than the cost, and incentive coefficient is more than the ratio of costs to outputs; and if knowledge sharing is implemented in industrial construction supply chain, the conditions should be satisfied, which are that the output capacity of knowledge sharing is higher than the sum of cost and risk, and the incentive intensity is higher than the ratio of the sum of cost and risk to the output capacity. These conclusions help us to formulate reasonable incentive mechanism.

1. Introduction
The implementation of industrial construction can be effectively promoted by supply chain management [1] and a complete knowledge system can effectively improve the performance of supply chain management from the perspective of knowledge management [2]. Knowledge sharing is regarded as the foundation of knowledge management and it is a process of diffusion across time and space from the knowledge owner to the knowledge receiver, which is achieved by communication between organizations [3]. The function is to realize the value increment of knowledge by promoting the integration of multi-knowledge [4]. However, the industrial construction supply chain involves many enterprises including design, production, transportation, and installation [5]. This knowledge sharing represents inter-organizational characteristics. At the same time, as knowledge is private capital and the core competitiveness of an enterprise, it is difficult to achieve knowledge sharing among organizations in a complex market environment considering the risks [6]. In addition, knowledge sharing is also limited by multiple factors, such as capital, time, and space, thereby reducing the efficiency of knowledge sharing in the industrial construction supply chain.

Incentive contract is important in defining financial and other rights and is required for knowledge sharing [7]. The purpose of the incentive contract is to promote—by means of economic
compensation—the behavior of knowledge sharing in the supply chain; this enhances the knowledge fit and the overall improvement of knowledge \[4\]. In the knowledge management of the industrial construction supply chain, knowledge sharing is a voluntary behavior. Because knowledge has the characteristics of privacy and value, when the benefit of knowledge sharing is less than the cost, the member enterprises are reluctant to share knowledge in the industrial construction supply chain. In order to improve knowledge sharing between member enterprises in industrial construction supply chain, core enterprises need to formulate incentive contracts to promote knowledge sharing behavior. However, before formulating these contracts it is difficult for core enterprises to judge whether the incentive coefficient in the contracts can promote knowledge sharing in industrial construction supply chain. Therefore, it is necessary to study the applicable conditions of incentive contract for knowledge sharing to provide guidance for core enterprises to formulate the incentive contracts in the industrial construction supply chain.

2. Research method

The methodology adopted in this paper is based on evolutionary game theory. The evolutionary game theory has been widely used in economics, finance, and organizational behavior to address work relationships and issues related to outcomes, uncertainty and risk \[8-11\]. In general, there is no knowledge sharing in contracts between member enterprises of industrial construction supply chain. In order to obtain better benefits, they will seek knowledge sharing in the process of project implementation, and this relationship is formed in the game. At the same time, they will change their strategies according to each other’s strategies. Thus, evolutionary game theory can be used in this study. Summarizing the previous literatures, the procedure of using the principal-agent theory is provided as follows:

- Step 1: Relevant hypotheses of the study are proposed.
- Step 2: The payment matrix of game based on the hypothesis is established.
- Step 3: The expected earnings function and dynamic replication equation of the participants in the game are provided.
- Step 4: According to the dynamic replication equation, the equilibrium points are obtained, and the Jacobian matrix is established based on Friedman\[12\] method.
- Step 5: The local stability of equilibrium points is analyzed.

3. An evolutionary game model of knowledge sharing based on incentive contract

An evolutionary game model of knowledge sharing based on incentive contract is proposed by this study, and it is used to analysis applicable conditions of the incentive contract. Before establishing the model, some assumptions are made based on relevant assumptions about the model of knowledge sharing, and relevant parameters are set in table 1, as follows:

H1. The income of incentive contract is calculated by linear incentive function, which is mainly composed of fixed income and knowledge sharing effort values. If the enterprises choose strategy N, they can still get fixed income in the incentive contract.

H2. If the enterprise chooses strategy S, the cost of knowledge sharing is also linearly related to their effort values.

H3. If the enterprise chooses different strategies, the risk taken by the party choosing strategy S has a linear relationship with their effort value.

| Code | Parametric description                                      |
|------|-----------------------------------------------------------|
| E    | Income of enterprise in the incentive contract            |
| e    | Knowledge sharing effort level of enterprise              |
| m    | Knowledge sharing output coefficient of enterprise        |
| n    | Risk coefficient of enterprise choosing strategy S       |
| β    | Incentive coefficient of enterprise in the incentive contract, 0<β<1 |
α Fixed income of enterprise in the incentive contract
q Cost coefficient of enterprise choosing strategy S
x The probability that enterprise 1 chooses strategy S, 0<x<1.
1-x The probability that enterprise 1 chooses strategy N
y The probability that enterprise 2 chooses strategy S, 0<y<1.
1-y The probability that enterprise 2 chooses strategy N

Based on the above hypotheses and game model of knowledge sharing, the evolutionary game model of knowledge sharing based on incentive contract in the industrial construction supply chain is established.

When the incentive contract is introduced, the knowledge sharing earnings function, cost function and risk function of enterprise 1 and enterprise 2 are expressed as follows:

\[ E = \alpha + \beta m e \]  
\[ C = q e \]  
\[ f = n e \]  

Then, when both enterprise 1 and enterprise 2 choose strategy N, the earnings function is expressed as follows:

\[ F(N, N) = \alpha \]  

When both enterprise 1 and enterprise 2 choose strategy S, the earnings function is expressed as follows:

\[ F(S, S) = E - C \]  

When both enterprise 1 and enterprise 2 choose different strategies, the earnings function of the enterprise who chooses strategy S is expressed as follows:

\[ F(S, N) = E - C - f \]  

When both enterprise 1 and enterprise 2 choose different strategies, the earnings function of the enterprise who chooses strategy N is expressed as follows:

\[ F(N, S) = \alpha \]  

According to the above functions, the payment matrix of knowledge sharing based on incentive contract is established, as shown in table 2.

Table 2. Payment matrix of knowledge sharing based on incentive contract

| Enterprise 1 | Enterprise 2 |
|-------------|-------------|
| S (y)       | N (1-y)     |
| S (x)       |             |
| a_1 + \beta_1 s_1 e_1 - q_1 e_1, & a_1 + \beta_1 s_1 e_1 - q_1 e_1 - n_1 e_1, |
| a_2 + \beta_2 s_2 e_2 - q_2 e_2 & a_2 |
| N (1-x)     |             |
| a_1, & a_1, a_2 |

The expected earnings function and reproduction dynamic equation of enterprise 1 and enterprise 2 are expressed as follows:

\[ \frac{dx}{dt} = x(1-x) \left[ y n_1 e_1 + \beta_1 m_1 e_1 - q_1 e_1 - n_1 e_1 \right] \]  
\[ \frac{dy}{dt} = y(1-y) \left[ x n_2 e_2 + \beta_2 m_2 e_2 - q_2 e_2 - n_2 e_2 \right] \]  

Then, the optimal probabilities that enterprise 1 and enterprise 2 choose strategy S can be obtained by making simultaneous equations (8) and (9) equal to 0:
From (14) and (15), there are five local equilibrium points, namely, (0, 0), (0, 1), (1, 0), (1, 1) and (x*, y*). The Jacobian matrix can be calculated as follows:

\[
J = \begin{bmatrix}
(t - 2x)yn_1e_1 + \beta_2m_1e_1 - q_1e_1 - n_1e_1 \\
y(t - y)n_2e_2 - (t - 2y)[x_2n_2e_2 + \beta_2m_2e_2 - q_2e_2 - n_2e_2]
\end{bmatrix}
\]

Then, the stability analysis functions of the equilibrium points can be obtained by analyzing the structure of Jacobian matrix, it is shown in table 3.

Table 3. Stability analysis functions of game of knowledge sharing based on incentive contract

| Equilibrium points | TrJ | DetJ |
|--------------------|-----|------|
| (0, 0)             | -\beta_1a_1e_1 + q_1e_1 + n_1e_1 | (\beta_1a_1e_1 - q_1e_1 - n_1e_1) |
|                    | - \beta_2a_2e_2 + q_2e_2 + n_2e_2 | (\beta_2a_2e_2 - q_2e_2 - n_2e_2) |
| (0, 1)             | \beta_1a_1e_1 - q_1e_1 - \beta_2a_2e_2 | (\beta_1a_1e_1 - q_1e_1 - \beta_2a_2e_2) |
|                    | + q_2e_2 + n_2e_2 | (\beta_2a_2e_2 - q_2e_2 - \beta_1a_1e_1) |
| (1, 0)             | \beta_1a_1e_1 - q_1e_1 - n_1e_1 | (\beta_1a_1e_1 - q_1e_1 - n_1e_1) |
|                    | + \beta_2a_2e_2 - q_2e_2 | (\beta_2a_2e_2 - q_2e_2 - \beta_1a_1e_1) |
| (1, 1)             | \beta_1a_1e_1 - q_1e_1 - n_1e_1 | (\beta_1a_1e_1 - q_1e_1 - n_1e_1) |
|                    | + \beta_2a_2e_2 - q_2e_2 - n_2e_2 | (\beta_2a_2e_2 - q_2e_2 - n_2e_2) |
| (x*, y*)           | 0 | (\beta_1a_1e_1 - q_1e_1 - \beta_2a_2e_2) |

According to the results of the stability analysis in table 3, the evolutionary game model of knowledge sharing based on incentive contract can be analyzed for different values of incentive coefficient, respectively, risk coefficient and cost coefficient.

(1) If \(\beta_1<q_1/m_1\) and \(\beta_2<q_2/m_2\), \(x*>1\) and \(y*>1\), which are not satisfied by the hypotheses. Thus, in this case, the evolutionary game model of knowledge sharing based on incentive contract only has four equilibrium points, namely (0 0), (0, 1), (1,0) and (1, 1). Then, local stability of these equilibrium points is analyzed, and it shows in table 4.

Table 4. Results of local stability analysis when \(\beta_1<q_1/m_1\) and \(\beta_2<q_2/m_2\)

| Equilibrium points | TrJ | DetJ | Local stability |
|--------------------|-----|------|-----------------|
| (0, 0)             | -   | +    | ESS             |
| (0, 1)             | +   | -    | Unstable        |
| (1, 0)             | +   | -    | Unstable        |
| (1, 1)             | +   | -    | Unstable        |

According to the results of the stability analysis in table IV, when \(\beta_1<q_1/m_1\) and \(\beta_2<q_2/m_2\), the dynamic phase of the evolutionary game of the knowledge sharing based on incentive contract between enterprise 1 and enterprise 2 in industrial construction supply chain is shown in figure 1.

The analysis results in table IV and figure 1 show that only one of the four equilibrium points has local stability, namely O point (0,0). It shows that if \(\beta_1<q_1/m_1\) and \(\beta_2<q_2/m_2\) in incentive contract,
whatever initial strategy choice is made, member enterprises will not share knowledge with repeated games in industrial construction supply chain.

Further, if \( q_1/m_1 > 1 \) and \( q_2/m_2 > 1 \), based on the hypotheses there is only one result that is \( \beta_1 < q_1/m_1 \) and \( \beta_2 < q_2/m_2 \). It shows that when the cost coefficient of knowledge sharing is higher than the output coefficient, even core enterprises want to use incentive contracts to promote knowledge sharing, the member enterprises will not share knowledge in industrial construction supply chain.

Fig 1. Dynamic phase when \( \beta_1 < q_1/m_1 \) and \( \beta_2 < q_2/m_2 \)

(2) If \( (n_1+q_1)/m_1 > \beta_1 > q_1/m_1 \) and \( (n_2+q_2)/m_2 > \beta_2 > q_2/m_2 \), the evolutionary game model of knowledge sharing based on incentive contract only has four equilibrium points, namely \((0,0)\), \((0,1)\), \((1,0)\), \((1,1)\) and \((x^*, y^*)\). Then, local stability of these equilibrium points is analyzed, and it shows in Table 5.

Table 5. Results of local stability analysis when \((n_1+q_1)/m_1 > \beta_1 > q_1/m_1\) and \((n_2+q_2)/m_2 > \beta_2 > q_2/m_2\)

| Equilibrium points | TrJ | DetJ | Local stability |
|--------------------|-----|------|-----------------|
| \((0,0)\)          | +   |      | ESS             |
| \((0,1)\)          |     |      | Unstable        |
| \((1,0)\)          | -   |      | Unstable        |
| \((1,1)\)          |     | +    | ESS             |
| \((x^*, y^*)\)      | 0   |      | Saddle point    |

According to the results of the stability analysis in Table 5, when \((n_1+q_1)/m_1 > \beta_1 > q_1/m_1\) and \((n_2+q_2)/m_2 > \beta_2 > q_2/m_2\), the dynamic phase of the evolutionary game of the knowledge sharing based on incentive contract between enterprise 1 and enterprise 2 in industrial construction supply chain is shown in Figure 2.

Fig 2. Dynamic phase when \((n_1+q_1)/m_1 > \beta_1 > q_1/m_1\) and \((n_2+q_2)/m_2 > \beta_2 > q_2/m_2\)

The analysis results in Table 5 and Figure 2 show that there are two local equilibrium points, including O point \((0,0)\) and C point \((1,1)\), and there is a saddle point, namely D point. It shows that if
\[(n_1+q_1)/m_1>\beta_1>q_1/m_1\text{ and } (n_2+q_2)/m_2>\beta_2>q_2/m_2\] in incentive contract, when \(x>x^*\) and \(y>y^*\), member enterprises will share knowledge with repeated games. In contrast, member enterprises will not share knowledge with repeated games in industrial construction supply chain.

Further, the probability of selecting strategy \(S\) is constituted by the area of triangle \(CDA\) and triangle \(CDB\) from figure 2. Similarly, the probability of selecting strategy \(N\) is constituted by the area of triangle \(ODA\) and triangle \(ODB\). \(S_S\) and \(S_N\) are used to represent the probability of strategy \(S\) and \(N\), and their functional equation is expressed as:

\[
S_S = \frac{1}{2} \left( \frac{n_1 + q_1 - \beta_1 m_1}{n_1} - \frac{n_2 + q_2 - \beta_2 m_2}{n_2} \right),
\]

\[
S_N = \frac{1}{2} \left( \frac{n_1 + q_1 - \beta_1 m_1}{n_1} + \frac{n_2 + q_2 - \beta_2 m_2}{n_2} \right).
\]

According to formula 38, the relationships between \(S\) and \(n, q, m, \beta\) are determined by the method of partial derivatives. Then, taking \(S_S\) as an example, the calculation results are as follows:

\[
\frac{\partial S_S}{\partial q_1} = \frac{1}{n_1} < 0, \quad \frac{\partial S_S}{\partial q_2} = \frac{1}{n_2} < 0, \quad \frac{\partial S_S}{\partial \beta_1} = \frac{m_1}{n_1} > 0, \quad \frac{\partial S_S}{\partial \beta_2} = \frac{m_2}{n_2} > 0, \quad \frac{\partial S_S}{\partial m_1} = \frac{\beta_1}{n_1} > 0,
\]

\[
\frac{\partial S_S}{\partial m_2} = \frac{\beta_2}{n_2} > 0, \quad \frac{\partial S_S}{\partial n_1} < 0, \quad \frac{\partial S_S}{\partial n_2} < 0.
\]

The above calculation results show that \(q_1, q_2\) and \(n_1, n_2\) are monotone-increasing function of \(S_S\), and \(m_1, m_2\) and \(\beta_1, \beta_2\) are monotone-decreasing function of \(S_S\). This indicates that improving the output coefficient and incentive coefficient of knowledge sharing can promote the probability of selecting strategy \(S\), and reducing cost and risk coefficient can also promote the probability of selecting strategy \(S\).

(3) When \(\beta_1>(n_1+q_1)/m_1\text{ and } \beta_2>(n_2+q_2)/m_2\), \(x^*<0\) and \(y^*<0\), which are not satisfied by the hypotheses. Thus, in this case, the evolutionary game model of knowledge sharing based on incentive contract only has four equilibrium points, namely \((0, 0), \(0, 1\), \(1,0)\) and \((1, 1)\). Then, local stability of these equilibrium points is analyzed, and it shows in table 6.

| Equilibrium points | TrJ | DetJ | Local stability |
|-------------------|-----|------|-----------------|
| \((0, 0)\)       | +   | +    | Unstable        |
| \((0, 1)\)       | +   | -    | Unstable        |
| \((1, 0)\)       | +   | -    | Unstable        |
| \((1, 1)\)       | -   | +    | ESS             |

According to the results of the stability analysis in table VI, when \(\beta_1>(n_1+q_1)/m_1\text{ and } \beta_2>(n_2+q_2)/m_2\), the dynamic phase of the evolutionary game of the knowledge sharing based on incentive contract between enterprise 1 and enterprise 2 in industrial construction supply chain is shown in figure 3.

Fig 3. Dynamic phase when \(\beta_1>(n_1+q_1)/m_1\text{ and } \beta_2>(n_2+q_2)/m_2\)
The analysis results in table VI and figure 3 show that there is only one local equilibrium point, namely C point (1, 1). It shows that if $\beta_1 > (n_1 + q_1)/m_1$ and $\beta_2 > (n_2 + q_2)/m_2$ in incentive contract, whatever initial strategy is made, member enterprises will share knowledge with repeated games in industrial construction supply chain.

In addition, if $n_1 + q_1 > m_1$ and $n_2 + q_2 > m_2$, based on the hypotheses it will not be happened that $\beta_1 > (n_1 + q_1)/m_1$ and $\beta_2 > (n_2 + q_2)/m_2$. It shows that when the output coefficient of knowledge sharing is higher than the sum of cost and risk coefficient, core enterprises can use incentive contract to ensure that member enterprises share knowledge in industrial construction supply chain.

4. Discussion

This paper has established an evolutionary game of knowledge sharing based on incentive contract in industrial construction supply chain, and the evolutionary rules of selecting knowledge sharing strategy based on incentive contract are revealed. The results are shown that introducing incentive contract can promote knowledge sharing between member enterprises in industrial construction supply chain. The result is consistent with many previous studies [9-13]. At the same time, this study also finds that the output capacity and incentive intensity of knowledge sharing have a positive impact on the probability of selecting knowledge sharing strategy, and the risk and cost have a negative impact on it in industrial construction supply chain. These findings are supported by many research literatures [8-11]. In addition, this study further finds that if the output capacity of knowledge sharing is less than the cost or incentive coefficient is less than the ratio of costs to outputs, the incentive contract can not promote knowledge sharing between member enterprises, therefore, the core enterprises need to meet two preconditions to formulate incentive contract promoting knowledge sharing between member enterprises in industrial construction supply chain, one is that the output capacity of knowledge sharing is higher than the cost, the other is that incentive coefficient is more than the ratio of costs to outputs. Meanwhile, in order to ensure that the incentive contract can make member enterprises to share knowledge, two conditions must be satisfied at the same time. One condition is that the output capacity of knowledge sharing is higher than the sum of cost and risk, the other condition is that the incentive intensity is higher than the ratio of the sum of cost and risk to the output capacity in industrial construction supply chain.

The research findings provide many valuable implications for practitioners. First, as knowledge sharing in industrial construction supply chain is a long-term and constantly changing process, in order to accurately grasp the information that are cost, risk, output and other of knowledge sharing, core enterprises should make a survey before formulating incentive contracts. When the cost coefficient of knowledge sharing is higher than the output coefficient, corresponding measures should be taken to reduce the cost or increase the output, and then the incentive contract should be used to promote knowledge sharing. Second, strengthening the development of knowledge sharing channels in industrial construction supply chain for reducing the cost and risk, such as using information technology [14-15]. Finally, although incentive contract could promote knowledge sharing, the preconditions of application need to be satisfied. Meanwhile, knowledge sharing between member enterprises in industrial construction supply chain can be further realized by adjusting the incentive coefficient.

5. Conclusion

In order to explore the application conditions of incentive contract for knowledge sharing in industrial construction supply chain, this study provides an evolutionary game model of knowledge sharing based on incentive contract, and the evolutionary rules of selecting knowledge sharing strategy based on incentive contract are revealed. The analysis results show the preconditions for applying incentive contract are that output capacity of knowledge sharing is higher than the cost, and incentive coefficient is more than the ratio of costs to outputs in industrial construction supply chain. It is also found that in order to achieve knowledge sharing in industrial construction supply chain, the conditions should be satisfied, which are that the output capacity of knowledge sharing is higher than the sum of cost and...
risk, and the incentive intensity is higher than the ratio of the sum of cost and risk to the output capacity. In addition, the relationships are revealed that the output capacity and incentive intensity of knowledge sharing have a positive impact on the probability of selecting knowledge sharing strategy, and the risk and cost have a negative impact on it in industrial construction supply chain. The results of this study provide theoretical support for applying incentive contract promoting knowledge sharing in industrial construction supply chain, and provide many implications for practitioners. At the same time, this study expands the application scope of evolutionary game theory.

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