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Dynamic Reputation Incentive Mechanism for BIM application in construction project

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Abstract: Building Information Modeling (BIM) is driving the innovation of construction project management and the development of the architecture, engineering and construction (AEC) industry. BIM application ability can effectively improve the competitiveness of AEC firms in the future market. However, in the actual construction project, the cost-benefit disequilibrium and information asymmetry among the participants seriously hinder the application and promotion of BIM. For dealing with the problem, this paper constructs a two-phase dynamic incentive model combining dual reputation incentive and explicit incentive for BIM application, and compares it with the explicit incentive model without considering reputation mechanism. Through the model itself and the comparison results, it can deduce the efficient equilibrium condition of dual reputation incentive model and the effective interval to achieve Pareto Optimality. The research results show that under certain conditions, introducing reputation mechanism can better motivate contractors to apply BIM in construction projects. Further research can consider the interaction between contractors to optimize the dual reputation incentive model.

Keywords： Building Information Modeling (BIM), Reputation mechanism, Incentive

INTRODUCTION

Construction project is an activity that integrates preliminary planning, scheme design, construction management, and property management. In the life cycle of a construction project, there are a large number of project participants, and the project information content is diverse and the number is huge. Therefore, problems such as fuzzy information data and serious loss of information often appear in collaborative management of construction projects. In turn, the management efficiency of the construction project is reduced, and it may even affect the normal operation of the construction project.

In recent years, Building Information Modeling (BIM) has triggered a tremendous change in AEC industry, which kindles more and more construction projects to implement BIM technology. BIM is a digital modern information technology platform, which can simulate all aspects of the whole life cycle of construction project design, construction, and operation through parameterized models.Studies have shown that BIM helps to integrate many functions of the construction industry to create a more interactive information sharing space, which leads to a significant improvement in the efficiency of construction project management.

However, existing studies show that even though BIM has obvious advantages in improving the efficiency of project management, BIM can only be applied to individual links of construction projects in practice. Shafiq et al. (2013) believe that the application of BIM in construction projects is limited to visualization and clash detection.

Construction projects to promote BIM will appear these problems mainly because there is a typical principal-agent (PA) relationships between the owner, the designer, the construction party and other contractors in construction projects (Zheng et al. 2017). Compared with the ordinary construction projects, project participants using BIM for project collaborative management makes imbalances of principal and agent ’ s costs and benefits more obvious. Specifically, using BIM to achieve collaborative management of construction projects means that agents (designers, construction parties, etc., hereinafter collectively referred to as "contractors") in PA relationship need to invest more costs and energy to master and apply BIM, such as introducing BIM technology and training BIM technicians, etc (collectively referred to as "BIM efforts" in this paper). Meanwhile, the owner as the principal can have a clear advantage in the cost-benefit problem. Firstly, the application of BIM will effectively improve the design quality of buildings. Detailed and accurate construction data can not only enable owners to undertake activities such as budgeting and tender-evaluating than before (Staub-French et al., 2011), but also significantly reduce the number of rework during the construction phase. Further, construction project participants through BIM information platform to realize sharing information, which can shorten the construction period, reduce the construction cost and effectively reduce the maintenance cost in the later period of the construction. That is to say, most of the participants who invest BIM efforts in BIM-based construction projects are agents, while most of the incremental benefits brought by them belong to the owners who are the principals. This is cost-benefit disequilibrium in PA relationship. In addition, from the perspective of information economics, there is obvious information asymmetry between the principal and the agent of the construction project (Ji et al.2020). The principal is in an information disadvantage and cannot accurately observe the behavior of the agent, the moral hazard problem hence appears. Under the dual influence of the cost-benefit disequilibrium and information asymmetry between the principal and the agent, based on the hypothesis of "economic man" in economics, an agent in a position of information superiority will weaken the client's goal and maximize its self-interests, which will make the construction project management unable to realize the Pareto Optimality.

Academia has always believed that incentive and punishment are effective mechanisms for improving the effectiveness of inter-organizational cooperation. The effect issues associated with BIM must be balanced by incentive in order to realize its full potential. As such, designing a reasonable and effective incentive mechanism is significant for the application of BIM in construction projects. Cao et al. (2016) study the incentive effect of four types of motivation on BIM implementation and conclude that image motivation and cross-project economic motivation are currently the strongest reasons for motivating project participants to implement BIM in construction projects. In addition, Chang. (2014) study the relationship between the implementation goals of BIM and the incentive of the project participants.

Features construction project determines the PA relationships between project participants generally is not a one-off, but multiple and dynamic. The principal hence can resort to the incentive dynamic improvement mechanism to motivate the agent, so as to expand the application degree of BIM in construction projects. Contractual relationship and reputation mechanism are commonly used to realize the dynamic improvement of the incentive mechanism in academia. Reputation incentive first put forward by Fama, it considers reputation incentive can serve as an incomplete replacement of incentive for contractors by owners. Even without explicit incentive, contractors will improve their current and future income by improving their reputation in the market. Branconi (2004) argues that implicit reputation incentive has a positive effect on avoiding speculation by agents. Shi et al. (2017) construct a multi-stage dynamic incentive model combining dual reputation and explicit incentive for the incentive of major project factory prefabricators. In addition, studies shows that reputation mechanism has a significant role in facilitating the implementation of BIM. Participants with high BIM capabilities seek to maximize BIM implementation to demonstrate their BIM capabilities, and thus to avoid their established image for embracing advanced technologies being contaminated. (Cao et al. 2016).

Through the above analysis, this paper finds that cost-benefit disequilibrium and information asymmetry of both parties in the PA relationship of construction projects must be fully considered, when promoting the application of BIM in ACE industry. Grounded in reputation mechanism，this paper hence constructs a two-phase dynamic incentive model combining dual reputation incentive and explicit incentive for BIM application in construction projects through the evolutionary game of reputation incentive between owner and contractors. The remainder of this paper is organized as follows. The next section puts forward the relevant hypotheses of the model, and constructs the dual reputation incentive model and explicit incentive model without considering reputation mechanism of BIM application. Section 3 calculates and analyzes the results of the model, and summarizes the effective equilibrium conditions and the effective range of the model for the introduction of the reputation mechanism to achieve incentives. Section 4 discusses the research results, summarizes the full text, and points out the deficiencies of the article and future research directions.

RESEARCH HYPOTHESES AND MODEL

The meanings of each role in this model are shown in Table 1.

2.1 Research hypotheses

Hypothesis 1. Both the owner and the contractor are completely rational, and they make decisions with the goal of maximizing the expected utility function of their own benefits.

Hypothesis 2. The owner of the construction project is the principal, and all parties other than the owner are agents. Each agent has the same output function, effort cost function and risk aversion degree for the investment of BIM. The cost-benefit impact between the various agents brought by BIM is negligible. All agents of the project are considered as a whole.

Hypothesis 3. The incentive contract based on the reputation mechanism is long-term and dynamic, which is usually divided into t phases. At the starting point of each phase, the principal has an estimate of the agent's qualifications , and the incentive contract in the latter phase is often affected by the effect of the contract in the previous phase. This paper divides the construction project into two phase .

Hypothesis 4. The output function of the contractor in phase t is Eq. (1).

$$x_t = h\gamma_t + ke_t + \varepsilon_t \quad (1)$$

In this paper, BIM output is the incremental benefits of BIM efforts in construction projects, which has various forms.

Hypothesis 5.BIM efforts will bring incremental costs. In practice, the cost will increase with the level of effort. The Contractor's efforts to upgrade a unit will cost more and more. The cost function hence is Eq. (2).

$$C(t) = \frac{\alpha e_t^2}{2(1+\theta)} = \frac{\alpha e_t^2}{2\phi} \quad (2)$$

In the cost function $0 < \theta < 1$, $(1+\theta)$ reflects the mechanism of implicit reputation incentive. Grounded in dual reputation incentive theory, the contractors with higher reputation value are more likely to receive the project, and the future revenue will increase accordingly. This model is measured by the reduction of current cost.

Hypothesis 6. The compensation function provided by the owner to the contractor in phase t is linear.

$$S_t = \varpi_t + \beta_t x_t \quad (3)$$

Hypothesis 7. The owner is risk neutral. The contractor is willing to pay the cost to avoid the risk, which is the risk averse type. Eq. (4) is the risk cost function of the contractor.

$$F_t = \frac{1}{2}\rho \mathrm{Var}(S_t) \quad (4)$$

Table 1

Symbols throughout the paper

Symbols	Explanation
x_t	Contractor's output in phase t
γ_t	Explicit reputation of contractor phase t (the contractor's ability and reputation), $\gamma_t \sim N(0,\ \sigma_\gamma^2)$
e_t	The level of effort the contractor put into BM in phase t (BIM effort)
h	Explicit reputation coefficient (the coefficient for the contractor to convert explicit reputation such as ability and reputation into output)
k	The effort level coefficient
ε_t	Exogenous random variables independent of BIM effort affecting the output function of phase t, $\varepsilon_t \sim N(0,\ \sigma_\varepsilon^2)$.
α	Marginal cost coefficient, （$\alpha > 0$）
ϕ	Implicit reputation incentive coefficient, $1 < \phi < 2$。
ϖ_t	Fixed remuneration paid by owner to contractor in phase t contract
β_t	Incentive coefficient provided by owner to contractor in phase t contract
ρ	Absolute risk aversion of contractors, $\rho > 0$

2.2 Two-phase dynamic incentive model combining dual reputation incentive and explicit incentive

2.2.1 Game process between principal and agent

In each phase, the owner formulates ϖ_t and β_t to maximize his own benefits under the constraints of IC and IR of the contractor. According to the given ϖ_t and β_t, the contractor chooses the appropriate e_t to maximize his own benefits.

2.2.2 Optimal incentive model of phase 2

1. Expected function of income

Under the rational assumption, the owner can observe the output of phase 1 at the beginning of phase 2. The owner hence can amend contractor's reputation according to x_1 and $\widehat{e_1}$ using Bayes' theorem ($\widehat{e_1}$ is the owner's inferred value of the contractor's 1 phase BIM effort level), and the amended 2 phase reputation is z, $z = E(\gamma_2|x_1)$. Grounded in the dual reputation incentive principle, the model introduces the key parameter τ to represent the explicit reputation factors.

$$\tau = \frac{\mathrm{Var}(h\gamma_1)}{\mathrm{Var}(h\gamma_1)+\mathrm{Var}(\varepsilon_1)} = \frac{h^2\sigma_\gamma^2}{h^2\sigma_\gamma^2+\sigma_\varepsilon^2} \quad (5)$$

$$z = E(\gamma_2|x_1) = \frac{[h\sigma_\gamma^2(x_1 - k\widehat{e_1}) + \sigma_\varepsilon^2\bar{\gamma}]}{h^2\sigma_\gamma^2+\sigma_\varepsilon^2} \quad (6)$$

$$\mathrm{Var}(\gamma_2|x_1) = \frac{h^2\sigma_\gamma^4}{h^2\sigma_\gamma^2+\sigma_\varepsilon^2} = \tau\sigma_\gamma^2 \quad (7)$$

The above formula indicates that the owner will amend contractor's reputation based on the observed information (that is "explicit reputation factor"). The degree of amendment will increase with the uncertainty of reputation, $0 < \tau < 1$.

The certainty equivalence income of risk neutral person is equal to the mean value of random income. And the certainty equivalence income of risk averse is equal to the mean value of random income minus risk cost. The expected function income of contractor in 2 phase is Eq. (8).

$$E(I_A) = E(S_2) - C(2) - F_t \quad (8)$$

The expected function of the contractor's income as follows.

$$E(I_{A2}) = \varpi_2 + \beta_2(hz + ke_2) - \frac{\alpha e_2^2}{2\phi} - \frac{1}{2}\rho\beta_2^2\left(h^2\tau\sigma_\gamma^2 + \sigma_\varepsilon^2\right) \quad (9)$$

The expected function of the risk neutral owner's income in 2 phase is Eq. (10).

$$E(I_P) = E(x_2) - E(S_2) \quad (10)$$

Simplify.

$$E(I_{P2}) = hz + ke_2 - [\varpi_2 + \beta_2(hz + ke_2)] = (1-\beta_2)(hz + ke_2) - \varpi_2 \quad (11)$$

2. Individual Rationality Constraint (IR Constraint)

Individual Rationality Constraint (IR Constraint) requires that the expected income in each phase of the contractor should not be less than the retained utility $\overline{\varpi_t}$ (,usually taking the empirical value of the ACE industry). Phase 1 outputs enhance the contractor's bargaining power in phase 2 contract negotiations, thereby changing the opportunities for external options. Thus, based on the general rule of double reputation incentive model, $\overline{\varpi_2} = f[E(I_{A2}) + E(I_{P2})]$.

IR_2 hence can be expressed as Eq. (12).

$$E(I_{A2}) = \varpi_2 + \beta_2(hz + ke_2) - \frac{\alpha e_2^2}{2\phi} - \frac{1}{2}\rho\beta_2^2\left(h^2\tau\sigma_\gamma^2 + \sigma_\varepsilon^2\right) \geq \overline{\varpi_2} \quad (12)$$

3. Incentive Compatibility Constraint (IC Constraint)

Incentive Compatibility Constraint (IC Constraint) requires that the BIM effort e_t selected by the contractor at each phase can maximize its own expected income. That is to say, $e_2 \in \arg\max E(I_{A2})$. Hence, IC_2 can be expressed as Eq. (13).

$$e_2 \in \arg\max\left[\varpi_2 + \beta_2(hz + ke_2) - \frac{\alpha e_2^2}{2\phi} - \frac{1}{2}\rho\beta_2^2\left(h^2\tau\sigma_\gamma^2 + \sigma_\varepsilon^2\right)\right] \quad (13)$$

4. The incentive model of phase 2 and its solution

To sum up, the incentive model of 2ed phase is as follows.

$$\max_{\varpi_2,\beta_2,e_2} E(I_{P2}) = (1-\beta_2)(hz + ke_2) - \varpi_2 \quad (14)$$

$$s.t\begin{cases} E(I_{A2}) \geq \overline{\varpi_2} & (IR_2) \\ e_2 \in \arg\max[E(I_{A2})] & (IC_2) \end{cases} \quad (15)$$

Academic research shows that IC constraint can be replaced by the first derivative of its equivalent function equal to zero (Wu el al.2007). Thus, $k\beta_2 - \frac{\alpha}{\phi}e_2 = 0$ can be obtained from $\frac{\partial E(I_{A2})}{\partial e_2} = 0$. Because $\frac{\partial^2 E(I_{A2})}{\partial e_2^2} = -\frac{\alpha}{\phi} < 0$, then there is e_2 make $E(I_{P2})$ take the maximum value.

The contractor's optimal BIM effort level in phase 2 can be expressed by Eq. (16).

$$e_2 = \frac{k\phi}{\alpha}\beta_2 \quad (16)$$

Under ideal conditions, IR is an active constraint. Thus, $E(I_{A2}) = \overline{\varpi_2} = f[E(I_{A2}) + E(I_{P2})]$.

It turns out that there exists β_2 that maximizes $E(I_{P2})$.

$$\beta_2 = \frac{k^2\phi}{k^2\phi + \alpha\rho\left(h^2\tau\sigma_\gamma^2 + \sigma_\varepsilon^2\right)} \quad (19)$$

2.2.3 Optimal incentive model of phase 1

Prior to the start of phase 2, the owner determines the incentive for phase 2 by judging the level of the contractor's reputation based on the observed outputs for phase 1. Hence, the difference between the model in phase 1 and phase 2 lies in that what both parties of PA relationship measure when making decisions is not the short-term gain of phase 1, but the overall gain of the two phases combined.

$$E(I_A) = E(I_{A1}) + E(I_{A2}) \quad (20)$$

$$E(I_P) = E(I_{P1}) + E(I_{P2}) \quad (21)$$

To sum up, the incentive model of 1 phase is as follows. In the model, $\overline{\varpi}$ is the empirical value of the ACE industry.

$$\max E(I_P) \quad (22)$$

$$s.t\begin{cases} E(I_A) \geq \overline{\varpi} & (IR_2) \\ e_1 \in \arg\max E(I_A) & (IC_2) \end{cases} \quad (23)$$

Referring to the solution of the optimal incentive model in 2 phase, $E(I_P)$ can take the maximum value when $e_1 = \frac{k\phi}{\alpha}(\beta_1 - \tau\beta_2)$.

$$\beta_1 = \frac{k^2\phi\tau\beta_2 - \alpha h\hat{\gamma}}{2k^2\phi} = \frac{k^2\phi(1-\tau+\tau\beta_2)}{k^2\phi + \alpha\rho\left(h^2\sigma_\gamma^2 + \sigma_\varepsilon^2\right)} \quad (24)$$

$$e_1 = \frac{k^3\phi^2\left[(1-\tau)k^2\phi - \alpha\rho h^2\sigma_\gamma^2\tau^2 + (1-2\tau)\alpha\rho\sigma_\varepsilon^2\right]}{\alpha\left[k^2\phi + \alpha\rho\left(h^2\sigma_\gamma^2 + \sigma_\varepsilon^2\right)\right]\left[k^2\phi + \alpha\rho\left(h^2\tau\sigma_\gamma^2 + \sigma_\varepsilon^2\right)\right]} \quad (25)$$

2.3 Explicit incentive model without considering reputation mechanism

This paper presents the explicit incentive model without considering the reputation mechanism, and proves the effectiveness of the reputation incentive model by comparing the two models.The specific model is as follows.

$$x = ke + \varepsilon \quad (26)$$

$$C = \frac{\alpha e^2}{2} \quad (27)$$

$$S = \varpi + \beta x \quad (28)$$

$$F = \frac{1}{2}\rho Var(S) = \frac{1}{2}\rho\beta^2\sigma^2 \quad (29)$$

$$E(I_A) = E(S) - C - F \quad (30)$$

$$E(I_P) = E(x) - E(S) \quad (31)$$

To sum up, the explicit incentive model without considering reputation mechanism is as follows.

$$\max_{\varpi,\beta,e} E(I_P) \quad (32)$$

$$s.t\begin{cases} E(I_A) \geq \overline{\varpi_2} & (IR) \\ e \in \arg\max E(I_A) & (IC) \end{cases} \quad (33)$$

$$\beta = \frac{k^2}{k^2 + \alpha\rho\sigma^2} = \frac{k^2}{k^2 + \alpha\rho\left(h^2\sigma_\gamma^2 + \sigma_\varepsilon^2\right)} \quad (34)$$

$$e = \frac{k^3}{\alpha k^2 + \alpha^2\rho\sigma^2} = \frac{k^3}{\alpha k^2 + \alpha^2\rho\left(h^2\sigma_\gamma^2 + \sigma_\varepsilon^2\right)} \quad (35)$$

RESULT AND DISCUSSIONS

3.1 The efficient equilibrium condition of dual reputation incentive model

It can be seen from Eq. (3) that in the two-phase dual reputation incentive model, the owner affects the contractor's future income (S_2) by adjusting the fixed remuneration (ϖ_2) paid to the contractor in the future. After comprehensively considering the whole process of the model construction, this paper concludes that the effective equilibrium conditions for the dual reputation incentive model of BIM application to exert its effect are $f - \beta_2 > 0$ and $e_1 > 0$. The derivation of $-\beta_2 > 0$ and $e_1 > 0$ is made according to the formula in Section 2.

I.

$$f - \beta_2 > 0$$

$$f > \beta_2 = \frac{k^2\phi}{k^2\phi + \alpha\rho\left(h^2\tau\sigma_\gamma^2 + \sigma_\varepsilon^2\right)} \quad (20)$$

II.

$$e_1 = \frac{k\phi}{\alpha}(\beta_1 - \tau\beta_2) > 0$$

$$\beta_1 - \tau\beta_2 > 0$$

$$\frac{k^2\phi\left[(1-\tau)k^2\phi - \alpha\rho h^2\sigma_\gamma^2\tau^2 + (1-2\tau)\alpha\rho\sigma_\varepsilon^2\right]}{\left[k^2\phi + \alpha\rho\left(h^2\sigma_\gamma^2 + \sigma_\varepsilon^2\right)\right]\left[k^2\phi + \alpha\rho\left(h^2\tau\sigma_\gamma^2 + \sigma_\varepsilon^2\right)\right]} > 0$$

$$\phi > \frac{\alpha\rho h^2\sigma_\gamma^2\tau^2 - (1-2\tau)\alpha\rho\sigma_\varepsilon^2}{k^2(1-\tau)}$$

Finally, the effective equilibrium condition of the two-phase dynamic incentive model combining dual reputation incentive and explicit incentive is Eq. (36).

$$\begin{cases} f > \frac{k^2\phi}{k^2\phi + \alpha\rho\left(h^2\tau\sigma_\gamma^2 + \sigma_\varepsilon^2\right)} \\ \phi > \frac{\alpha\rho h^2\sigma_\gamma^2\tau^2 - (1-2\tau)\alpha\rho\sigma_\varepsilon^2}{k^2(1-\tau)} \end{cases} \quad (36)$$

3.2 Efficient interval for Pareto Optimality in dual reputation incentive model

After comparing the incentive effect of the two models， this paper found that the size of any parameter in the model cannot change the two unequal relations between $\beta_2 > \beta$ and $e_2 > e$, namely, $\beta_2 > \beta$ and $e_2 > e$ are always true. Hence, the PA relationship between owner and contractor in construction projects can by introducing reputation incentive mechanism to realize Pareto Optimality, the key depends on whether the model meets the two conditions $\beta_1 < \beta$ and $e_1 \geq e$.

To simplify the results, let $A = \alpha\rho\left(h^2\tau\sigma_\gamma^2 + \sigma_\varepsilon^2\right)$, $B = \alpha\rho\left(h^2\sigma_\gamma^2 + \sigma_\varepsilon^2\right)$. Finally, the effective interval of the Pareto Optimality dual reputation incentive model is Eq. (39). Namely, when the key parameter τ representing explicit reputation factor and the key parameter ϕ representing implicit reputation factor satisfy Eq. (39), Pareto optimality can be achieved by introducing a dual reputation mechanism into the explicit incentive contract provided by the owner.

$$\frac{B[k^2\phi^2+(A-k)\phi-A]}{(k^2+B)A\phi} < \tau \leq \frac{(k^4+k^2B)\phi^3+(k^2A+AB-k^4)\phi^2-(k^2A+k^2B)\phi-AB}{(k^2+B)[k^2\phi^3+(A+B)\phi^2]} \quad (39)$$

CONCLUSIONS

Introducing the explicit reputation incentive for the qualifications of the contractor perceived by the owner and the implicit reputation incentive that reputation can bring higher corporate reputation and future benefits, which can better realize the long-term incentive effect of project contractors. Based on game theory and principal-agent theory, this paper constructs an incentive model , analyzes the effective equilibrium conditions of reputation incentive model, and obtains the efficient interval for Pareto Optimality by comparing with the explicit incentive model without considering the reputation mechanism.The results show that under certain conditions, introducing reputation incentive mechanism can better motivate contractors to apply BIM and achieve Pareto Optimality.

Although this study has some innovations, it is not comprehensive enough to establish the incentive model of BIM application only from the incentive perspective of project management, and there is room for further optimization of the model. Future research can be carried out from this perspective.

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