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CONTRACT THEORY-BASED BLOCKCHAIN REWARD AND PENALTY MECHANISM FOR CONSTRUCTION TENDERING AMONG MULTIPLE STAKEHOLDERS

Zijun Zhan[1], Yaxian Dong[2], Daniel Mawunyo Doe[1], Yuqing Hu[2], Shuai Li[3], Shaohua Cao[4], and Zhu Han[1]
[1]University of Houston, Houston, USA
[2]The Pennsylvania State University, University Park, USA
[3]University of Tennessee, Knoxville, USA
[4]China University of Petroleum (East China), Qingdao, China.

Abstract

With the prosperity of the Web 3.0 era, the construction sector is turning to blockchain-based tendering to address stakeholder conflicts. However, bid rigging among suppliers and information asymmetry between suppliers and the general contractor (GC) potentially undermine the GC utility. To this end, we introduce contract theory into the blockchain-based tendering framework to augment the utility of GC. Simulation results indicate a potential 20.7% profit increase for the GC, due to fostering competition among suppliers, such as material delivery time, compared to traditional blockchain-enabled bidding processes.

Introduction

Construction projects typically require the procurement of materials, a process commonly facilitated via tendering. To select competent and qualified suppliers, the lowest price (Enshassi and Modough, 2012) and comprehensive bid evaluation (van der Meer et al., 2022) methods are primarily employed for their bid evaluation. Meanwhile, the mainstreaming tendering procedures are manual and e-tendering, respectively. However, several drawbacks, such as extremely time-consuming (Santoso and Bourpanus, 2019) and heavily reliant on the third party (Chen et al., 2016), remain in current tendering procedures, thereby posing motivation to augment the accuracy, automation, transparency, security, fairness, and efficiency in terms of the tendering procedures.

To this end, scholars have become increasingly interested in developing efficient and automatic tendering systems (Dong et al., 2023). In addition, in light of the tendering process being mainly used by governments and companies as a dominant procurement method (Mali et al., 2020), security issues are imperative to be resolved. Notably, given the legal and security issues and lack of transparency in the e-tendering process, the authors in (Torkanfar et al., 2023) developed a distributed e-tendering system via the integration of blockchain, public key infrastructure (PKI), and interplanetary file system (IPFS). Meanwhile, with the prosperity of the Web 3.0 era (Zhan et al., 2023), some scholars in the construction domain have attempted to implement blockchain technology into the tendering system to achieve a secure and fair tendering process (Zhang et al., 2023; Yutia and Rahardjo, 2019). In the recent past, a blockchain-based tendering system for construction projects has been proposed, which employs decentralized smart contracts to execute the tendering process, a decentralized storage system to exchange and store relevant off-chain documents, and a decentralized application to enhance interaction between the GC and suppliers (Ahmadisheykhsarmast et al., 2023).

Nevertheless, certain shortcomings persist within the blockchain-based tendering framework. In this framework, the selection of competent suppliers heavily relies on their submitted Request for Proposals (RFPs). In this way, the bidding initiative is not in the hands of GC, thus causing severe consequences, such as prevalent misconduct of bid rigging. In addition, suppliers' confidential information may also compromise the utility[1] of GC. For instance, in the United States, most participants reported experiencing or anticipating delays in the delivery of materials (Alsharef et al., 2021). Apart from this, some truck companies prioritize proximity orders and are reluctant to transport across state lines to avoid the risk of material delivery delays due to policy changes (Ren et al., 2023). Therefore, when facing concurrent material delivery orders, the priority level for delivering GC's material that GC is unknown. Since construction work requires the support of these upstream manufacturing plants and trucking companies in the supply chain, such information asymmetry issues between GC and suppliers might lead to delayed delivery and financial losses. Although penalty clauses are deployed when designing contracts to avoid material delivery delays, such as mandatory fines per day (Bergantiños and Lorenzo, 2019), the GC remains unable to control the risk of delayed material delivery during the supplier screening phase. Therefore, we aim to enhance existing blockchain-based tendering by considering two primary issues, ***i) GC does not completely possess the bidding initiative***, and ***ii) the information asymmetry between the GC and suppliers***.

Methodology

Regarding aforesaid issues, Nobel-winning contract theory (Li et al., 2024) excels in resolving information asymmetry and can transfer the initiative from suppliers to GC ingeniously. To this end, we propose a novel tendering framework that leverages blockchain technology and contract theory together, thereby ensuring a fair and transparent tendering process and optimizing the GC's utility. The proposed framework comprises several key Steps, as depicted in Figure 1. First, the GC will initiate a prequal-

[1]It is a measure of the benefit or value that an individual places on a particular choice.

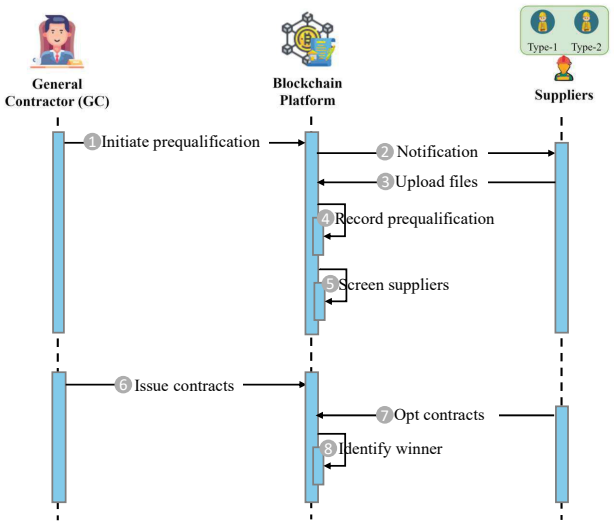


Figure 1: Sequence diagram of blockchain-based and contract theory-enabled tendering.

ification process to screen honest and qualified suppliers for participation in the tendering process. Suppliers will then upload their qualification documents as required by the GC for evaluation. Next, compiled smart contracts will be employed to screen suppliers according to predefined conditions. After that, a set of contract bundles will be designed and issued by the GC based on the contract theory for suppliers. Notably, the contract bundles will be selected by suppliers based on their actual confidential information (Bolton and Dewatripont, 2004). Subsequently, the smart contract will automatically identify the winning supplier based on previously defined metrics. Finally, the GC will sign with the winning supplier. In summary, our main contributions are summarized as follows:

1. To address the bid-rigging issue, we propose a blockchain and contract theory-based tendering framework. This framework enables the GC to take ownership of the tendering process while ensuring a fair and efficient tendering process for suppliers.
2. Under information asymmetry, we systematically model the tendering process of a blockchain-based construction project and formulate an optimization problem with the supplier's delivery time as the optimization variable. To address this problem, we employ contract theory to design a set of contract bundles that compel competition among suppliers under their confidential information.
3. The simulation and related numerical analysis results of the contract theory-based tendering model are presented. We compare the impact of different key parameters on the results and demonstrate the feasibility and effectiveness of the proposed model.

Blockchain-based contract theory procedure

To illustrate the blockchain and contract theory-based tendering framework, especially the connection between the blockchain and contract theory, we will delve into the details of our proposed tendering framework.

Algorithm 1: Blockchain-based contract theory

Input: timestamp, supplierAddress
Output: winning supplier, S_w

1 **if** *Invoke* ***DataCollectorContract*** **then**
  `// Obtain historical data`
2 data ⇐requestHistoricalData(timestamp, supplierAddress);
  `// Provide obtained data to GC`
3 $\mathscr{D}$ ⇐HistoricalDataCollected(timestamp, data);
4 **end**
5 As per $\mathscr{D}$ to partition suppliers into different types, $\theta = \{\theta_H, \theta_L\}$;
  `// Obtain contract bundles`
6 **T** ⇐ContractTheory(θ);
7 **if** *Invoke* ***SupplierSelectionContract*** **then**
  `// Use contract bundles in smart contract`
8 ContractBundle ⇐**T**;
9 Shortlist qualified suppliers;
10 Record selection results of suppliers;
11 Identify the winning supplier, S_w;
12 **end**

First of all, our proposed tendering framework, as depicted in Figure 1, which mechanism is analogous to the blockchain-based tendering framework proposed in (Ahmadisheykhsarmast et al., 2023). The critical difference is that we have integrated the contract theory into the blockchain-based tendering system, Steps 5-8 in Figure 1, and the detailed procedure is illustrated in Algorithm 1. Concretely, GC will first utilize blockchain to collect trustworthy data to evaluate the potential delivery time that suppliers can do (Lines 1-4 in Algorithm 1). Subsequently, as per evaluation results, GC will design contract bundles with the utilization of contract theory (Lines 5-6 in Algorithm 1). Then, the GC will code smart contracts as per calculated contract bundles (Lines 7-12 in Algorithm 1). Eventually, the GC will deploy the smart contract on the blockchain, thus enabling an autonomous and transparent tendering process, i.e., award the material delivery order to the supplier who opts for the strictest contract bundle, thereby effectively reducing the risk of delayed delivery.
It is worth noting that we utilize immutability and transparency two crucial properties of blockchain when designing the tendering framework. As for immutability, GC will trace the historical delivery data of the supplier by using smart contract ***DataCollectorContract***. Regarding transparency, our proposed framework will enable GC and suppliers to oversee the whole tendering process, i.e., the running process of smart contract ***SupplierSelectionContract***, including contract bundle selection and winning supplier identification. In addition, in light of our proposed tendering framework is enhanced as per (Ahmadisheykhsarmast

et al., 2023), thus it can be deployed on the Ethereum [2] as well.

In the remainder of this paper, we will present the mathematical model of blockchain and contract theory-enabled tendering process and numerical simulation comparison results to demonstrate the effectiveness of our proposed framework.

Contract theory model

Contract theory background

We consider K types of construction materials, collectively denoted by $\mathscr{M} = \{M_1, \cdots, M_k, \cdots, M_K\}$, to be tendered in the construction project. The execution sequence and interdependencies of various materials in the construction project implementation plan give rise to varying degrees of importance for different materials. We use δ_k to represent the importance of material M_k. Additionally, each material has a specific delivery time requirement to satisfy construction scheduling needs. While timely delivery of M_k is preferable, advance or delayed delivery may occur due to unforeseen circumstances. For ease of modeling, we assume that regardless of whether M_k is delivered early or late, the difference between the on-time delivery and both the earliest and the latest delivery times are identical.

In this paper, since the tendering process is similar for each material, we only consider the tendering process for M_k. As for tendering, the GC will solicit several suppliers to bid publicly for M_k. Without loss of generality from a mathematical perspective, we assume that GC calls only 2 suppliers to bid for M_k tendering, denoted as $\mathscr{S}_k = \{S_k^1, S_k^2\}$. Akin to (Doe et al., 2023), we can easily extend to a practical scenario where multiple suppliers together tender for M_k.

For simplicity, we will use S_1 and S_2 to represent two suppliers in the remainder of this paper. Each supplier can be denoted as S_n[3] and has a unique identity type, θ_n, corresponding to the material delivery time, which may influence by the count of concurrent delivery and delivery priority level for GC's material that suppliers possess. Due to privacy concerns, the exact identity type of the suppliers is unknown to the GC, resulting in information asymmetry. Thus, the GC can only stipulate the delivery time of M_k based on the public information submitted by suppliers, which we denote as T_k^{max}. However, setting the delivery time as T_k^{max} may not maximize the GC's utility, and arbitrary delivery time settings can result in supplier dissatisfaction. In a nutshell, under information asymmetry, it becomes challenging to maximize the utility of GC. Therefore, we have integrated contract theory with the blockchain-based tendering scheme proposed in (Ahmadisheykhsarmast et al., 2023).

[2] https://ethereum.org/whitepaper

[3] $n \in \{1,2\}$

Supplier model

For clarity exposition, we assume S_n with only two possible identity types, θ_H and θ_L. We define $\theta_H > \theta_L$[4], and each identity type corresponds to a different extent of advance delivery requirement with respect to T_k^{max}, represented by T_k^H and T_k^L, in which $T_k^H > T_k^L$. For the sake of modeling, we will drop the subscript k and use T_i to indicate advance delivery requirement, i.e., $i \in \{H, L\}$.

In addition, we assume that the tendering will use the comprehensive tendering method, a commonplace bidding model in the construction industry (van der Meer et al., 2022). As per our initial assumption, the GC follows Steps 1-4 of the framework depicted in Figure 1 to comprehensively evaluate and shortlist several suppliers. Subsequently, the GC implements Steps 5-8 to identify the ideal supplier using a multilateral contract theory-based (Bolton and Dewatripont, 2004)[5] tendering scheme. We assume that the average bid of selected suppliers in Figure 1 is $\bar{R}$. The utility function of S_n can be defined as follows:

$$U_{S_n} = \omega(\theta, \bar{R}) - \phi(T_i) - p(\delta_k) + r(\bar{R}), \tag{1}$$

where $\omega(\cdot)$ represents the profit that S_n can earn for this project. $\phi(\cdot)$ denotes the cost function for the supplier to transport the construction materials. $p(\cdot)$ represents the penalty imposed on the supplier if they fail to deliver within the delivery time specified in the signed contract. Finally, $r(\cdot)$ represents the revenue generated by the blockchain platform for S_n.

As this paper adopts the comprehensive tendering model, the GC only needs to pay the successful bidder with $\bar{R}$. The difference in profit among suppliers is primarily determined by their identity type θ. Specifically, the better the delivery, the more intangible wealth the supplier will gain, such as a relatively high probability of getting the next order. Therefore, we define the profit function that S_n can obtain from the project as:

$$\omega(\theta_i, \bar{R}) = \theta_i \bar{R}. \tag{2}$$

In light of the stricter delivery time requirement, i.e., T_i, the supplier will possess a lower concurrent delivery order or necessitate the supplier to set GC as a high priority, potentially impacting its profit. Therefore, we define the cost of S_n is related to T_i:

$$\phi(T_i) = \alpha(\bar{T} + T_i), \tag{3}$$

where α is the coefficient of suppliers' cost, and $\bar{T}$ is the initial cost when suppliers' delivery time requirement is T_k^{max}.

The penalty function for construction material not delivered before the delivery time requirement imposed on S_n is related to the importance of the materials and the punctuality of delivery, which is defined as:

[4] Due to the θ_H type supplier with fewer concurrent delivery orders and will set GC's delivery order as the high priority.

[5] The multilateral contract theory is akin to the bidding process, where the winner takes all.

$$p(\delta_k) = P\delta_k \times \tau, \tag{4}$$

where $P\delta_k$ represents the penalty charged for the breach, in which P is a constant coefficient, and τ denotes the probability of a supplier breaching the contract.

The payoff function of operating a blockchain platform includes two main components: the revenue generated by the blockchain platform and the expenses required to operate it (e.g., human resources and hardware equipment). According to (Griffiths et al., 2017), the benefits derived from using a blockchain platform are typically associated with the project's bid $\bar{R}$. As a result, we define the blockchain payoff function as:

$$r(\bar{R}) = \Delta\bar{R} - C, \tag{5}$$

where $\Delta\bar{R}$ represents the reduced transaction cost generated by the blockchain, and C denotes the cost of operating the blockchain.

Following the above analysis, the utility function of S_n can be summarized as:

$$U_{S_n} = \theta_i\bar{R} - \alpha(\bar{T} + T_i) - \varphi + \rho, \tag{6}$$

For clarity, we use φ to denote $p(\delta_k)$, and ρ to represent $r(\bar{R})$.

General Contractor Model

The utility function of the GC is defined as follows:

$$U_{GC} = \pi(T_i) - \xi(\bar{R}) + p(\delta_k) + r(\bar{R}), \tag{7}$$

where $\pi(\cdot)$ represents the revenue function of the GC, and $\xi(\cdot)$ denotes the project funds that the GC pays to the supplier.

The revenue function of the GC is defined by

$$\pi(T_i) = \alpha' \ln(D + \varepsilon T_i), \tag{8}$$

where α' is a coefficient and D represents the revenue earned when the material delivery time is T_k^{max}. Also, GC can proactively control the delivery time of M_k earlier than the default delivery time setting T_k^{max}, so as to effectively reduce the risks of delayed delivery, thus we utilize εT_i to denote the additional revenue earned by GC.

The remuneration function paid by the GC to the supplier is defined as follows:

$$\xi(\bar{R}) = \beta\bar{R}, \tag{9}$$

where β is the project remuneration coefficient due to market fluctuations. In this article, assuming that the supply and demand in the market are in equilibrium, we set $\beta = 1$.

In summary, the utility function of the GC can be expressed as:

$$U_{GC} = \alpha' \ln(D + \varepsilon T_i) - \bar{R} + \varphi + \rho. \tag{10}$$

Contract definition and problem formulation

Definitions of contract theory

Analogous to (Li et al., 2024), we assume that the GC faces competition from two risk-neutral suppliers[6] for an indivisible material supply order, without loss of generality and for the sake of simplicity. The cases with multiple risk-neutral suppliers can be studied similarly. As discussed earlier, each supplier S_n may have two identity type for supplying M_k, given by:

$$\theta = \begin{cases} \theta_H, & \lambda_n, \\ \theta_L, & 1 - \lambda_n, \end{cases} \tag{11}$$

where λ_n denotes the probability that the GC evaluates the identity type of S_n as θ_H, which can be determined by using empirical-based methods or data mining techniques. Consistent with (Bolton and Dewatripont, 2004), we assume that $\lambda_n = \lambda$, and all suppliers are identical ex-ante. Without loss of generality, we can restrict the GC to symmetric auctions where suppliers are treated equally.

During the tendering process, suppliers compete with each other to secure a contract and maximize their profits. In such a competitive scenario, suppliers take into account not only the contract bundles they choose but also the contract bundles that their competitors may opt for. To reflect this scenario, we present the types of contracts that the GC will offer during the tendering process in the following Definition 1.

Definition 1 (*Competed Delivery Time Requirement*)**.** *Suppliers' delivery time requirements will depend on their respective potential identity type, denoted by* $\mathbf{T} = \{T_{HH}, T_{HL}, T_{LH}, T_{LL}\}$.

To illustrate, T_{HH} denotes the contract variable designed by GC for S_n when the identity types of both suppliers are θ_H. Nevertheless, T_{HH} is a temporary variable set by GC during contract design, and the actual contracts issued are based on the potential identity type of each supplier. Consequently, in this study, only two types of contracts are issued by the GC, namely, T_H and T_L.

During the tendering process, suppliers have the freedom to choose either the same or different contracts. However, it is worth noting that their bid success rate may differ depending on the contracts they opt for. To provide clarity on this matter, Definition 2 is presented:

Definition 2 (*Bidding Success Rate*)**.** *Suppliers' probability of winning the material delivery order depends on their potential identity type, denoted by* $\mathbf{x} = \{x_{HH}, x_{HL}, x_{LH}, x_{LL}\}$.

For instance, x_{HH} represents the probability that supplier S_n wins the order when the identity type of both suppliers is θ_H.

[6]The supplier will be indifferent to risk when making decisions, i.e., the supplier is rational.

As there is only one indivisible construction project, the GC can only select one successful bidder among all suppliers. As a result, it is essential to ensure that the probability of successful bidding for all suppliers, who choose different types of contracts, must be less than or equal to 1. To formalize this requirement, Definition 3 is proposed:

Definition 3 (*Feasibility*)**.** *Supplier S_n has feasibility constraints on the probability of winning the order, i.e.,* $2x_{HH} \leq 1; 2x_{LL} \leq 1; x_{HL} + x_{LH} \leq 1$.

For example, x_{HH} represents the identity type of both suppliers as θ_H. In this case, x_{HH} is the bid success rate for both suppliers, and only one supplier will ultimately succeed in the tendering process, leading to the constraint $2x_{HH} \leq 1$.

With the previous definitions, we have established a mathematical framework for tendering scenarios. However, it is important to note that a rational supplier will only participate in a tendering project if it is profitable for them. Therefore, GC needs to design contracts in a way that ensures positive utility for suppliers. This idea is represented mathematically through Definition 4.

Definition 4 (*Individual Rationality, IR*)**.** *IR denotes that the GC designs the contract in a manner that S_n agrees to it only if there are guaranteed positive benefits.*

Considering the competition among suppliers, we redefined the utility function of S_n as:

$$U_{S(\theta_i,x_i,T_i)} = \sum_{j=H,L} \lambda_j(\theta_i \bar{R} x_{ij} - \alpha(\bar{T} + T_{ij}) - \varphi + \rho), \quad (12)$$

where $\lambda_H = \lambda$, and $\lambda_L = 1 - \lambda$. The physical meaning of (12) is that since there is only one indivisible material delivery order, the probability of S_n bidding success will depend on the contract chosen by other suppliers. Concretely, if the other supplier chooses the H-type contract with probability λ_H and the L-type contract with probability λ_L, S_n will have different probabilities of bid success, as defined in Definition 2. It is important to note that the effect of $\mathbf{x}$ is only on the supplier reward function. This is because the probability of receiving a reward for a successful bid is dependent on another supplier, even if they select the contract of their type and devote their best efforts.

Therefore, we can express the *IR* constraint as:

$$U_{S(\theta_i,x_i,T_i)} \geq 0, \quad i = H, L. \quad (13)$$

While the *IR* constraint ensures supplier participation in tendering, it does not guarantee that each supplier will choose the contract specifically designed for them, which would not maximize GC's utility. To ensure that each supplier selects only contracts suitable for their identity type, we introduce Definition 5.

Definition 5 (*Incentive Compatibility, IC*)**.** *IC denotes that suppliers can only maximize their benefits if they choose the contract that matches their identity type, i.e.,*

$$U_{S(\theta_i,x_i,T_i)} > U_{S(\theta_i,x_j,T_j)}, \quad i = H, L; j \neq i. \quad (14)$$

From (14), we can intuitively see that when a supplier chooses a contract that does not match its identity type, it will result in lower revenue. Therefore, a rational supplier will choose only the contract that meets its identity type, maximizing its benefits and satisfying GC's requirements.

Problem formulation

This paper proposes that the GC maximizes its profit by formulating a series of contracts. Specifically, the optimization problem of the GC is formulated as **P1**:

$$\begin{aligned}
\mathbf{P1} \quad \max_{\mathbf{T}} \quad & \Pi_{GC} = 2 \sum_{i=H,L} \sum_{j=H,L} \lambda_i(\lambda_j U_{GC(T_{ij})}) && \text{(15a)}\\
s.t. \quad & U_{S(\theta_i,x_i,T_i)} \geq 0, \quad i = H, L, && \text{(15b)}\\
& U_{S(\theta_i,x_i,T_i)} > U_{S(\theta_i,x_j,T_j)}, \quad i = H, L; j \neq i, && \text{(15c)}\\
& 2x_{HH} \leq 1, 2x_{LL} \leq 1, x_{HL} + x_{LH} \leq 1, && \text{(15d)}\\
& 0 \leq T_{ij} < T_k^{max}, \quad i = H, L; j \neq i. && \text{(15e)}
\end{aligned}$$

The optimization objective of **P1** is to maximize the expected benefit of the GC. Constraint (15b) is the *IR* constraint on the supplier. Constraint (15c) represents the *IC* constraint on the supplier. Constraint (15d) is the feasibility constraint in the tendering process, and finally, constraint (15e) sets a limit on the material delivery time requirements of the supplier that should be met by the GC.

Optimal contract

Due to the presence of multiple non-convex constraints, solving **P1** is computationally intractable (Zhan et al., 2023). To overcome this issue, we aim to simplify **P1** by leveraging Propositions 1, 2, and 3, the detailed proof can be referred to (Bolton and Dewatripont, 2004).

Proposition 1. $x_{HH} = x_{LL} = \frac{1}{2}, x_{HL} = 1, x_{LH} = 0$.

Proposition 2. *If IR constraint of type θ_L hold, IR constraint of type θ_H will automatically hold.*

$$U_{S(\theta_L,x_L,T_L)} \geq 0 \Rightarrow U_{S(\theta_H,x_H,T_H)} \geq 0. \quad (16)$$

Proposition 3. *If IC constraint of type θ_H is binding, then IC constraint of type θ_L will automatically hold.*

$$\begin{aligned}
U_{S(\theta_H,x_H,T_H)} &= U_{S(\theta_H,x_L,T_L)} \\
&\Rightarrow U_{S(\theta_L,x_L,T_L)} > U_{S(\theta_L,x_H,T_H)}.
\end{aligned} \quad (17)$$

By using Propositions 1, 2, and 3, and temporarily relaxing constraint (15e), we can transform the intractable problem **P1** into a tractable one, denoted as **P2**.

$$\begin{aligned}
\mathbf{P2} \quad \max_{T_{ij}} \quad & \Pi_{GC} = 2 \sum_{i=H,L} \sum_{j=H,L} \lambda_i(\lambda_j U_{GC(T_{ij})}) && \text{(18a)}\\
s.t. \quad & U_{S(\theta_L,x_L,T_L)} = 0, && \text{(18b)}\\
& U_{S(\theta_H,x_H,T_H)} = U_{S(\theta_H,x_L,T_L)}. && \text{(18c)}
\end{aligned}$$

By observing the two equality constraints in **P2**, we can obtain expressions for T_{LH} and T_{HH} in terms of T_{LL} and T_{HL}, respectively. Specifically, we have

$$T_{LH} = \frac{(1-\lambda)(\frac{1}{2}\theta_L\bar{R} - \alpha T_{LL}) - \alpha\bar{T} - \varphi + \rho}{\lambda\alpha}, \quad (19)$$

$$T_{HH} = \frac{\frac{1}{2}\theta_H\bar{R} + \frac{1-\lambda}{2}\theta_L\bar{R} - (1-\lambda)\alpha T_{HL} - \alpha\bar{T} - \varphi + \rho}{\lambda\alpha}. \quad (20)$$

For convenience, we define $T_{LH} = g(T_{LL})$ and $T_{HH} = f(T_{HL})$ and substitute these expressions into the objective function of the optimization problem. Hence, the optimal contract can be obtained by solving the following optimization problem, given by (21):

$$\begin{aligned} T_{ij}^* = arg\max_{T_{ij}} 2[&\lambda_H(\lambda_H U_{GC(f(T_{HL}))} + \lambda_L U_{GC(T_{HL})}) \\ &+ \lambda_L(\lambda_H U_{GC(g(T_{LL}))} + \lambda_L U_{GC(T_{LL})})]. \end{aligned} \quad (21)$$

First, we obtain the second-order derivatives of the optimization function with respect to T_{HL} and T_{LL}, respectively. Specifically, we have

$$\frac{\partial^2\Pi}{\partial(T_{LL})^2} = -\left[p_1\frac{(\varepsilon g'(T_{LL}))^2}{(D+\varepsilon g(T_{LL}))^2} + p_2\frac{\varepsilon^2}{(D+\varepsilon T_{LL})^2}\right], \quad (22)$$

$$\frac{\partial^2\Pi}{\partial(T_{HL})^2} = -\left[p_3\frac{(\varepsilon f'(T_{HL}))^2}{(D+\varepsilon f(T_{HL}))^2} + p_1\frac{\varepsilon^2}{(D+\varepsilon T_{HL})^2}\right], \quad (23)$$

where p_1, p_2, and p_3 are defined as $(1-\lambda)\lambda$, $(1-\lambda)^2$, and λ^2, respectively.

Then, since both second-order derivatives are negative, we can determine T_{ij}^* by taking the first-order derivatives of T_{HL} and T_{LL}. Specifically, we have

$$T_{LL}^* = T_{LH}^* = \frac{\frac{1}{2}(1-\lambda)\theta_L\bar{R} - \alpha\bar{T} - \varphi + \rho}{\alpha}, \quad (24)$$

$$T_{HL}^* = T_{HH}^* = \frac{\frac{1}{2}\theta_H\bar{R}}{\alpha} + T_{LL}^*. \quad (25)$$

Finally, we should also check whether T_{ij}^* satisfies constraint (15e) in **P1**. If this constraint is not satisfied, we can use various convex optimization tools such as Gurobi or CVX in Matlab to obtain the optimal solution.

Results

Comparison methods

To provide a comprehensive evaluation of our proposed blockchain-enabled and multilateral contract-based tendering scheme, we compare it with the following benchmark methods.

1. *Multilateral Contract in Complete Information Scenario* (Bolton and Dewatripont, 2004): This method assumes that the GC possesses complete information about the supplier's identity type and, as a result, designs contracts that can extract all the profits of the supplier. As such, we employ this method as an upper bound for performance evaluation.
2. *Bilateral Contract in Incomplete Information Scenario* (Doe et al., 2023): This method assumes that multiple material shipping orders are simultaneously available for the GC, enabling them to issue exclusive shipping order contracts to each supplier.
3. *Multilateral Contract without blockchain in Incomplete Information Scenario*: This scheme differs from the one proposed in this paper only in that it excludes blockchain; all other parameters remain identical.
4. *Traditional Tendering Scheme in Incomplete Information Scenario* (Ahmadisheykhsarmast et al., 2023): This scheme leverages the conventional tendering method employed in the construction sector to identify material suppliers for the GC on the blockchain platform.

For ease of reference in subsequent discussions, we refer to our proposed scheme and the four benchmark comparison methods as *Optimal contract*, *Complete contract*, *Bilateral contract*, *WoBC contract*, and *No contract*, respectively.

Experiment parameters

To indicate the high and low identity type of S_n with respect to M_k, we set θ_h and θ_L as 0.1 and 0.02, respectively. We categorize the importance levels of M_k into five categories, namely extremely low, low, medium, high, and extremely high, and represent them using {1, 2, 3, 4, 5}. We use key parameters with reference to studies involving blockchain-based construction payment management and blockchain-based tendering scheme (Ahmadisheykhsarmast et al., 2023; Griffiths et al., 2017; Bidhive, 2018; Brown et al., 2006).

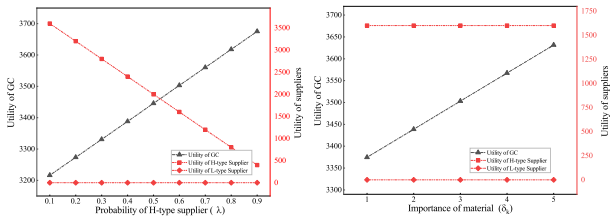
Discussion and result analysis

Contract analysis

In Figure 2, we depict the trend of utility changes for the GC, θ_L type supplier, and θ_H type supplier when varying key parameters. Notably, the utility of the θ_L type supplier remains at 0 for all four parameter variations due to the contract theory extracting the entire profit of the lowest-rated supplier, which aligns with previous research (Zhang and Han, 2017; Li et al., 2022; Doe et al., 2023).

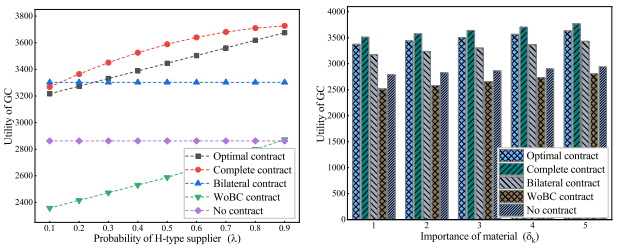
As shown in Figure 2a, when the identity types of θ_H increases, the utility of the GC also increases while that of θ_H type suppliers decreases. This result is intuitive as a higher λ value causes the GC to tailor contracts exclusively to θ_H type suppliers, extracting more profit.

Figure 2b reveals that when material importance δ_k increases, the GC's utility gradually increases. This outcome arises because heightened δ_k values necessitate a stricter delivery time requirement for materials, enabling the GC



(a) (b)

Figure 2: Contract-based tendering scheme for comparison of GC, θ_H and θ_L type suppliers' utilities as parameters vary.



(a) (b)

Figure 3: Contract-based tendering scheme for comparison with other four benchmark methods as parameters vary.

to extract more profit and thereby reduce risk. Notably, the utility of θ_H type suppliers remains constant across δ_k variations. This result stems primarily from the supplier's lead time increasing alongside δ_k. In other words, although the supplier's cost coefficient increases, the GC also obtains a more lenient delivery requirement, thereby reducing supplier delivery costs and leaving the utility of θ_H type suppliers unchanged.

Utility of GC

In Figure 3a, it is evident that the *Optimal contract*, *Complete contract*, and *WoBC contract* lead to an increasing trend for the GC's utility as λ increases. This result arises from varying the supplier's delivery time requirement as λ increases. In contrast, the *Bilateral contract* and *No contract* exhibit no change when λ increases since these methods do not affect the supplier's delivery time requirement. Specifically, in the *Bilateral contract*, the GC formulates designated contracts for suppliers with different identity types. Therefore, varying λ does not impact the supplier's delivery time requirement or the GC's utility. As for the *No contract*, it is intuitive that the supplier's delivery time requirement will not change irrespective of λ.

The reasons for the increase in GC's utility depicted in Figure 3b are similar to our analysis of Figure 2b, where an increase in δ_k leads to the extraction of more profit from the supplier by the GC. This increased profit stems from tailoring the contract to mitigate GC's own risk, resulting in an increase in the GC's utility as δ_k increase.

Based on the findings presented in Figure 3, we can determine the effectiveness ranking of the different contracts for GC's utility as follows: *Complete contract* $>$ *Optimal contract* $>$ *Bilateral contract* $>$ *No contract* $>$ *WoBC contract*. The *Complete contract* outperforms all other methods because the GC is aware of the supplier's identity type before contract formulation and can extract the maximum profit possible. Next, the *Optimal contract* generates more profit for the GC than the *Bilateral contract* by incorporating a competition mechanism during the contract formulation. Information asymmetry is the reason why the *No contract* method is inferior to the other three contract theory-enabled methods. Finally, the reason why the *WoBC contract* ranks last is that conventional tendering incurs an excessive amount of administration cost compared to the blockchain-based approach. Typically, administration costs range from 2% to 3% of the contract value (Bidhive, 2018; Brown et al., 2006), whereas blockchain cost remains fixed, which typically amounts to around $750, including the cost of smart contract deployment and invocation, prequalification files submission, and evaluation and contract awarding, etc., for completing a tendering project on Ethereum. (Ahmadisheykhsarmast et al., 2023). Consequently, blockchain will generate more revenue as the contract value increases.

Conclusion

Considering information asymmetry and bid-rigging undermining the GC's utility, this paper proposed a blockchain and multilateral contract theory-based construction tendering framework. To promise the effectiveness of multilateral contract theory, the GC first utilized the blockchain to acquire trustworthy data. Then, with the utilization of contract theory, the GC can provide precise material delivery time via the smart contract for suppliers to opt for. The simulation results demonstrated that the proposed multilateral contract theory-based method improves the GC's profit by approximately 20.7% in comparison with the traditional bidding method, with only a 5% profit difference displayed compared to the performance-optimized upper bound complete information scenario, the ideal situation. Furthermore, the proposed framework benefits the scenarios where information asymmetry is prevalent, such as construction payment management and material transportation processes. In future work, we will take the continuity of different materials into consideration, and will not assume the tolerance for advanced and delayed delivery are identical since delayed delivery will cause more severe consequences.

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