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# Game-theoretic analysis of blockchain-enabled subcontracting model in construction projects

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**Abstract**: Blockchain-enabled subcontracting model has been developed to address the issue of bid shopping in construction projects. However, the impact of this blockchain application on the decision-making of project stakeholders and its economic outcomes has not been thoroughly examined. This study establishes a game-theoretic framework to evaluate the economic implications of stakeholders' behaviors in the construction project subcontracting process. Utilizing this framework, the study investigates how the blockchain-enabled subcontracting model influences stakeholders' decision-making and economic outcomes when compared to the traditional subcontracting model. The findings of this examination indicate that the blockchain application can effectively reduce opportunistic behaviors, leading to mutually beneficial outcomes for the stakeholders. This outcome contributes to the existing knowledge by 1) elucidating the practical implications of blockchain-based subcontracting models in the construction industry, bridging the gap between new technological applications and industry practices, and 2) illustrating that blockchain technology promotes ethical decision-making among General Contractors (GC) and Subcontractors (Subs) during the subcontracting process, ultimately improving quality and profitability by reducing the risks of claims and disputes.

**Keywords:** blockchain; bid shopping; construction; game theory; smart contract; subcontracting

## 1. Introduction

In construction projects, subcontracting is essential because approximately 80%–90% of construction work is performed by subcontractors (Subs). In the subcontracting process, most general contractors (GCs) consider the lowest bid price as the key determining factor in the final Sub selection process [1–3].

In this traditional subcontracting model, the GC can conduct bid shopping to increase its individual profits. Bid shopping is an unethical behavior that an opportunistic GC discloses the bid price of a Sub to another to lower the other sub's bid price by negotiating based on the revealed price [4–6]. Even though this behavior can lower the final bid price, it may have the negative side effect of enabling unqualified Subs to win the bid, thereby lowering quality standards, increasing claims and disputes, delaying project completion, and causing cost overruns [4,5,7]. Subs also may pursue an opportunistic behavior by lowering their bid price based on the information obtained through bid shopping to win the bid and aggressively seek change orders in the construction phase to restore the profit loss caused by the lowered bid [3,8]. Moreover, such Subs may use shortcuts and substandard materials in their works to reduce costs and compensate for the profit loss due to the GC's bid shopping [3,8]. As a result, the opportunistic behaviors from the GC and Subs can create a lose-lose game in the subcontracting, which means both stakeholders can get a bad reputation and be financially damaged.

Rather than engaging in a lose-lose dynamic, GCs and Subs can adopt a win-win approach characterized by mutual trust and adherence to fair and ethical practices. This collaborative environment can lead to improved outcomes for both parties. In this framework, GCs refrain from bid shopping, thereby fostering a trustworthy relationship with Subs. Meanwhile, Subs are encouraged to develop realistic bid estimates and commit to their construction responsibilities, avoiding opportunistic behaviors such as generating change orders or disputes to manipulate profits post-bid award. However, establishing such trust is a complex challenge within the construction industry, as it requires both parties to prioritize win-win principles and actively avoid opportunistic tendencies. According to Martin and Benson [9], the relationships between the GC and Subs in construction projects are typically transactional, cost-driven, and adversarial, and they are characterized by injustice, mistrust, and skepticism. In this setting, each stakeholder may focus on gaining as much as they can on each occasion [10], and may find opportunistic behaviors tempting [11], which would ultimately lead to distrust and adversarial relationship between the stakeholders [12].

To address the above critical issue in the subcontracting process, Pishdad-Bozorgi and Yoon [13] introduced a blockchain-enabled smart contract system. The system utilizes a blockchain-enabled smart contract to decentralize and automate the bidding process, effectively mitigating the general contractor's opportunity for opportunistic profit-driven behaviors, such as bid shopping. However, despite the integration of blockchain technology, empirical verification remains lacking in two key areas: 1) how the blockchain-enabled subcontracting model fosters trust-enhanced behaviors, and 2) methods for measuring the economic benefits derived from these trust-enhanced behaviors. Consequently, a systematic validation of this approach is necessary to elucidate the effects of the blockchain-innovated subcontracting model and to promote its practical applications within the construction industry.

To address the identified research gaps and limitations, this study aims to establish a game-theoretic framework to evaluate the impact of blockchain technology on the construction subcontracting process and its associated economic implications. This framework enables a comprehensive game-theoretic analysis of the strategic interactions between GCs and Subs under both traditional and blockchain-enabled subcontracting models. Additionally, this study empirically investigates the economic effects of blockchain technology on the subcontracting dynamics within construction projects through simulations utilizing the developed framework.

## 2. Methodology

The methodology used in this paper consists of four main steps: 1) developing a game-theoretic framework to analyze and compare the outcomes of the decision makings consisting of profit- and trust-driven behaviors of the GC and Subs in the subcontracting process; 2) exploring the blockchain-enabled smart contract system that can prevent profit-driven behaviors by making the process automated and decentralized; 3) designing role-playing simulations in two settings: the traditional and the smart contract-enabled subcontracting processes; and 4) conducting the simulations and analyzing the results through the developed game-theoretic framework to validate the economic benefits of blockchain applications in the subcontracting process. Figure 1 illustrates the research methods and procedure of this study.

In Step 1, we employ game theory to establish a framework for the theoretical examination of the payoffs associated with the decisions made by GC and Subs in the subcontracting process. This approach allows us to create systematic parameters and functions aimed at quantitatively estimating these payoffs. The resulting framework will facilitate a theoretical comparison of various decision-making scenarios within the subcontracting process, which is crucial for validating the effectiveness of smart contract-enabled subcontracting practices in preventing bid shopping. In Step 2, we explore the mechanisms of blockchain-enabled smart contracts as a solution to the bid shopping dilemma in subcontracting. We will also examine the smart contract system developed in the research conducted by Pishdad-Bozorgi and Yoon [13]. This exploration serves two main purposes: 1) to provide a theoretical justification for the potential of blockchain-enabled smart contracts to mitigate bid shopping issues in subcontracting and 2) to establish a practical system for smart contract-enabled subcontracting. Step 3 involves the design of role-playing simulation scenarios that encompass both conventional subcontracting processes and blockchain-enabled subcontracting processes. These scenarios will detail the subcontracting workflow and the relevant information that influences the decisions made by GCs and Subs. Through this interactive role-playing game, we aim to derive parameter values for decision payoffs across different scenarios, which will be applicable within the game-theoretic framework established in Step 1. Finally, in Step 4, we will 1) conduct role-playing games based on the conventional subcontracting process and the smart contract-enabled subcontracting process using the system introduced in Step 2; 2) compute and compare the payoffs resulting from the decisions made by GCs and Subs in various scenarios based on the game-theoretic framework developed in Step 1; and 3) validate the overall effectiveness of smart contract-enabled subcontracting processes. The methodologies outlined above collectively provide a structured and theoretical validation of the effectiveness of smart contract-enabled subcontracting, particularly in addressing the issue of bid shopping. Detailed discussions of each stage are presented in Sections 3, 4, and 5.

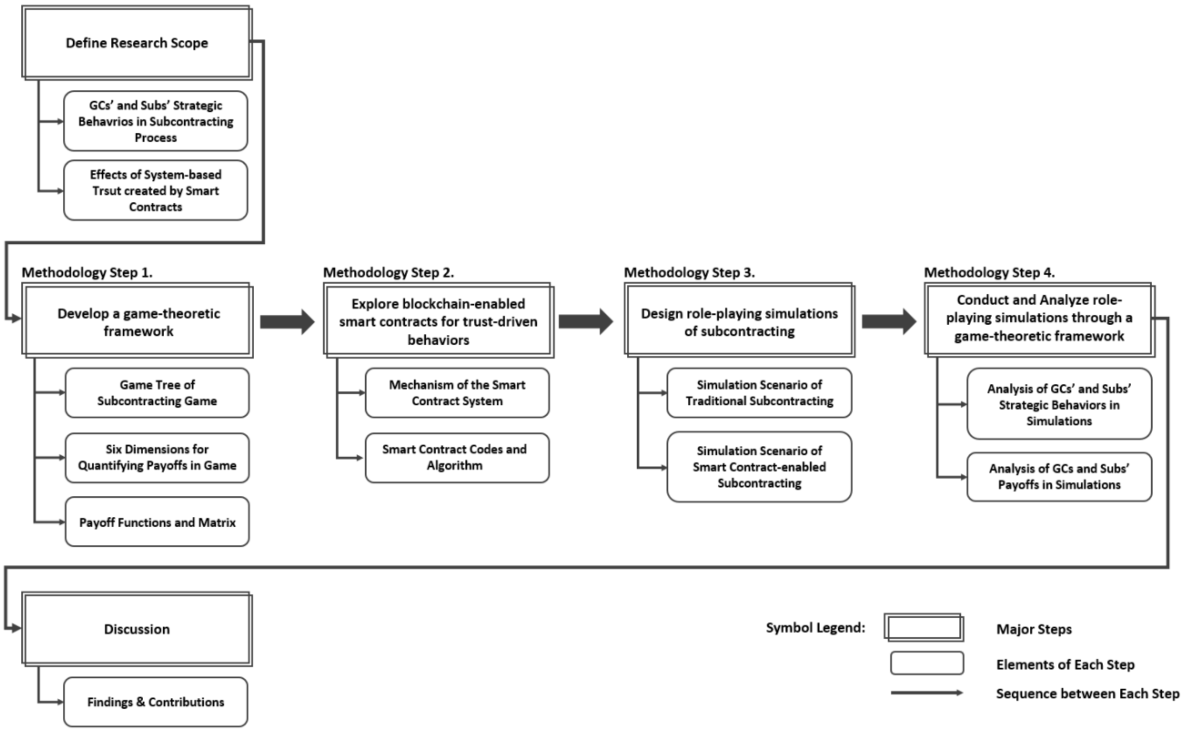


**Figure 1.** Research method and procedure.

## 3. Game-theoretic framework development

### *3.1. Profit- and trust-driven behaviors (decision makings) in subcontracting processes*

Game theory is a mathematical theory that can be applied to any social interaction involving two or more decision-makers (players) with two or more strategies that lead to different outcomes (payoffs) [14]. It enables one to analyze the payoffs of each decision *in situ*ations where one player's strategies will influence the actions of the other(s) [15]. In the construction domain, many researchers [16–19] have applied the game theory to understand the decision-making processes of construction stakeholders and identify the optimized decision-making process during the bidding phase of a construction project. However, game-theoretic analyses of the subcontracting model are still in their early stages even though it can critically influence project quality and the relationships between the GC and Subs.

The subcontracting process is a situation where two different stakeholders (e.g., GC and Subs) are interdependent and expect trusting behavior of each other. According to Swinth [20], trusting behavior in an interdependent relationship means enduring an ambiguity in decision-making for both stakeholders to achieve the beneficial event, if either instead makes a non-trusting choice, the other will experience a harmful event. In other words, when both stakeholders engage in trusting behaviors, no stakeholder will deliberately hurt the other to satisfy his or her own needs [21]. Based on the concept of trusting behavior, this study defines the GC's and Subs' two different strategic behaviors in the subcontracting process: profit- and trust-driven behaviors.

A profit-driven behavior is a behavior where a stakeholder takes a decision path with apparent results of increasing short-term and individual profits. For the GC, an example of profit-driven behavior would be conducting bid shopping during the bidding process to reduce the bid prices of the Subs. For the Subs, an example of profit-driven behavior is creating unethical change orders after winning the bid at a lower price. Moreover, this behavior includes using shortcuts and substandard materials in the construction phase to reduce costs and increase profits. In contrast, trust-driven behavior is a behavior where a stakeholder takes a decision path with ambiguous results but without hurting the other. An example of a trust-driven behavior practiced by the GC would be running a fair bidding process without bid shopping. An example of a trust-driven behavior practiced by the Subs would be their commitment to complete the construction project within the expected budget.

Based on the two different behaviors from the two different stakeholders, the subcontracting process has a sequential game in which players select the abovementioned strategies in some predefined order [22,23]. In this game, the player who decides the strategic behavior later has information from the behavior of the opposing player. For example, in the subcontracting process, the Subs choose their strategic behaviors based on the GC's strategic behavior. Figure 2 shows the game tree of this sequential game.

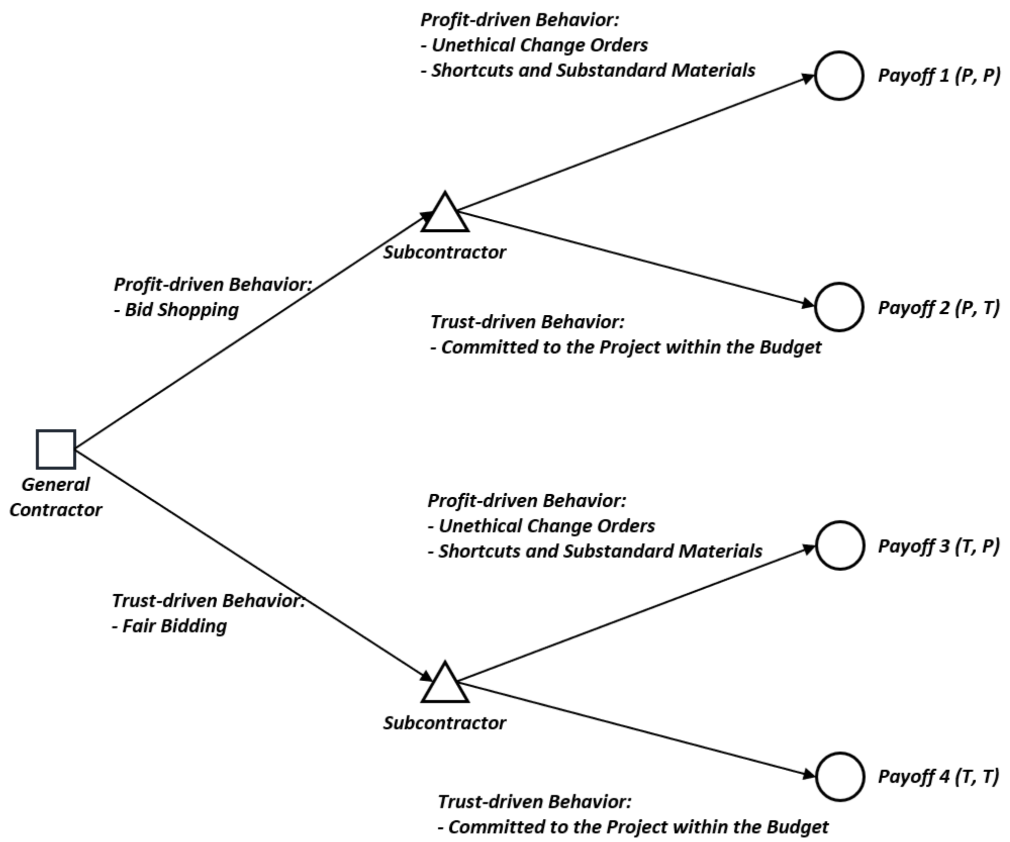


**Figure 2.** Game tree of subcontracting game in construction projects.

### *3.2. Dimensions for quantifying the payoffs of strategic behaviors in subcontracting processes*

To estimate the payoffs of each strategy pair, we define six dimensions for quantifying the profit and loss generated because of the strategic behaviors of the GC and the Subs (Table 1). We developed these six dimensions inspired by the study of Loebecke *et al.* [24]. They provided six dimensions to quantify the value of transferred knowledge in the co-opetition game environment. Raweewan and Ferrell Jr [25] applied these dimensions to quantify the value of information sharing in the supply chain collaboration. Yoon and Pishdad-Bozorgi [26] also adapted the dimensions to quantify the payoffs of the owner's and contractors' decisions of their strategic behaviors to determine the project delivery and contracting methods.

**Table 1.** Six dimensions for quantifying profit and loss in the subcontracting process.

| Dimensions | Definitions |
| --- | --- |
| GC's strategic profit ($P_B$) | Additional profit generated by bid shopping |
| GC's loss due to Subs' strategic behaviors ($C_{UC}$) | Cost generated by unethical change orders or the use of shortcuts and substandard materials |
| Subs' strategic profit ($P_{UC}$) | Profit generated by unethical change orders or the use of shortcuts and substandard materials |
| Subs' loss due to GC's strategic behaviors ($C_B$) | Decreased bid price due to bid shopping |
| Risks of claims or disputes ($R$) | Claims or disputes generated because of mistrust and profit-driven behaviors of Subs |
| Synergy generated because of trust and committed collaboration ($S$) | Additional value generated when the players trust and collaborate with each other for mutual success |

The dimensions in this study include the GC's strategic profit, GC's loss due to Subs' strategic behaviors, Subs' strategic profit, Subs' loss due to the GC's strategic behaviors, risks of claims and disputes, and synergy generated because of trust and committed collaboration between the GC and the Subs. The GC's strategic profit ($P_B$) is the increased profit generated by reducing the bid price through bid shopping. The GC's loss due to Subs' strategic behaviors ($C_{UC}$) is associated with the costs that the Subs create through unethical change orders or the use of shortcuts and substandard materials. The Subs' strategic profit ($P_{UC}$) is the increased profit generated by creating unethical change orders or using shortcuts and substandard materials in the construction phase. The Subs' loss due to the GC's strategic behaviors ($C_B$) is the decreased bid price because of bid shopping by the GC. The risk of claims or disputes ($R$) refers to the loss due to claims or disputes between the GC and the Subs because of the mistrust and adversarial relationship created by the profit-driven behaviors of the Subs. This dimension has been introduced in several studies that have addressed bid shopping [5,7] and the contractor–subcontractor relationship [27,28]. These studies highlighted those opportunistic practices (i.e., bid shopping and unethical change orders) can introduce risks related to claims or disputes between the GC and the Subs. Synergy ($S$) is the additional value provided to the GC and the Subs when they committedly trust and collaborate with each other. This dimension ($S$) has been introduced in various studies on game theory application [24–26]. When the players are in the context of *Co-opetition*, where cooperation and competition exist simultaneously among the players in the game, synergy can be generated. In the game of the subcontracting process, in a *Co-opetition* situation, the GC and the Subs cooperate with each other to complete a project successfully while seeking to increase their individual gains and profits. When the GC and Subs committedly trust and collaborate with each other to complete a project successfully, they will create synergetic values. Even though synergy is a conceptual dimension and difficult to quantify, several studies have highlighted its significant impact. For example, Kale and Arditi [29] demonstrated that the synergy between the GC and the Subs (i.e., trust and positive relationship) is positively and strongly associated with successful performance in construction projects. Manu *et al.* [27] highlighted that synergy is crucial for achieving the optimum benefits of supply chain integration and collaboration in the construction domain. Manu *et al.* [27] also demonstrated the effects of the synergy by using empirical data from four case studies. Accordingly, we include synergy as one of the dimensions to describe the added value for the GC and the Subs in successful projects.

### *3.3 Payoff matrix of subcontracting game for construction projects*

By applying the dimensions listed in Table 1, we construct a payoff matrix of the subcontracting game for construction projects. The matrix indicates payoffs for the GC and the Subs when they engage in different pairs of strategic behaviors in the game. For example, the matrix consists of four sets of strategic behavior profiles of the GC and the Subs, and the profiles are illustrated as (GC's profit- or trust-driven strategies, Subs' profit- or trust-driven strategies). Profit- and trust-driven behaviors are denoted (P) and (T), respectively. Subsequently, the set of strategic behavior profiles is given as (P, P), (P, T), (T, P), and (T, T). The GC's and the Subs' payoffs in the context of each strategic behavior pair can be estimated using the following functions:

GC's payoff in the context of (P, P) = $P_B - C_{UC} - R$ (1)

Subs' payoff in the context of (P, P) = $P_{UC} - C_B - R$ (2)

GC's payoff in the context of (P, T) = $P_B$ (3)

Subs' payoff in the context of (P, T) = $-C_B$ (4)

GC's payoff in the context of (T, P) = $-C_{UC} - R$ (5)

Subs' payoff in the context of (T, P) = $P_{UC} - R$ (6)

GC's payoff in the context of (T, T) = $S$ (7)

Subs' payoff in the context of (T, T) = $S$ (8)

All the functions for each payoff are presented in the payoff matrix (Table 2). We apply the developed matrix to analyze and compare the payoffs of the subcontracting game based on the game-theoretic interpretation of the *Nash equilibrium*.

**Table 2.** Payoff matrix of subcontracting game in construction projects.

| | | Subcontractors | |
|---|---|---|---|
| | | Profit-driven Behaviors (P) | Trust-driven Behaviors (T) |
| **General Contractors** | Profit-driven Behaviors (P) | ($P_B - C_{UC} - R$), ($P_{UC} - C_B - R$) | $P_B$, $-C_B$ |
| | Trust-driven Behaviors (T) | ($-C_{UC} - R$), ($P_{UC} - R$) | $S$, $S$ |

*3.4. Nash equilibrium of subcontracting game in construction projects*

The *Nash equilibrium* is a strategic profile in which each player's strategy is optimal when considering the other players' strategy [30]. In this state, a player cannot gain additional benefits by deviating from the selected strategy when the opposing player does not deviate [31]. In the subcontracting game, when the GC assumes that the Subs' strategy is profit-driven behaviors (P), the GC increases its payoffs by practicing profit-driven behaviors (P). When the GC assumes that the Subs' strategy is trust-driven behaviors (T), the GC can increase its payoffs by practicing trust-driven behaviors (T). This is because the GC considers that the profit generated by the successful completion of a project through synergy with the Subs is higher than the profit generated by bid shopping, which may lead to the risks of claims and disputes. In the case of the Subs, when the GC practices profit-driven behaviors (P), the Subs can increase their payoffs by engaging in profit-driven behaviors (P) if they believe that the risks of claims and disputes are insignificant. However, if they consider these as significant, they can increase their payoffs by practicing trust-driven behaviors (T). In this case, if the GC practices trust-driven behaviors (T), the Subs can increase their profits in a successful project through synergy by practicing trust-driven behaviors (T) and avoid the significant risks of claims and disputes. Accordingly, based on the definition of the *Nash equilibrium*, the strategy sets (P, P) or (P, T) and (T, T) represent a *Nash equilibrium* state.

However, the subcontracting game is a sequential game in which the players decide their strategy in a predefined order (Figure 2). Furthermore, the relationships between the GC and the Subs in the construction industry are typically transactional, cost-driven, and adversarial, and they are characterized by injustice, mistrust, and skepticism [9]. In this setting, each stakeholder focuses on gaining as much as possible on each occasion [10], and opportunistic behaviors are potentially tempting [11]. Consequently, the GC is unlikely to practice trust-driven behaviors in its turn and would prefer profit-driven behaviors, which correspondingly results in the Subs choosing to practice profit-driven behaviors. It limits their optimized strategic behaviors in the *Nash equilibrium* state to the strategy set (P, P), in which the stakeholders adversely affect each other with the risks of disputes and claims and reduction of project quality, or to the strategy set (P, T), in which only the Subs are adversely affecting owing to the profit-driven behavior of the GC. In other words, the GC and the Subs are trapped in the negative *Nash equilibrium* sets, in which at least one player has negative payoffs despite its optimized strategy by considering the opposing player's strategy. The aforementioned studies highlighting the bid-shopping-related issues and the adversarial relationship between the GC and the Subs support this game-theoretic interpretation.

Various studies of social interactions and trust relationships can theoretically explain the above interpretation of the negative *Nash equilibrium* sets in the subcontracting process. Hofstede *et al.* [32] argued that people are likely to engage in risky behaviors because they want to avoid uncertainty by reducing ambiguities in their decision makings. This explanation supports why the GC and Subs likely choose profit-driven behaviors in the subcontracting process, eliminating the ambiguity in their decision-making by securing apparent individual profits. However, Bennis *et al.* [21] and Swinth [20] argued that if there is trust in the interdependent relationship, the stakeholders can endure the ambiguity not hurting each other. Accordingly, the prevalent opportunistic behaviors conducted by the GC and Subs in the subcontracting process demonstrate the lack of trust between GC and Subs. As a result, this study can theoretically conclude that the lack of trust leads to the negative *Nash equilibrium* sets in the subcontracting process.

## 4. Blockchain-enabled subcontracting model

### *4.1. Blockchain applications in construction projects*

Blockchain applications have been widely studied to improve diverse aspects of construction projects. For example, Elghaish *et al.* [33] proposed an interconnected financial management system based on a blockchain-enabled smart contract. The system enables construction stakeholders in different project lifecycle stages to invoke and record their financial transactions safely and automatically, with no third-party involvement through a smart contract. This system can expedite the payment process, remove human errors in invoices, and eliminate unethical behaviors of retaining contractor’s payments. Kiu *et al.* [34] investigated the potentials of an electronic document management (EDM) system based on blockchain technology. By leveraging blockchain, the EDM system can provide the data used in the system with immutability, traceability, and transparency, which enables to prevent data manipulation and mitigate liability issues in construction projects. To facilitate these approaches of blockchain applications in construction projects, Singh *et al.* [35] investigated the barriers to implementing blockchain-enabled smart contracts in construction projects. It highlighted the key barriers such as economic and market conditions, insufficient awareness and education about blockchain technology, and limited digital technology integration in specific cultural and societal context, offering a future research direction to facilitate blockchain applications in construction projects.

### *4.2. Blockchain-enabled Smart Contracts for Subcontracting Model*

Aligning with the studies introduced above, a blockchain-enabled smart contract can be applied to subcontracting process in construction projects. A blockchain-enabled smart contract application can potentially encourage trust-driven behaviors in transactional relationships such as subcontracting processes. The users of the smart contract can trust that the data used for executing the contract and its digital codes or protocols are immutable and traceable because they are encrypted and stored in the blockchain [36]. Furthermore, the codes and protocols of a smart contract ensure that the contract is executed automatically based on the digital data, which enables the users to trust that the contract will be executed based on the predefined term without human intervention to modify or falsify the terms with malicious intent [37,38]. Consequently, the advantages can enforce an agreement between untrusted parties without the involvement of a trusted third party [39]. By applying these advantages, Pishdad-Bozorgi and Yoon [13] have proposed a blockchain-enabled smart contract system for the subcontracting process, which is consisting of two main stages: quality-based and price-based evaluations.

In the quality-based evaluation stage, the Subs provide quality information without price to the GC. The GC evaluates this information and assigns a quality score to each Sub. Then, the GC inputs their minimum quality score into the smart contract-enabled decentralized application (DApp) by using the blockchain network. The score can be determined by the GC's own evaluation methods (i.e., the analytic hierarchy process (AHP) method or the technique for order of preference by similarity (TOPSIS) method). Next, the Subs input their quality scores and bid prices to the DApp. Subsequently, the smart contract in the DApp filters out low-quality Subs based on its contract codes that are based on the minimum quality score provided by the GC and the quality scores input by each Sub. The Ethereum blockchain network records the contract codes, minimum score, and each Sub's quality scores to ensure their immutability and traceability. In the next stage of price-based evaluation, the smart contract in the DApp identifies the lowest bidder by using its contract codes and delivers the identity of this bidder and the associated bid price to the GC. Because the smart contract identifies the lowest bidder by using predefined digital codes, there is no human intervention for negotiating the bid price by disclosing bid prices, which is called bid shopping. In addition, the Subs can trust the transparency and fairness of the bidding process because all of the data used in the smart contract and bidding process are recorded in the blockchain network for immutability and traceability. The system framework is illustrated in Figure 3, and Figure 4 shows the smart contract algorithms and codes to filter out low-quality Subs and determine the lowest bidder. The codes are developed using *Solidity ver. 0.7*, a programming language designed for the Ethereum Virtual Machine.

This blockchain-enabled smart contract system does not allow the GC to practice profit-driven behavior in the bidding process by eliminating any opportunity available for the GC to intervene in the bidding process and disclose the Subs' price data. It is a major difference between the existing contractual systems and the blockchain-enabled smart contract system. This difference can force GC to decide the trust-driven behavior in the game tree of the subcontracting process, affecting the subsequent decision made by Subs. However, despite the approach using blockchain technology, it was unable to empirically verify 1) how the new subcontracting model leveraging blockchain-enabled system can create trust-enhanced behaviors and 2) how to measure the practical effects of the trust-enhanced behaviors in the subcontracting processes. Accordingly, the systematic validation of the approach is still needed to clarify the technology-innovated subcontracting model's effects and thereby promote its practical applications in the construction industry.

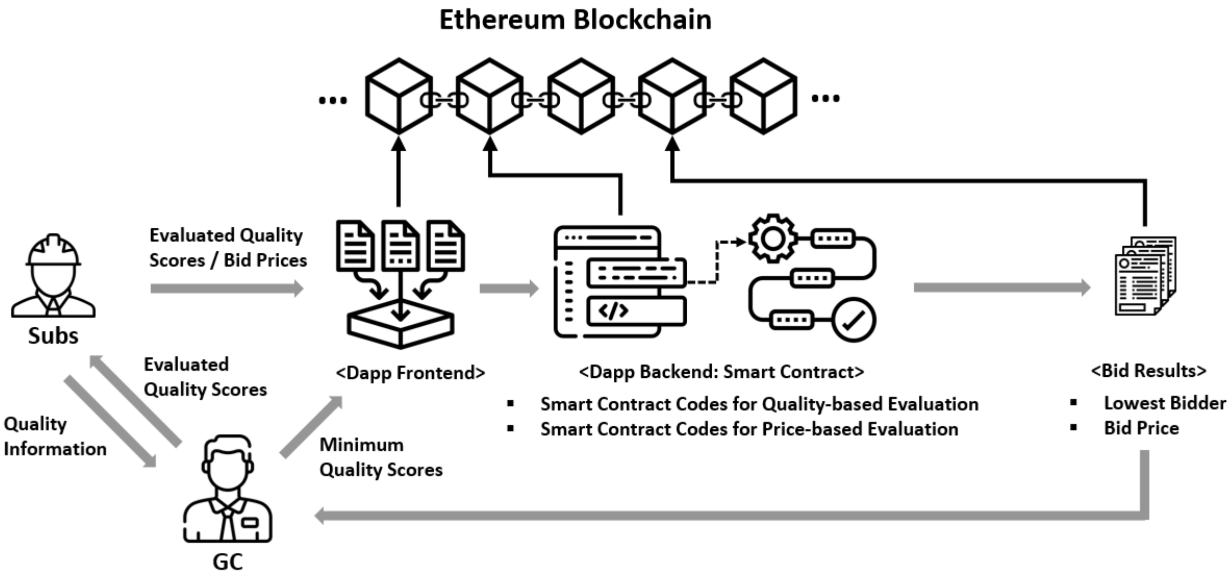


**Figure 3.** Framework of smart contract system for trust-enhanced bidding process.

```
pragma solidity >=0.7.0 <0.9.0;

contract EthicalBidding {
   uint8 min_quality;
   bool limit_bidders;
   bool auction_closed = false;

   constructor( uint8 min_q, bool limited_bidders ){
      require(min_q <= 100, "Too high");
      min_quality = min_q;
      limit_bidders = limited_bidders;
   }

   struct Bid {
      uint256 cost;
      uint8 sub_q;
   }
   Bid[] bids;

   function addBid(uint256 cost, uint8 min_q) public {
      require(!checkBids(), "All bid slots consumed");
      Bid memory b = Bid(cost, min_q);
      bids.push(b);
   }
⋮
```

```
⋮
event BidClosed( uint256 cost, uint8 minimum_quality );

   function closeAuction() public {
      require(checkBids() || !limit_bidders, "Contract not ready to close");

      require(!auction_closed, "Auction Already Closed");
      auction_closed = true;

      uint256 lowestBidCost = 2**256 - 1;
      Bid memory lowestBid;

      for (uint i = 0 ; i < bids.length ; i++){
         if (bids[i].sub_q < min_quality) continue;

         if (bids[i].cost < lowestBidCost){
            lowestBidCost = bids[i].cost;
            lowestBid = bids[i];
         }
      }

      emit BidClosed(lowestBid.cost, lowestBid.sub_q);
   }
}
```

1. **Quality-based Evaluation:** If the Sub's quality score is under the predefined minimum quality, the codes will skip the Sub in the contract process and continue to examine the next Sub's quality score.
2. **Price-based Evaluation:** When the Sub's quality score exceeds the predefined minimum quality, the code will examine whether the Sub's bid price is the lowest.

**Figure 4.** Smart contract algorithms and solidity codes [13].

## 5. Role-playing simulation game through proposed framework

In this section, this study empirically verifies the effects of the blockchain application on the GC's and Subs' strategic behaviors in the subcontracting game by performing a role-playing simulation and analyzing the results through the proposed framework.

*5.1. Role-playing simulation games*

The simulation is composed of two separated hypothetical subcontracting games. In the first game, the participants simulate the traditional subcontracting process. The player who plays the GC selects a Sub for its project by following the lowest bid price method, considering that all the Sub candidates are similarly qualified for the project. The GC decides whether to practice profit-driven behaviors (i.e., Bid shopping) or trust-driven behaviors (i.e., Fair bidding without bid shopping). The players who play the Subs submit their bid prices to the GC. The Subs are informed that the proper bid price ranges from $90,000 to $95,000. They will earn 10% of the submitted bid price as a profit. For example, if a Sub wins the bid with a bid price of $93,000, the Sub will earn $9300. As the bid price decreases to less than $90,000, the percentage of profit decreases by 2% for every $1000. If a Sub wins the bid with an $86,000 bid price, the Sub will earn 2% (10%–8%) of the submitted bid price, which is $1720. This means that the Subs cannot make any profit if their bid is lower than $85,000. Accordingly, the Subs will not bid less than $85,000. In this setting, in response to the GC's strategic behavior, the Subs decide whether to practice profit-driven behaviors (i.e., creating unethical change orders in the construction phase) or trust-driven behaviors (i.e., being committed to complete the project within the budget). If the Subs decide to create unethical change orders after winning the bid, the Subs have a 50% chance of successfully securing change orders in the construction phase. When the Subs succeed in securing change orders, they can earn 5% of the bid price as additional profit from the change orders. For example, if a Sub, who won the bid with $85,000, succeeds in securing change orders, the Sub will earn $4250 (5% of $85,000) as an additional profit. In this setting, the expected value of the additional profit will be $2125 (50% of $4250). However, this can increase the risks of claims or disputes in the project. Moreover, the Subs are informed that profit-driven behaviors, including unethical change orders, may negatively affect their reputation and future relationship with the GC. For the convenience of the players playing the Subs, profit information is provided (Table 3).

**Table 3.** Profit information for subcontractors.

| Bid Prices | $85,000 | $86,000 | $87,000 | $88,000 | $89,000 | $90,000 | $91,000 | $92,000 | $93,000 |
|---|---|---|---|---|---|---|---|---|---|
| Profits | $0 | $1720 | $3480 | $5280 | $7120 | $9000 | $9100 | $9200 | $9300 |
| $P_{UC}$ | $2125 (50% of 4250) | $2150 (50% of 4300) | $2175 (50% of 4350) | $2200 (50% of 4400) | $2225 (50% of 4450) | $2250 (50% of 4500) | $2275 (50% of 4550) | $2300 (50% of 4600) | $2325 (50% of 4650) |
| Total Profits | $2125 | $3870 | $5655 | $7480 | $9345 | $11,250 | $11,375 | $11,500 | $11,625 |

*** $P_{UC}$: additional profits due to profit-driven behaviors.**

The second game has the same conditions as the first game, but the GC is not allowed to practice profit-driven behaviors (i.e., bid shopping) because the GC and the Subs employ the afore-introduced smart contract system to conduct the bidding process.

Based on the provided guidelines and information, a total of 20 experienced construction professionals with diverse roles such as architect, project manager, structural/site engineer, subcontractor, *etc.*, along with 13 construction graduate students, who understand the construction subcontracting processes, actively participated in the simulation game. These participants possessed a comprehensive understanding of the subcontracting process and were able to discern optimal behaviors pertinent to real-world business scenarios. The 33 individuals formed eight groups for the simulation, with each group comprising a single player representing the GC and two to four players representing the Subs involved in the subcontracting process. Each group engaged in simulations involving both the traditional subcontracting process and the implementation of blockchain-enabled subcontracting processes.

### *5.2. Game-theoretic analysis of simulation results and discussion*

In the first simulation game, all the GCs in the eight groups choose to practice profit-driven behaviors by engaging in bid shopping. Except for the GC of group #3, all GCs of the other groups successfully reduced bid prices through this strategic behavior, bid shopping. It created an additional profit ($P_B$) for the GCs and a loss for the Subs ($C_B$). This opportunistic behavior from the GC and the adverse impact were aligned with several studies of bid shopping [4–6]. In response to the GCs' profit-driven behaviors, the Subs of groups #1, #4, #6, and #7 decided to create unethical change orders to compensate for the loss due to bid shopping, which is a profit-driven behavior of the Subs. It generated an additional profit ($P_{UC}$) for the Subs and a loss for the GCs ($C_{UC}$). In addition, it led to the risks of claims and disputes ($R$). This result aligns with the studies of adverse side effects created by bid shopping [4,5,7]. However, the Subs of groups #2, #3, #5, and #8 practiced trust-driven behaviors to enhance their reputation and reduce the risks of claims and disputes. This finding indicates that the GC has the upper hand in this subcontracting game, implying that curbing the GC's profit-driven behavior can be the foundation for a trustworthy relationship between the GC and the Subs.

Consequently, groups #1, #4, #6, and #7 had the strategic behavior pair of (P, P), in which both the GC and the Subs adversely affected each other through their profit-driven behaviors, which resulted in a lose-lose game. Groups #2, #3, #5, and #8 had the strategic behavior pairs of (P, T), in which the GCs' strategic behaviors adversely affected the Subs, but the Subs did not practice profit-driven behaviors. Table 4 shows the game's first and final bid prices, and Table 5 summarizes the additional profits and losses generated due to the strategic behaviors of the GCs and Subs in the game. The strategic behavior pairs are described in Table 6.

This simulation result matches the game-theoretic interpretation that the GC and the Subs will be in the negative *Nash equilibrium* state (P, P) or (P, T) in the traditional subcontracting process. In this setting, at least one stakeholder incurs a monetary loss. At worst, both the GC and the Subs incur monetary losses, in addition to facing the risks of disputes and claims, as well as poor project quality, which can negatively affect their reputation in the construction industry. Despite the past studies that explored the collaborative relationships between GCs and Subs and their win-win outcomes due to their trust-driven behaviors [40,41], our result demonstrates that the GC and Subs are still likely to choose profit-driven behaviors. These unreasonable behaviors can be explained by the socio-psychological tendency to engage in risky behaviors by reducing ambiguities in their decision-making results [32]. However, Bennis *et al.* [21] and Swinth [20] argued that if trust exists in the interdependent relationship, the stakeholders can endure the ambiguity in decision results, not hurting each other. Accordingly, this study concludes that the above simulation result of negative *Nash equilibrium* state (P, P) or (P, T) is caused by the lack of trust between the GC and Subs.

In the second simulation game, the GCs in any of the groups are prohibited from practicing profit-driven behaviors because the blockchain-enabled smart contract system prevents them from pursuing bid shopping in the bid process. This creates system-based trust among the Subs that the bid process is fair and honest, which helps the Subs to choose their strategic behaviors accordingly [13]. Subsequently, system-based trust significantly affects the result of the subcontracting game. Except for group #8, the Subs in the other groups practiced trust-driven behaviors. They were committed to the project without engaging in unethical and opportunistic practices such as creating unethical change orders or using substandard materials. Based on the studies of Bennis *et al.* [21] and Swinth [20], this result shows the enhanced trust between the GC and Subs because the Subs endure the ambiguity in their decision results and do not exploit the GC through unethical change orders and/or using substandard materials.

Consequently, seven groups, except for group #8, were in the positive *Nash equilibrium state* (T, T), leading to the payoff pair ($S$, $S$) (Table 6). This game-theoretic interpretation shows that the system-based trust created by a blockchain-enabled smart contract places the GC and the Subs in a win-win game within the subcontracting process by promoting the trust-driven behaviors of the GC and the Subs in the subcontracting process. In this state, the GCs and Subs never incur monetary losses due to the opposing players' opportunistic behaviors, and the risks of disputes and claims arising from unethical practices in the project are minimized (Table 7). Ultimately, the construction project will have better quality and profits with reduced risks of claims and disputes.

## 6. Limitations and future studies

The role-playing game in this study simulates a subcontracting process based on hypothetical data (i.e., the amount of bid price and additional profit resulting from change orders) designed for the simulation. This study acknowledges that the bid prices and additional profit resulting from change orders can differ in real-world construction projects. Especially, a significant increase or decrease in strategic profits such as $P_B$ and $C_{UC}$ may affect the GC's and Subs' decisions regarding their behaviors. Accordingly, in future research, it is advisable to conduct a pilot test within a real-world construction project to further strengthen and validate the findings of this study. Comparing the results of such a pilot test with the theoretical analysis presented in this research would enhance the robustness of our conclusions. Nevertheless, the game-theoretic analysis of the simulations still demonstrates how the blockchain-enabled smart contract affects the behaviors of GC and Subs in the subcontracting process. It also proves that the system-based trust created by the blockchain application has the potential to lead to mutual success in the project.

**Table 4.** Bid prices in role-playing simulation games.

| Group # | 1st Simulation Game: Traditional Subcontracting Process | | 2nd simulation Game: Smart Contract-enabled Subcontracting Process |
|---|---|---|---|
| | Lowest bid price before bid shopping | Lowest bid price after bid shopping | Lowest bid price |
| Group #1 | $88,000 | $87,500 | $88,000 |
| Group #2 | $90,500 | $88,000 | $90,500 |
| Group #3 | $89,000 | $89,000 | $90,000 |
| Group #4 | $90,000 | $86,000 | $88,000 |
| Group #5 | $89,000 | $86,900 | $89,000 |
| Group #6 | $93,000 | $91,000 | $89,000 |
| Group #7 | $90,000 | $89,000 | $89,000 |
| Group #8 | $89,000 | $87,500 | $85,000 |

**Table 5.** Additional profits and losses due to strategic behaviors in the 1st game.

| **Group #** | **GC's strategic profit ($P_B$)** | **GC's loss due to Subs' strategic behaviors ($C_{UC}$)** | **Subs' strategic profit ($P_{UC}$)** | **Subs' loss due to GC's strategic behaviors ($C_B$)** |
|---|---|---|---|---|
| Group #1 | $500 | $2188 | $2188 | $500 |
| Group #2 | $2500 | *N/A* | *N/A* | $2500 |
| Group #3 | *N/A* | *N/A* | *N/A* | *N/A* |
| Group #4 | $4000 | $2150 | $2150 | $4000 |
| Group #5 | $2100 | *N/A* | *N/A* | $2100 |
| Group #6 | $2000 | $2275 | $2275 | $2000 |
| Group #7 | $1000 | $2225 | $2225 | $1000 |
| Group #8 | $1500 | *N/A* | *N/A* | $1500 |

**Table 6.** Strategic behavior pairs in role-playing simulation games.

| **Group #** | **Strategic Behavior Pairs in the 1st Game** | **Strategic Behavior Pairs in the 2nd Game** |
|---|---|---|
| Group #1 | (P, P) | (T, T) |
| Group #2 | (P, T) | (T, T) |
| Group #3 | (P, T) | (T, T) |
| Group #4 | (P, P) | (T, T) |
| Group #5 | (P, T) | (T, T) |
| Group #6 | (P, P) | (T, T) |
| Group #7 | (P, P) | (T, T) |
| Group #8 | (P, T) | (T, P) |

**Table 7.** GCs' and Subs' payoff pairs resulting from strategic behaviors.

| Group # | Payoff Pairs in 1st Simulation Game | Payoff Pairs in 2nd Simulation Game |
|---|---|---|
| Group #1 | ($500 – $2188 – *R*, $2188 – $500 – *R*) | (*S*, *S*) |
| Group #2 | ($2500, – $2500) | (*S*, *S*) |
| Group #3 | (0, 0) | (*S*, *S*) |
| Group #4 | ($4000 – $2150 – *R*, $2150 – $4000 – *R*) | (*S*, *S*) |
| Group #5 | ($2100, –$2100) | (*S*, *S*) |
| Group #6 | ($2000 – $2275 – *R*, $2275 – $2000 – *R*) | (*S*, *S*) |
| Group #7 | ($1000 – $2225 – *R*, $2225 – $1000 – *R*) | (*S*, *S*) |
| Group #8 | ($1500, –$1500) | (0, $1500 – *R*) |

Another limitation is related to quantifying the synergy (*S*) in the games. Several studies have highlighted the practical benefits of synergy (*S*) between the GC and the Subs. For example, Miller *et al.* [42] revealed that the mutual cooperation based on trust between GC and Subs can enable lean construction practices, which can effectively reduce construction project costs. In addition, Tan *et al.* [40] found that collaborative/partnering relationships based on mutual trust and respect leads to successful project, enabling better profits for GC and Subs in the project. The above examples show the practical value of the synergy generated by trust and committed collaboration between GC and Subs in construction projects. However, the simulation performed herein was unable to quantitatively estimate the said benefits. This limitation made it challenging to quantitatively compare the payoffs generated by the GC's and Subs' strategic behaviors. However, even though the value of synergy cannot be quantitatively estimated, the result still shows the positive *Nash equilibrium* state (T, T) is better option than the negative *Nash equilibrium* state of (P, P) or (P, T), in which at least one player is adversely affected.

In the face of the aforementioned limitations, the work presented herein can be developed further and improved in several ways. First, the game-theoretic framework and simulation game presented herein can be applied to real-world construction projects with construction professionals to obtain in-depth, more specific insights based on actual data. Second, a method to quantitatively estimate the benefits of synergy (*S*) in the subcontracting process can be developed and combined with the framework presented herein to facilitate deeper analysis and comparison of the strategic behaviors' payoffs. We expect the present study to serve as a foundation for future studies on this topic.

## 7. Conclusions

The lack of trust between the GC and Subs results in opportunistic behaviors in the traditional subcontracting model in the construction domain. Those behaviors, including GC's committing bid shopping and Subs' creating unethical change orders, have a negative impact on project quality and costs by causing the use of substandard materials as well as claims and disputes in the construction phase. This study argues that the blockchain application in the subcontracting process can promote trust-driven behaviors of the GC and Subs through its decentralization and automation of the process, leading to economic benefits, which is a win-win game for both stakeholders. This study validated the argument by developing and simulating a game-theoretic framework to examine the implication of the blockchain-innovated subcontracting model. The detailed theoretical and practical implications of this study are provided below.

### *7.1. Theoretical implications*

The findings of this study offer both empirical and theoretical evidence demonstrating that blockchain technology has the potential to foster trust-driven behaviors within the construction subcontracting process. People are likely to engage in risky behaviors because they want to avoid uncertainty by reducing ambiguities in their decision makings [32]. The simulation result of the traditional subcontracting process aligns with this explanation. The GC and Subs are likely to choose profit-driven behaviors, eliminating the ambiguity in their decision-making by securing apparent individual profits even though the decisions hurt each other. This opportunistic choice shows the lack of trust between the GC and Subs because if there is trust in an interdependent relationship, the stakeholders can endure the ambiguity, not hurting each other [20,21]. However, the simulation results of the blockchain-enabled subcontracting process showed the change in the GC's and Subs' decision-making from avoiding uncertainty through opportunistic behaviors to enduring the ambiguity in decision results, which reveals that blockchain technology creates trust.

Additionally, this study undertook an analysis of behavioral outcomes within the simulations utilizing a game-theoretical framework, distinguishing between profit-driven and trust-driven strategic behaviors. The analysis provided a theoretical validation of the practical effects of trust engendered by blockchain technology. These findings significantly enhance the existing body of knowledge by elucidating the positive impact of the technology-innovated subcontracting model on the construction industry, thereby bridging the gap between the implementation of new technologies and their practical applications within the sector.

### *7.2. Practical implications*

This study makes several contributions to the construction industry, particularly through its practical implications. Firstly, by highlighting the enhanced outcomes derived from trust-driven behaviors, it encourages GCs and Subs to engage in ethical decision-making throughout the subcontracting process. This shift towards ethical practices is anticipated to result in improved project quality and profitability while minimizing the risks associated with claims and disputes. Secondly, the research equips construction managers with valuable insights into the application of innovative technologies, such as blockchain, to cultivate trust and mitigate opportunistic behaviors. By facilitating a new subcontracting model, this knowledge serves as an important managerial takeaway, especially given that implementing technological solutions in the construction sector often demands substantial time and effort for learning and demonstrating their benefits. Finally, from the perspective of policymakers, the findings of this study can inform the development of industry-specific or firm-specific regulations and incentives that promote fair and ethical behaviors within subcontracting processes through the application of blockchain technology.

## Conflicts of interests

The authors declared that they have no conflicts of interests.

## Authors' contribution

Conceptualization, J.H.Y. and P.P.; Methodology, J.H.Y. and P.P.; Validation, J.H.Y.; Formal analysis, J.H.Y.; Writing—original draft preparation, J.H.Y.; Writing—review and editing, J.H.Y. and P.P.; Supervision, P.P.

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