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A MECHANISM FOR SMART CONTRACTS TO MEDIATE PRODUCTION BOTTLENECKS UNDER CONSTRAINTS

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ABSTRACT

Central project managers devote massive efforts to monitor, track, coordinate, and take actions to diagnose and prognose governed constraints and remove them to enable a reliable workflow. The blockchain-enabled smart contract can streamline the work process by predefining "intelligent" consensus to facilitate central managers' jobs. However, the inability of smart contracts to handle unexpected events under complicated environments posited challenges in realizing it automatically. This study aimed to develop adaptive mechanism to mediate production bottlenecks caused by constraints. First, the research identified the four main types of constraints and their levels of variability from a prefabricated project. Then, a simulation model was established to quantify the impacts of different constraints and determine the fair payment rules. Lastly, different constraint-bundled scenarios and execution policies were developed and encoded in the smart contracts for automated executions. Smart contracts can assist construction managers to motivate reliable production and minimize waste caused by bottlenecks in the system.

KEYWORDS

Constraint, simulation, smart contracts, Shapley value, modular construction

INTRODUCTION

This study aims to improve production flow by modeling potential scenarios integrated with smart contracts during planning to assist the team in making informed decisions that lead to a reliable flow. Enabling a reliable construction workflow requires timely identification and removal of constraints under dynamic construction scenarios (Javanmardi et al., 2020). Koskela (1999) identified that at least seven types of constraints must be removed during the planning stage: design and working method, components and materials, laborers, equipment and tools, space, prerequisite work, and external conditions. However, such a task requires central project managers to be proactive and increasingly detailed iterative planning actions to identify and remove constraints to make ready before the tasks are released into production (Sacks et al., 2020).

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The recent advance of blockchain-enabled smart contracts showed great promise to streamline the construction process by infusing "intelligent" consensus in smart contracts to facilitate central managers' jobs (J. Li et al., 2019; Mason & Escott, 2018). However, various research pointed out the difficulties of establishing such a consensus. For example, Hunhevicz et al. (2021) argued that complicated construction environments posited various uncertainties in smart contract executions. Therefore, ensuring the flexibility to handle unexpected events when designing smart contracts was crucial for successful implementation. Hamledari & Fischer (2021a) mentioned that smart contracts heavily rely on individuals who design the underlying consensus to enable its "smart" in automation. Nevertheless, Lu et al. (2021) stated that construction resources (e.g., workers, equipment, materials) could be turned into smart construction objects with properties of awareness, communicativeness, and autonomy to enable communications between the construction process and blockchain networks. Such a theory indicated the supporting flows (e.g., workers, equipment, materials) could be used as a "Check" mechanism in smart contracts to decentralize and enhance production. However, there are research gaps in converting intangible process-level constraints into tangible smart contract manageable consensus explicitly to enable automation and enhance the intelligence of a decentralized governance mechanism.

This study aimed to develop an adaptive smart contract by encoding constraints and quantifying their interactive relationships as management consensus. First, this study identified the four main constraints for a construction project and defined various levels of variabilities for each constraint. Then, a simulation model integrated with the Shapley value algorithm was developed with permutation and combination to quantify the impacts of different constraints and determine the fair payment rules. Lastly, different constraint-bundled scenarios and related payment policies were encoded in the smart contracts for automated executions. Test scenarios were generated to validate and verify the smart contract implementations. The developed smart contracts provide a solution to automatically handle dynamic constraint events with minimum central managers' efforts. The developed smart contract prototype can be extended to model Koskela (1999)'s seven types of constraints with suitable adjustments to project needs.

LITERATURE REVIEW

Constraint Management

In construction management, Koskela (2000) developed a systematic transformation-flow-value (TFV) production theory to streamline the construction production process. Here, the transformation focuses on converting inputs to products; the flow theory emphasizes construction task, material, and information hand-offs; and the value theory stresses customer satisfaction. Specifically, the flow perspective treats production as flows of processes to improve their reliability and eliminate waste. Koskela (1999) suggested that at least seven types of constraints should be removed during construction planning: construction materials, tools and equipment, laborers, prerequisite work, design and working methods, space, and weather. While the constraints widely exist in practice, it takes construction professionals significant time and effort to identify and eliminate them to achieve the desired production pace and reliable workflow (Javanmardi et al., 2020).

In the past decades, it has been shown that constraint removal has a significant relationship with workflow reliability (Jang & Kim, 2008). Hamzeh et al. (2016, 2015) identified constraint removal during make-ready impacts construction lookahead plans and eventually affects project duration. Liu et al. (2011) further revealed a positive relationship between workflow reliability and constraint removal through a case study. In recent years, research was also developed to visualize various constraints and integrate constraint removal efforts (He et al., 2023; He, Liu, Zhang, et al., 2022). Although research on constraint removal is abundant, there has been a lack of research on quantifying the interrelated relationships between different constraints in terms of project schedule and cost. This research will fill this gap.

SMART CONTRACT IN CONSTRUCTION

The term "smart contract" was coined by Szabo (1994). He defined the smart contract as "a computerized transaction protocol that executes the terms of a contract." The smart contract runs on a blockchain and can execute predefined consensus automatically once certain events are detected. All the transaction data will be recorded in a distributed ledger, namely blockchain, to track conditioned events and executions. Smart contracts showed a 200% improvement in information-sharing accuracy compared with traditional digital payment tools (Hamledari & Fischer, 2021a). Smart contracts demonstrated great potential in streamlining the construction business, such as assigning progress payments (Hamledari & Fischer, 2021b), coordinating supply chain orders (Lu et al., 2021), and triggering rework where defects occurred (Wu et al., 2021). The introduction of smart contracts in the construction industry can remedy the deficiencies of centralized control (Yang et al., 2020) and enhance process automation (Mason & Escott, 2018).

Construction projects are characterized by dynamic and uncertain processes that involve tangible and intangible constraints interrelated with each other. Although smart contracts have been widely adopted in the construction industry, they are not inherently "intelligent" enough to handle different uncertainties ex-ante, and their design heavily relies on individuals who construct the underlying consensus. Poorly designed smart contracts may lead to irreversible financial loss (Hamledari & Fischer, 2021a). Hence, ensuring the flexibility of smart contracts in handling unexpected events is critical for their successful implementation in the real world (Hunhevicz et al., 2021). Various research efforts have been made to facilitate the practical adoption of smart contracts by modeling constraints in their design. For instance, Wu et al. (2021) proposed a formal ontology to represent constraints in construction quality regulations, aiming to improve blockchain's interoperability and support the auto-generation of smart contracts by strengthening the reasoning ability of ontology. Another study by X. Li et al. (2022) highlighted the challenges in developing adaptive smart contracts that can provide solutions for constraints, risks, uncertainties, and disturbances. They acknowledged that including them in each transaction leads to redundancy and low latency for the blockchain network. Furthermore, Chen, Liu, Zhang, et al. (2023) conducted a simulation study to elaborate on various levels of prerequisite work readiness as the primary constraint for smart contracts to enforce a reliable critical path workflow. Simulating different "what-if" scenarios and conducting cost-benefit tradeoffs in real-time demonstrated significant implications for robust smart contract consensus design. Dounas & Lombardi (2022); He, Liu, Wang, et al. (2022) emphasized the importance of standardized smart contract design to enhance context awareness. However, the design of smart contracts barely considered the seven types of constraints that are the leading factors of construction "waste." This study aims to investigate the interactive constraint relationships to present a situation-awareness smart contract.

DATA COLLECTION

Data was collected from a high-rise residential building project in Singapore that utilized the modular construction method for Prefabricated Bathroom Unit (PBU) installation. The project aimed to complete 120 PBU installations, with equal distributions of three different types: 40 PBUA, 40 PBUB, and 40 PBUC. The project had three major participants: a PBU fabricator responsible for off-site fabrication and delivery, a crane and operator responsible for platform installation and lifting, and workers responsible for installation. The major constraints included uncertain and out-of-sequence PBU arrival due to the fabricator's preference for producing PBUs in a large batch, crane unavailability due to fully scheduled lifting activities, and a minimal number of workers assigned for installation to maximize profitability. This worsened the vicious cycle of arrival-lifting-installation. Besides, heavy rainfall was frequent in Singapore (Shen et al., 2018), which can significantly hinder installation productivity. Therefore, considering external conditions (e.g., precipitation intensity) as the fourth constraint is also crucial during the project planning stage.

RESEARCH METHODS

Figure Figure 1 presents the research framework, which involves six main steps. First, the study identified four key constraints for the real case project, namely external conditions (EC), material availability (MA), equipment availability (EA), and labor availability (LA). In step 2, the research defined three levels of variability for each constraint and used them to construct a simulation model that generated 81 possible scenarios. The scenarios were evaluated based on cost, and a Shapley value approach was used to determine fair reward/penalty sharing rules. In step 5, the researchers programmed all the scenarios and payment terms into smart contracts to incentivize collaborations and ensure high reliability. Finally, the framework's validity and effectiveness were tested through various scenarios input.

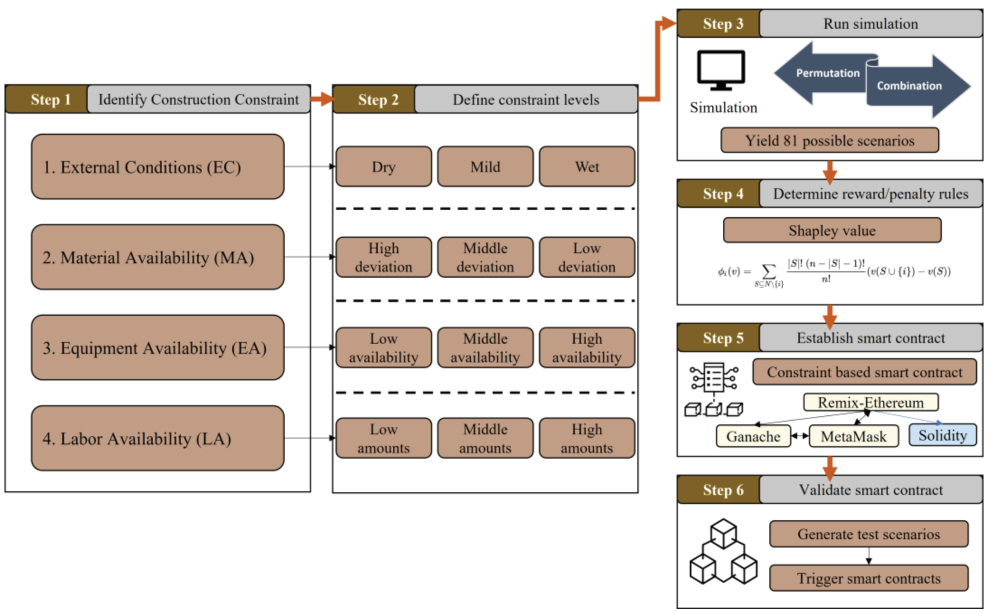

Figure 1: Research framework

Simulation Modeling

The research collected data on 74 PBU loading platform assemblies and 139 PBU hoisting activities. The productivity distribution processing can be referred from previous work (Chen et al., 2022). Productivity distribution is used used to build a simulation model that considers four main constraints: precipitation intensity (EC), PBU delivery reliability (MA), crane availability (EA), and assigned worker amounts (LA). These variables were used to evaluate the impacts on the project's overall outcomes.

The weather in Singapore can be categorized into dry, wet, and mild seasons, as reported by the National Environment Agency (2009). The historical daily precipitation data for 2017 was obtained by web scraping from the Meteorological Service Singapore (2023), which provided 151 daily precipitation intensity records for dry weather and 91 and 123 records for mild and wet weather, respectively. Larsson & Rudberg (2019) identified that different levels of precipitation intensity affect work efficiency, with the efficiency decreasing as precipitation intensity increases. Based on their findings, different weather conditions have varying precipitation intensity probability distributions, which are displayed in Figure 1. The reliability levels for PBU, crane, and workers, as well as the simulation workflow, can be found in our previous work (Chen, Liu, Li, et al., 2023; H. Li et al., 2023), which also outlines the three different levels of reliability for each constraint as summarized in Table 1. These different levels of variability can be combined and permuted to produce 81 possible scenarios.

The simulation recorded the project duration of 120 PBU installations, and the wait time for the crane and installation workers. The project cost includes PBU material costs, crane rental costs, workers' salaries, and indirect costs. Each PBU costs $5,400 to fabricate, $648,000 for 120 PBUs in total. Crane costs $1,200/day, one installation team costs $1,000/day, and the indirect cost is $2,000/day. The project outcomes will be quantified in terms of cost to evaluate the marginal contributions from each constraint.

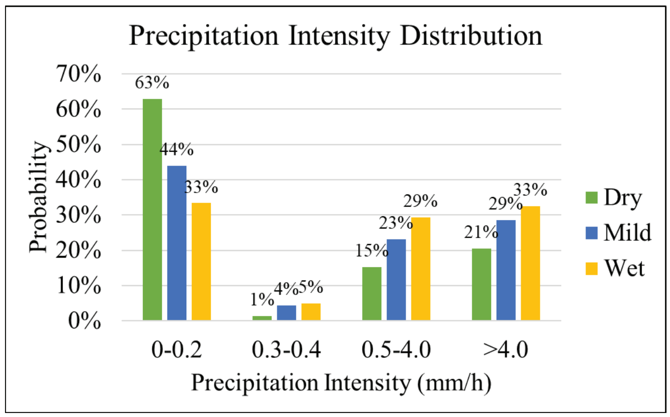

Figure 2: Influence of Precipitation on Construction Efficiency Based on Different Weather Conditions

Table 1: Reliability Level for Four Constraints

Reliability	Measurements	
EC	Precipitation Intensity	Distribution
High	Dry	DISC(0.63, 1, 0.64, 0.6, 0.79, 0.5, 1, 0.3)
Middle	Mild	DISC(0.44, 1, 0.48, 0.6, 0.71, 0.5, 1, 0.3)
Low	Wet	DISC(0.33, 1, 0.38, 0.6, 0.67, 0.5, 1, 0.3)
MA	PBU Delivery Deviation	Distribution
High	(0,8]	DISC(1/3, PBU_x, 1/3, PBU_y, 1, PBU_z)
Middle	(8,14]	DISC(11/18, PBU_x, 15/18, PBU_y, 1, PBU_z)
Low	(14,24]	DISC(15/18, PBU_x, 17/18, PBU_y, 1, PBU_z)
EA	Crane Availability	Distribution
High	>= 80%	80%
Middle	(60%, 80%)	70%
Low	<= 60%	60%
LA	Assigned Worker Amounts	Distribution
High	(7, 10]	U(66, 76)
Middle	(4, 7]	U(80, 90)
Low	<= 4	U(100, 111)

Note: DISC(Cumulative Probability, Value, ...) : discrete probability distribution; U(a, b) : Uniform Distribution

SHAPLEY VALUE CALCULATION

The Shapley value method is a way to fairly and efficiently share benefits among a group of players (Parrachino et al., 2006). It assumes that a collaboration of *n* players can be represented by a set of players *N*, and a coalition of players *S*, with *v(S)* measuring the sum of payoffs from members of *S* due to cooperation. Each player's contribution to the coalition can be measured using the formula:

$$\varphi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(n-|S|-1)!}{n!} (v(S \cup \{i\}) - v(S)) \quad (1)$$

Where n is the total number of players, $v(S \cup \{i\}) - v(S)$ is the difference of worth when adding player i in coalition S, and $S \subseteq N\{i\}$ is the subsets S of N not containing player i. This formula can be used to calculate the fair reward or penalty for each player.

For example, suppose the objective is to determine the equitable reward for PBU fabricators in a scenario where all players (MA, EA, and LA) take part in a High (H) reliability collaboration, where the benchmark is Middle (M) reliability collaboration. The Shapley value method can be employed in the following manner:

1. Calculate the marginal value of adding each player (MA, EA, and LA) to the coalition, which can be represented as $[\Delta v_{\emptyset,MA}, \Delta v_{EA,MA}, \Delta v_{LA,MA}, \Delta v_{(EA,LA),MA}]$, and their values are [$1,722, $630, $504, $42].
2. Determine the scaling factor for each subset size, which averages the effect of the rest of the team members, ignoring their composition and focusing solely on the player's marginal contribution. The scaling factors for $[\Delta v_{\emptyset,MA}, \Delta v_{EA,MA}, \Delta v_{LA,MA}, \Delta v_{(EA,LA),MA}]$ are [1/3, 1/6, 1/6, 1/3], respectively.
3. Calculate the fair reward for each player by multiplying the scaling factor for each subset size by the marginal value of adding that player to the coalition and summing the results. The fair rewards for players PBU fabricator (responsible for MA) are 1/3 × $1,722 +1/6 × $630+1/6 × $504 +1/3 × $42 = $777.

Therefore, according to the Shapley value method, PBU fabricators, crane, and workers should receive benefits of $777, $861, and $21,672 when all players participate in the High collaboration. Shapley values can be negative if a player's participation causes a decrease in overall project performance, indicating that the player should be penalized for their contribution. For example, once (M, M, M) has been set as benchmark, the penalties for case (L, L, L) can be calculated by forming the following eight combinations: (M, M, M), (L, M, M), (M, L, M), (M, M, L), (L, L, M), (L, M, L), (M, L, L), (L, L, L).

Table 2: Sample of Shapley Value Calculation

Case	(MA, EA, LA)	Duration	Total Cost	Difference	PBU SV	Crane SV	Worker SV
1	(M, M, M)	44.24	$ 833,808	$ -	$ -	$ -	$ -
2	(H, M, M)	43.83	$ 832,086	$ 1,722	$ 1,722	$ -	$ -
3	(M, H, M)	44.01	$ 832,842	$ 966	$ -	$ 966	$ -
4	(M, M, H)	39.04	$ 811,968	$ 21,840	$ -	$ -	$ 21,840
5	(H, H, M)	43.86	$ 832,212	$ 1,596	$ 1,176	$ 420	$ -
6	(H, M, H)	38.92	$ 811,464	$ 22,344	$ 1,113	$ -	$ 21,231
7	(M, H, H)	38.70	$ 810,540	$ 23,268	$ -	$ 1,197	$ 22,071
8	(H, H, H)	38.69	$ 810,498	$ 23,310	$ 777	$ 861	$ 21,672

*SV: Shapley value

SMART CONTRACT DEVELOPMENT

Eighty one possible scenarios formulated "management intelligence" and were translated into smart contract codes in Solidity language (version 0.8.14). This research developed smart contracts in Remix-Ethereum (version 0.29.2), which has an online Integrated Development Environment (IDE) that is a powerful toolset for developing, deploying, debugging, and testing Ethereum and Ethereum Virtual Machine (EVM)-compatible smart contracts. The IDE also has the desktop version for programmers who prefer the performance or security on their own hard drives. Besides, this study utilized Ganache (version 7.2.0) to create a private Ethereum blockchain and created accounts for three parties: PBU fabricator, crane, and installation workers. Ganache enables setting a personal Ethereum blockchain on the local network for testing and development so that the smart contract programmer can simulate different blockchain nodes in one computer before practical implementation. Ganache provides a Remote Procedure Call (RPC) link that allows smart contracts to run on the fetched blockchain network. The Remix-Ethereum can enter the PRC link in the "Environment" tab to deploy developed smart contracts in created blockchain. Once the blockchain is deployed, project participants can use MetaMask 10.11.3 (a decentralized crypto wallet) as a tool to interact with the blockchain and smart contract. Once all the settings have been settled, different scenarios can be generated to test the validity and effectiveness of proposed smart contracts.

RESULTS

The simulation outputs are summarized in Table 3. The results of non-weather consideration were also included in the table. Without weather considerations, the average project duration for 27 scenarios is 32.27 days, and the wait time for the crane and installation worker team are 0.97 hours/PBU, and 0.34 hours/PBU, respectively. While with weather (dry) considerations, the project duration is 46.17 days, showing a 43.08% increase. Figure 2 indicates that even during dry weather, there are precipitation intensities >4.0 and 0.5-4.0 mm/h, which cause a decrease in production efficiency, ultimately resulting in a significant increase in overall durations compared to situations without weather considerations. The crane and installation workers' wait times were 1.81 hours/PBU and 0.21 hours/PBU, respectively. This led to an 87.63% increase in crane wait time and a 37.52% decrease in installation worker team wait time under weather assumptions. The crane had more idle time, while the installation workers were busier. Project duration increased by 14.95% for mild weather (53.07 days) and by 23.62% for wet weather (57.08 days) compared to dry weather. Crane idle time increased by 23.07% (2.23 hours/PBU) for mild weather and by 36.18% (2.47 hours/PBU) for wet weather, while workers' wait time decreased by 18.43% and 26.05%, respectively. These results suggest that severe weather (increased precipitation intensity) can increase project duration and crane idle time, while putting more pressure on installation workers. Weather affects task productivity, and the worker installation capacity cannot match the high PBU delivery and crane capacity during turbulent weather. According to the Goldratt & Cox (1984), a bottoleneck operation is the operation that limits the capacity of the entire production process, and it can be identified by high levels of capacity utilization of the resources. Therefore, the activities of installation workers became the bottlenecks in this production process.

Table 3: Comparisons of 108 Scenarios from Simulation

	Without Weather (Chen et al., 2023)			With Weather (Dry)			With Weather (Mild)			With Weather (Wet)		
(MA, EA, LA)	Duration	Crane WT*	Worker WT	Duration	Crane WT	Worker WT	Duration	Crane WT	Worker WT	Duration	Crane WT	Worker WT
(L,L,L)	38.90	1.01	0.55	53.71	1.97	0.29	61.73	2.47	0.23	66.22	2.77	0.19
(L,L,M)	37.40	0.94	0.80	48.18	1.48	0.46	54.59	1.87	0.38	57.72	2.02	0.29
(L,L,H)	35.70	0.79	0.92	44.76	1.21	0.58	48.86	1.41	0.40	52.41	1.62	0.35
(L,M,L)	37.30	1.40	0.42	53.38	2.46	0.26	61.49	2.94	0.22	65.98	3.23	0.19
(L,M,M)	34.30	1.19	0.56	47.13	1.92	0.35	53.23	2.29	0.27	56.52	2.47	0.21
(L,M,H)	32.70	1.04	0.68	43.05	1.60	0.44	47.66	1.86	0.33	51.27	2.04	0.31
(L,H,L)	37.80	1.88	0.47	52.86	2.79	0.23	60.56	3.29	0.21	65.96	3.64	0.18
(L,H,M)	34.10	1.53	0.53	46.86	2.31	0.34	52.26	2.59	0.20	56.95	2.90	0.23
(L,H,H)	31.60	1.35	0.59	42.53	1.94	0.38	48.11	2.28	0.33	50.28	2.33	0.23
(M,L,L)	34.20	0.64	0.17	51.68	1.79	0.13	61.25	2.45	0.11	64.71	2.60	0.12
(M,L,M)	33.00	0.56	0.44	45.67	1.26	0.24	51.90	1.67	0.17	56.33	1.91	0.17
(M,L,H)	31.60	0.43	0.58	41.36	0.96	0.31	46.76	1.22	0.22	50.10	1.44	0.17
(M,M,L)	33.70	1.13	0.11	51.39	2.32	0.10	59.72	2.80	0.09	64.93	3.19	0.10
(M,M,M)	30.40	0.84	0.21	44.24	1.69	0.13	51.33	2.13	0.11	55.21	2.36	0.10
(M,M,H)	28.30	0.67	0.31	39.04	1.25	0.11	45.01	1.63	0.11	49.06	1.84	0.10
(M,H,L)	33.10	1.48	0.08	51.43	2.66	0.08	60.10	3.24	0.08	64.71	3.54	0.09
(M,H,M)	29.60	1.18	0.15	44.01	2.05	0.08	50.97	2.51	0.08	55.37	2.74	0.09
(M,H,H)	27.20	0.95	0.21	38.70	1.63	0.09	45.30	2.01	0.09	48.78	2.22	0.08
(H,L,L)	33.80	0.64	0.12	52.02	1.85	0.12	60.22	2.35	0.12	64.99	2.70	0.12

(H,L,M)	32.00	0.50	0.36	45.35	1.32	0.20	52.33	1.71	0.17	56.24	1.92	0.15
(H,L,H)	30.20	0.33	0.47	41.22	0.92	0.30	46.51	1.23	0.21	49.92	1.37	0.18
(H,M,L)	33.00	1.06	0.05	51.64	2.31	0.09	60.04	2.85	0.09	64.82	3.18	0.10
(H,M,M)	28.80	0.74	0.09	43.83	1.67	0.09	51.38	2.11	0.10	55.22	2.34	0.10
(H,M,H)	26.70	0.52	0.16	38.92	1.26	0.11	45.52	1.65	0.11	48.79	1.86	0.10
(H,H,L)	32.40	1.42	0.02	51.14	2.67	0.07	60.08	3.25	0.08	64.88	3.56	0.09
(H,H,M)	28.30	1.07	0.04	43.86	2.06	0.07	51.08	2.50	0.08	54.95	2.73	0.09
(H,H,H)	25.20	0.82	0.05	38.69	1.64	0.08	45.03	1.97	0.08	48.81	2.20	0.09
Average	32.27	0.97	0.34	46.17	1.81	0.21	53.07	2.23	0.17	57.08	2.47	0.16

*WT: Wait Time (Hours/PBU)

Table 4 presents the rewards and penalties under 81 scenarios for PBU fabricators, crane operators, and installation workers responsible for MA, EA, and LA under different weather conditions. Each value is aggregated using generated cost from simulation and Shapley value calculation described previously. The value corresponds to the marginal contributions of this responsible specialty under that scenario. Figure 3 visualizes the Shapley values based on the marginal contributions from each participant, with the height of each bar column indicating the Shapley value payments or contributions of each participant. Figure 3 (a) showed that without considering the impact of weather, PBU delivery excelled over than other two factors in contributing to successful project outcomes. With weather considerations and as weather conditions got worse, the installation workers dominated the project contributions. During wet weather, the contributions from higher reliability of crane and PBU delivery are minimum. It is essential to prioritize installation worker assignments either by assigning an extra installation team or extending the working time to overcome extreme external conditions. These 81 payment rules will be encoded into smart contracts as an incentive mechanism to enable reliable constraint removal for decentralized production planning.

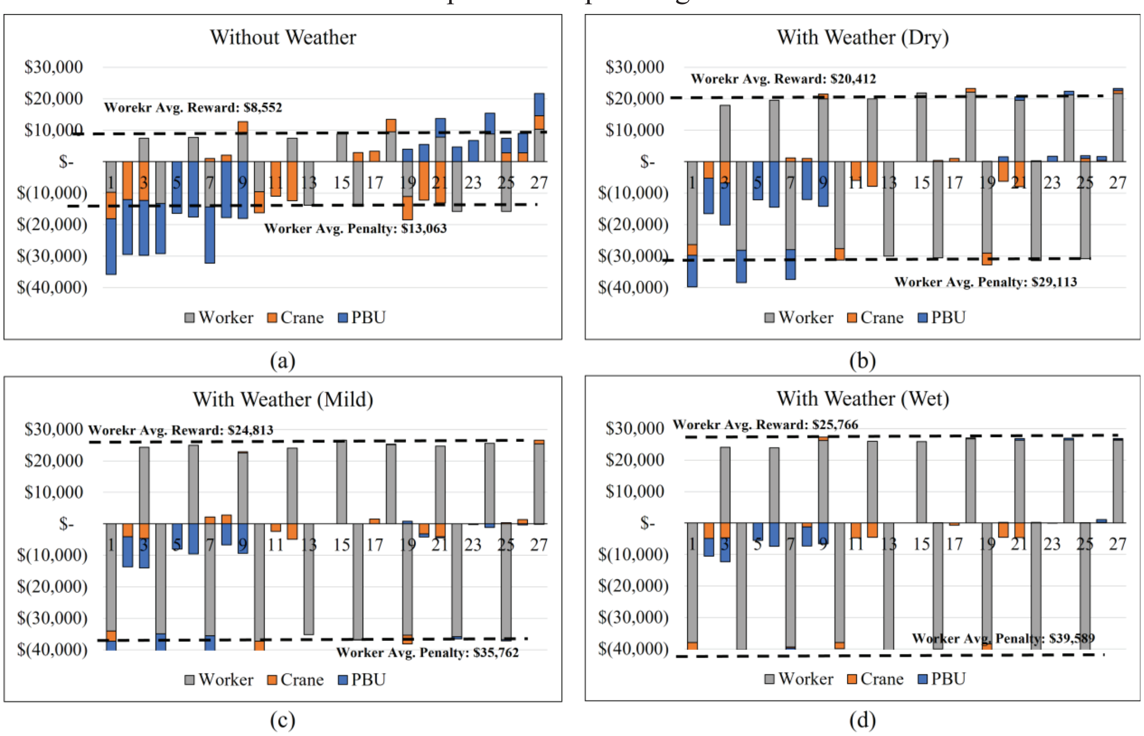

Figure 3: Shapley Value Payments Under Different Weather Scenarios: (a) Without Weather; (b) With Weather (Dry); (c) With Weather (Mild); (d) With Weather (Wet)

Table 4: Payments Based on Shapley Value for 108 Scenarios

	With Weather (Dry)			With Weather (Mild)			With Weather (Wet)		
(MA, EA, LA)	PBU SV	Crane SV	Worker SV	PBU SV	Crane SV	Worker SV	PBU SV	Crane SV	Worker SV

(L,L,L)	-$10,038	-$3,402	-$26,334	-$6,454	-$3,157	-$34,069	-$5,656	-$2,590	-$37,996
(L,L,M)	-$11,340	-$5,208	$0	-$9,639	-$4,053	$0	-$5,670	-$4,872	$0
(L,L,H)	-$13,370	-$6,755	$17,941	-$9,338	-$4,655	$24,367	-$7,588	-$4,732	$24,080
(L,M,L)	-$10,248	$0	-$28,140	-$7,707	$0	-$34,965	-$4,956	$0	-$40,278
(L,M,M)	-$12,138	$0	$0	-$7,980	$0	$0	-$5,502	$0	$0
(L,M,H)	-$14,490	$0	$19,488	-$9,555	$0	$24,969	-$7,392	$0	$23,940
(L,H,L)	-$9,436	$1,211	-$27,979	-$5,446	$2,219	-$35,539	-$5,425	-$343	-$39,382
(L,H,M)	-$12,054	$1,050	$0	-$6,699	$2,793	$0	-$6,069	-$1,239	$0
(L,H,H)	-$14,210	$1,477	$19,975	-$9,352	$350	$22,526	-$6,587	$1,057	$26,236
(M,L,L)	$0	-$3,612	-$27,636	$0	-$4,410	-$37,254	$0	-$1,890	-$38,010
(M,L,M)	$0	-$6,006	$0	$0	-$2,394	$0	$0	-$4,704	$0
(M,L,H)	$0	-$7,875	$19,971	$0	-$4,872	$24,066	$0	-$4,536	$25,998
(M,M,L)	$0	$0	-$30,030	$0	$0	-$35,238	$0	$0	-$40,824
(M,M,M)	$0	$0	$0	$0	$0	$0	$0	$0	$0
(M,M,H)	$0	$0	$21,840	$0	$0	$26,544	$0	$0	$25,830
(M,H,L)	$0	$399	-$30,597	$0	-$42	-$36,792	$0	$126	-$40,026
(M,H,M)	$0	$966	$0	$0	$1,512	$0	$0	-$672	$0
(M,H,H)	$0	$1,197	$22,071	$0	$147	$25,179	$0	$252	$26,754
(H,L,L)	$147	-$3,801	-$29,022	$847	-$2,786	-$35,399	-$266	-$2,366	-$38,444
(H,L,M)	$1,533	-$6,195	$0	-$1,008	-$3,192	$0	$168	-$4,494	$0
(H,L,H)	$1,078	-$7,910	$19,516	-$378	-$4,074	$24,696	$490	-$4,592	$26,320
(H,M,L)	$336	$0	-$31,416	-$777	$0	-$35,805	$210	$0	-$40,572
(H,M,M)	$1,722	$0	$0	-$210	$0	$0	-$42	$0	$0
(H,M,H)	$1,113	$0	$21,231	-$1,176	$0	$25,578	$546	$0	$26,418
(H,H,L)	$910	$973	-$30,863	-$343	$392	-$36,799	$119	$35	-$40,768
(H,H,M)	$1,176	$420	$0	-$336	$1,386	$0	$861	$231	$0
(H,H,H)	$777	$861	$21,672	-$126	$1,197	$25,389	$427	$123	$26,320

*SV: Shapley Value

VALIDATIONS

Test scenarios are generated to validate the smart contract executions, as shown in Figure 4. In this study, smart contracts can only be triggered by a mutual-agreed database. The database can be integrated with various platforms, representing the physical state of the current construction performance. To facilitate data input, this study encoded “2”, “1”, and “0” as the high, middle, and low reliability level, respectively. The environment was be set up as Ganache Provider with four initiated accounts. The first step involved inputting participants’ information and corresponding constraint levels. Given a scenario in that wet weather, high reliability for PBU delivery, crane, and worker involvement was detected from the database, the decoded labels were “0”, “2”, “2”, and “2,” correspondingly. According to the simulation results, the PBU fabricator, crane, and installation workers should receive 427, 123, and 26,320 ether (1 ether = $1 in this study), respectively. In step 2, once the smart contract was successfully activated, the “SendNotice” function would broadcast to the blockchain network regarding the payment amounts for each participant. Step 3 showed that smart contracts could successfully recognize the situations and will assign the correct amounts of payments under this scenario. Solidity provides *transfer()* function that can easily transfer the ether to targeted accounts. Once the transactions were performed, all the information was updated and stored in the blockchain simultaneously, where project participants could view the transactions through Ganache or their digital wallet. The results demonstrated the validity of the developed smart contracts.

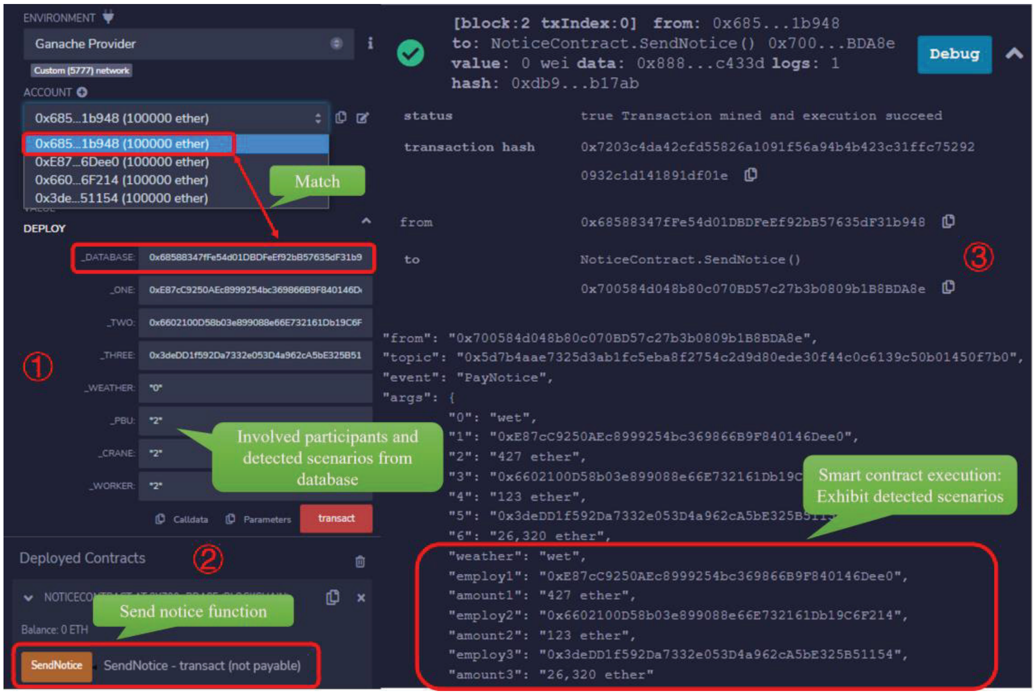

Figure 4: Smart Contract Executions in Remix-Ethereum

CONCLUSIONS

Smart contracts hold immense potential in streamlining the construction process by specifying detailed task planning and enforcing consensus executions. Nonetheless, the dynamic and uncertain nature of construction projects, coupled with tangible or intangible constraints, poses challenges to the effectiveness of smart contracts in dealing with uncertainties ex-ante, relying heavily on individuals who design the underlying consensus. To enhance situation awareness in a decentralized constraint removal system, this study modeled the interactions of constraints in the smart contract consensus, developing a simulation model by permutating four constraint levels to generate 81 scenarios. An equitable payment method based on the Shapley value algorithm was established to incentivize reliable constraint removal. The findings revealed that installation workers dominated project contributions during adverse weather conditions, as installation speed is slower than PBU delivery and crane activities. Consequently, the installation capacity fails to keep up with the delivery and lifting capacity, thereby underscoring the importance of ensuring sufficient installation workers/teams on-site to guarantee project success during extreme weather conditions. Notably, the smart contract executions attested to the accuracy and validity of the developed framework.

This research makes two contributions. Firstly, it quantified the dominant constraints in the face of interactive uncertainties. The flow of constraints is challenging to model and quantify in terms of project outcomes. However, the simulation, which integrated the Shapley value algorithm, exhaustively evaluated all possible scenarios and identified the marginal contributions of improving each constraint. Consequently, project managers can determine the most effective sequence to remove constraints. Secondly, the study integrated blockchain and lean constraint removal theory to enhance smart contracts' situation awareness in dynamic construction environments. Decentralizing construction management requires smart contracts to be "intelligent" enough to function similarly to centralized project managers. The developed smart contract anticipated the governed constraints before the tasks were released into production. Thus, the smart contract focuses on the make-ready process, proactively avoiding situations where crews wait for conditions to mature instead of reactively resolving them with centralized control intervention.

LIMITATIONS

This study has several limitations. First, due to the limitations of the available data, this research only considered the four major constraints that impacted the projects in smart contracts, whereas Koskela (1999) suggested that at least seven types of constraints should be removed during construction planning. Future research can investigate modeling seven constraints and their interactive relationships in smart contracts. Second, this study assumed the extracted information from a database could be used to activate smart contract executions. However, it is difficult to establish a comprehensive database as well as construct contextualization that guarantees reliable smart contract execution. The deployment in the test environment represents another limitation.

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