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A Blockchain-Based Optimization Model for Smart 4PL Network Design in Off-Site Construction

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Abstract

This study proposes a Blockchain (BC)-integrated Fourth-Party Logistics (4PL) model to improve efficiency and Transparency (TR) in Off-Site Construction (OSC) supply chains. A bi-objective optimization model is developed to minimize total network costs and maximize transparency, determining optimal locations for preprocessing centers, selecting Third-Party Logistics (3PL) providers, assigning installation teams, and planning material flows. Validation using the General Algebraic Modeling System (GAMS) software and sensitivity analysis shows that the model significantly reduces logistics costs and delays. Notably, partial BC integration achieves 65% transparency with only a 3.75% cost increase, offering a cost-effective solution. The framework enables construction stakeholders to leverage Industry 4.0 technologies to enhance collaboration and mitigate risks.

Keywords: Fourth-party logistics, Blockchain, Network design, Off-site construction, Multi-objective optimization, Supply chain management.

1 | Introduction

The adoption of Off-Site Construction (OSC) has brought notable improvements in efficiency and sustainability compared to traditional methods [1]. However, OSC projects continue to face significant supply chain challenges, including poor stakeholder coordination, logistical inefficiencies, and the temporary nature of construction operations [2]. While Fourth-Party Logistics (4PL) models have emerged as potential solutions to integrate these fragmented networks, their effectiveness remains limited by issues of Transparency (TR) and trust between participants [3].

Blockchain (BC) technology offers a promising approach to enhancing 4PL systems through its decentralized, tamper-proof record-keeping capabilities and smart contract functionality [4]. By implementing BC, OSC supply chains can achieve greater visibility of material flows, automated contract execution, and improved

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dispute resolution [5]. This integration enables more reliable data for optimizing logistics decisions while reducing administrative overhead [6], [7].

This study develops an enhanced BC-integrated 4PL network design model for OSC supply chains using a bi-objective Mixed-Integer Linear Programming (MILP) approach. The model aims to minimize total network costs and maximize operational transparency by determining optimal locations for preprocessing centers, selecting Third-Party Logistics (3PL) providers, assigning installation teams, and planning material flows. The integration of a BC-based tracking system ensures real-time, verifiable, and immutable recording of all material and component flows across the network.

The research is designed to answer the following pivotal questions: 1) How can the integration of preprocessing centers and BC-enabled tracking optimize the logistics network design for cost and transparency in OSC? 2) What conditions justify the added costs of BC integration in a 4PL network? 3) How does BC impact the selection of 3PLs based on their transparency scores? 4) Under what project scales do BC's transparency benefits outweigh its costs? And 5) how can immutable transaction records reduce disputes in multi-stakeholder OSC environments?

Building on prior work in 4PL optimization [8] and construction supply chains [9], this study makes three contributions: 1) A novel bi-objective mathematical model that integrates BC transparency metrics directly into 4PL network design, 2) empirical validation showing a significant reduction in logistics costs and delays, with partial BC integration achieving 65% transparency for only a 3.75% cost increase, and 3) practical guidelines for implementing permissioned BC in construction logistics, including configurations for recording 3PL routing data.

The remainder of this paper is organized as follows. Section 2 surveys the relevant literature on the OSC supply chain, 4PL, and BC technology. The problem statement and the development of a mathematical model are detailed in Sections 3 and 4, respectively. Section 5 discusses the sensitivity analyses and managerial insights, and finally, Section 6 offers concluding remarks and suggests practical directions for future research.

2 | Literature Review

The integration of OSC supply chains and 4PL has attracted significant attention for its potential to address inefficiencies and coordination challenges in construction projects. Recent advancements in BC technology further enhance this integration by introducing transparency, automation, and trust into supply chain operations. This review synthesizes key contributions from both domains and highlights the emerging role of BC in optimizing OSC supply chains.

2.1 | Off-Site Construction Supply Chain Management

The Previous research has employed various approaches to enhance OSC supply chains. Golpira [10] introduced a Mixed-Integer Linear Programming (MILP) model with Vendor-Managed Inventory (VMI) strategies, while Hsu et al. [11] addressed demand fluctuations using stochastic programming. Later studies improved production-logistics coordination [9] and supplier selection [12], incorporating sustainability [13], [14] and robust optimization for uncertainty management [15].

2.2 | Fourth-Party Logistics in Supply Chain Management

4PL models have advanced logistics through network design, routing optimization, and disruption management. Key studies include Huang et al. [16] on customer behavior, Yin et al. [8] on uncertainty handling, and recent innovations in demand surge solutions [17], [18] and green logistics [19]. However, integration with OSC still lacks solutions for transparency and trust challenges.

2.3 | Blockchain-Enabled Innovations In Construction

BC technology is transforming OSC and 4PL networks by enhancing coordination and transparency. Recent studies demonstrate its diverse applications: Liu et al. [5] developed a BC platform for production management, while Kim et al. [20] improved supply chain reliability using Bayesian theory. In procurement, Kim and Kim [21] showcased BC's role in automating transactions, and Msawil et al. [22] highlighted its effectiveness in contract administration. Additional research by Sun et al. [23] identified critical implementation factors, and Scott et al. [24] provided foundational insights into BC's construction potential. These advancements collectively address key challenges in OSC supply chains through decentralized, secure solutions.

2.4 | Research Gaps and Integration Potential

While significant progress has been made in OSC supply chain optimization and 4PL network design, the integration of BC technology remains underexplored. This study bridges this gap by proposing a novel bi-objective model that combines the strategic advantages of 4PL with BC's transparency, enabling cost-effective, trustworthy decision-making in multi-project OSC environments.

3 | Problem Statement

3.1 | Problem Definition

In this section, a 4PL network is designed to help active players in the supply chain of OSC projects reduce complexity, costs, and inefficiency, while simultaneously maximizing operational transparency through BC integration. To do so, the designed network consists of raw materials suppliers, structural manufacturing workshops, preprocessing centers, and project sites. It is also assumed that for transportation between different levels of the chain, the 4PL cooperates with different 3PLs based on their availability, time, cost, and BC capabilities.

On the other hand, since some measures may not be cost-effective for structural manufacturers, 4PL is looking to set up preprocessing centers that use the concept of resource sharing to preprocess some of the raw materials supplied by suppliers before delivering them to prefabricated workshops at a lower cost than the suppliers. Finally, to install the structures on the project site, 4PL collaborates with various installation teams to deploy them across projects based on geographical conditions and cost.

A key innovation of this model is the integration of a BC-based tracking system managed by the 4PL. All material and component flows are recorded on an immutable distributed ledger, providing stakeholders with real-time, verifiable, and transparent data on the status and location of shipments. This argument enhances trust, accountability, and coordination across the fragmented supply chain.

The suggested bi-objective network model can make the proper decisions concerning: 1) minimizing the total 4PL network costs (including BC transaction costs), and 2) maximizing the total transparency score of the network. Furthermore, it determines the optimal locations for preprocessing centers, selects 3PL providers, assigns installation teams, and plans transport volumes.

Fig. 1 illustrates the overall structure of the problem environment, including the flow of materials, information, and the integration point for BC data recording.

3.2 | Assumptions

The assumptions considered in this study are as follows:

I. It should be noted that the completion of the structure's installation marks the end of the project, and all steps should be taken to minimize the total cost of project delays.

II. The capacity and cost of each potential logistics service provider, including pre-processor centers and 3PLs, are predefined.

III. The required demand from each component for each project site is known in advance.

IV. The unit cost and the transparency score for recording and verifying a unit of material/component flow via the BC are predefined for each 3PL provider and each route.

V. All material and component flows within the network are recorded on the BC, ensuring full traceability.

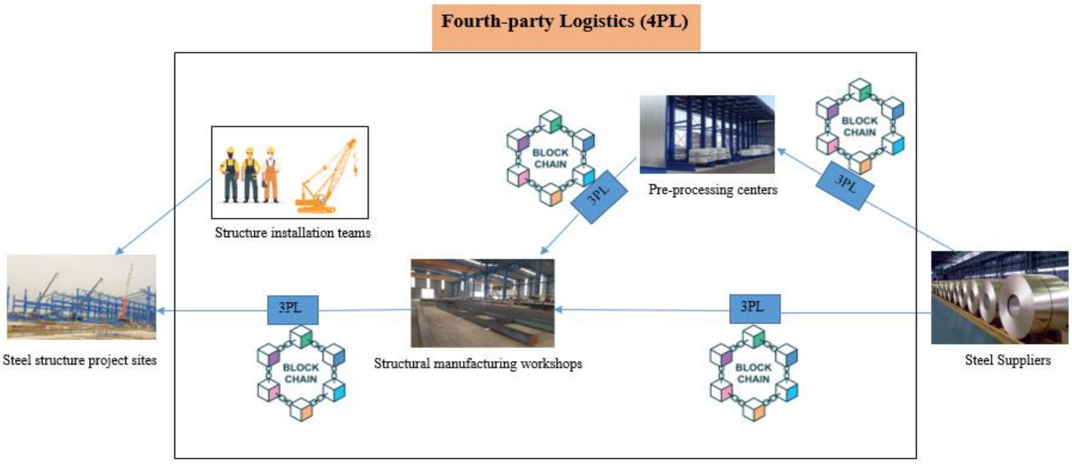

Fig. 1. Overall structure of the problem environment.

4 | Mathematical Model

In this section, a bi-objective optimization framework is presented to address the integrated BC–4PL network design problem for OSC supply chains. The model aims to simultaneously minimize the total network cost and maximize the overall operational transparency. The complete notation is defined in the *Appendix*. The model is solved using the epsilon-constraint method to generate Pareto-optimal solutions.

$$\begin{aligned}\text{Min obj 1} = {} & \sum_{b} H_b \times x_b + \sum_{i}\sum_{b}\sum_{v}\sum_{m} z'^{m}_{ibv}\, g_b + \sum_{i}\sum_{j}\sum_{m}\sum_{v} c^{m}_{ijv}\, dis_{ij}\, y^{m}_{ijv} \\ & + \sum_{i}\sum_{b}\sum_{m}\sum_{v} c'^{m}_{ibv}\, dis'_{ib}\, y'^{m}_{ibv} + + \sum_{b}\sum_{j}\sum_{m}\sum_{v} c''^{m}_{bjv}\, dis''_{bj}\, y''^{m}_{bjv} \\ & + \sum_{j}\sum_{p}\sum_{k}\sum_{v} c'''^{k}_{jpv}\, dis'''_{jp}\, y'''^{k}_{jpv} + \sum_{l}\sum_{p} ci_{lp}\, o_{lp} + \sum_{p} cl_p\, w_p \\ & + \sum_{i}\sum_{p}\sum_{m} price_{im}\, dem_{mp} + \sum_{i}\sum_{j}\sum_{m}\sum_{v} bc^{m}_{ijv} z^{m}_{ijv} \\ & + \sum_{i}\sum_{b}\sum_{m}\sum_{v} bc'^{m}_{ibv} z'^{m}_{ibv} + \sum_{b}\sum_{j}\sum_{m}\sum_{v} bc''^{m}_{bjv} z''^{m}_{bjv} \\ & + \sum_{j}\sum_{p}\sum_{k}\sum_{v} bc'''^{k}_{jpv} z'''^{m}_{jpv}.\end{aligned} \tag{1}$$

The objective function minimizes network costs, so that the first and second terms calculate the costs of establishing and operating preprocessing centers, respectively. The third to sixth terms consider the costs of moving through 3PL. The seventh term calculates the cost of assigning the installation team to projects. The eighth term measures the cost of delaying projects, and the ninth term measures the cost of procuring raw materials from suppliers. The tenth, eleventh, twelfth, and thirteenth terms calculate the costs associated with recording and verifying material and component flows on the BC platform to ensure data integrity and traceability.

$$\text{Max obj 2} = \sum_{i}\sum_{j}\sum_{m}\sum_{v} tr_{ijv}^{m} z_{ijv}^{m} + \sum_{i}\sum_{b}\sum_{m}\sum_{v} tr'^{m}_{ibv} z'^{m}_{ibv} + \sum_{b}\sum_{j}\sum_{m}\sum_{v} tr''^{m}_{bjv} z''^{m}_{bjv} + \sum_{j}\sum_{p}\sum_{k}\sum_{v} tr'''^{k}_{jpv} z'''^{m}_{jpv}. \tag{2}$$

The second objective function maximizes the network's total transparency score, calculated by summing the transparency coefficients of all recorded material and component flows.

$$\sum_{j}\sum_{v} z_{ijv}^{m} + \sum_{b}\sum_{v} z'^{m}_{ibv} \leq F_{im}, \qquad \forall i, m. \tag{3}$$

$$\sum_{i}\sum_{m}\sum_{v} z'^{m}_{ibv} \leq cap_{b}, \qquad \forall b. \tag{4}$$

Eqs. (3) and *(4)* consider the supplier's supply capacity and the processing capacity of the preprocessing centers, respectively.

$$\sum_{m} e_{mk} dem_{mp} = d_{pk}, \qquad \forall p, k. \tag{5}$$

Eq. 5 calculates the amount of raw materials required for each project based on the relationship between each required component and the raw materials.

$$z_{ijv}^{m} \leq MM\, y_{ijv}^{m}, \qquad \forall i, j, v, m. \tag{6}$$

$$z'^{m}_{ibv} \leq MM\, y'^{m}_{ibv}, \qquad \forall i, b, v, m. \tag{7}$$

$$z''^{m}_{bjv} \leq MM\, y''^{m}_{bjv}, \qquad \forall b, j, v, m. \tag{8}$$

$$z'''^{k}_{jpv} \leq MM\, y'''^{m}_{jpv}, \qquad \forall j, p, v, k. \tag{9}$$

Eqs. (6)-(9) state that current is transferred between different points in the network when the corresponding 3PL is selected between them.

$$\sum_{p} dem_{mp} = \sum_{i}\sum_{j}\sum_{v} z_{ijv}^{m} + \sum_{i}\sum_{b}\sum_{v} z'^{m}_{ibv}, \qquad \forall m. \tag{10}$$

Eq. (10) states that the total fulfilled demand of each raw material from each supplier is divided and shipped between the preprocessing centers and the structural manufacturing workshops.

$$y_{ijv}^{m} + y'^{m}_{ibv} = 1, \qquad \forall i, j, b, v, m. \tag{11}$$

Eq. (11) states that each raw material supplied from a supplier can only be sent to one of the preprocessing centers or prefabrication production workshops.

$$o_{lp}\, a_{lp} \leq r, \qquad \forall l, p. \tag{12}$$

Eq. (12) considers the coverage radius associated with the assignment of installation teams to project sites.

$$t^{m}_{ijv}y^{m}_{ijv} + t'^{m}_{ibv}\, y'^{m}_{ibv} + t''^{m}_{bjv}\, y'^{m}_{bjv} + t'''^{k}_{jpv}\, y'''^{k}_{jpv} + q_{pj} + o_{lp}\, t_{lp} = ct_{p}, \quad \forall i, j, b, p, m_{p}, k_{p}, v. \tag{13}$$

$$w_{p} \geq ct_{p} - dd_{p}, \qquad \forall p. \tag{14}$$

Eq. (13) calculates the actual completion time of each project, and finally *Eq. (14)* calculates the amount of time deviation or delay compared to the planned time for each project.

5 | Sensitivity Analysis

In this section, the performance and applicability of the proposed bi-objective model, which optimizes both cost and transparency in the prefabricated construction supply chain through integration facilitated by 4PL, are investigated. The analysis focuses on the trade-off between these objectives and on the impact of key BC-related parameters on the Pareto-optimal solutions. For this purpose, three types of sensitivity analysis are conducted. Also, it should be noted that the formulated model in sub-section 2.3 has been implemented in GAMS 24.1.2 using the CPLEX 12.6 solver, and the tests were run on an Intel (R) Core (TM) i7 CPU and 4.00 GB RAM.

5.1 | Impact of Blockchain Unit Cost on Network Design

The unit cost of BC recording is a critical factor. We analyzed its impact by varying BC from -50% to +50% of its base value and observing the change in total cost for a fixed transparency level of 80%.

Fig. 2 shows an approximately linear relationship between the BC unit cost and the total network cost. A 50% decrease in BC reduces the total cost by approximately 4%, while a 50% increase raises it by about 6.5%. This sensitivity is significant but not catastrophic, demonstrating the model's resilience to fluctuations in BC service pricing. This analysis assures managers that the proposed network design remains feasible even if BC technology costs experience moderate volatility. It also highlights the potential for significant cost savings if BC becomes cheaper in the future.

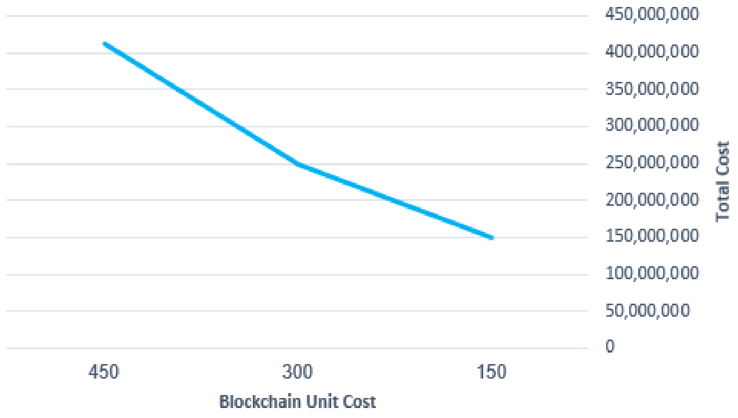

Fig. 2. Effect of Blockchain unit cost variation on total network cost.

5.2 | Effect of Transparency Score Coefficients on 3PL Selection

This analysis examines how the transparency score coefficients influence 3PL selection. We increased the TR coefficient for a specific, mid-cost 3PL provider by 20% and observed the change in its allocated flow volume.

As shown in *Fig. 3*, a 20% increase in a 3PL's transparency coefficient led to a 44% increase in the volume of goods allocated to it. It demonstrates that the model is highly responsive to the quality of tracking services. 3PL providers can gain a competitive advantage and significantly increase their market share within the 4PL network by investing in technologies that enhance traceability and data reliability (e.g., IoT sensors and improved API integration). For the 4PL manager, this underscores the importance of accurately assessing and incentivizing transparency capabilities when onboarding 3PL partners.

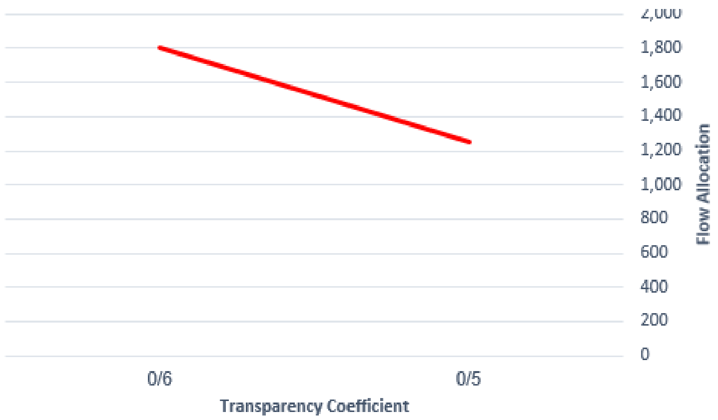

Fig. 3. Change in allocated flow to third-party logistics vs. transparency coefficient.

5.3 | Scenario-Based Analysis: Full vs. Partial Blockchain Integration

We compared three scenarios to evaluate the cost of different transparency strategies:

Scenario 1. No BC integration (baseline).

Scenario 2. Partial integration (tracking only finished components from workshops to sites).

Scenario 3. Full integration (tracking all material and component flows).

The results in *Fig. 4* provide a clear quantitative basis for strategic decision-making. *Scenario 2* (partial integration) achieves 65% transparency at only a 3.75% cost increase over the baseline. It suggests that tracking only final components captures a large portion of the transparency benefits related to on-time delivery and installation, making it an excellent cost-effective strategy for many firms. *Scenario 3* (full integration) offers the highest transparency (85%) but at an 8.3% cost premium. This strategy is justified for high-risk projects, valuable cargo, or industries with strict regulatory requirements where end-to-end traceability is paramount.

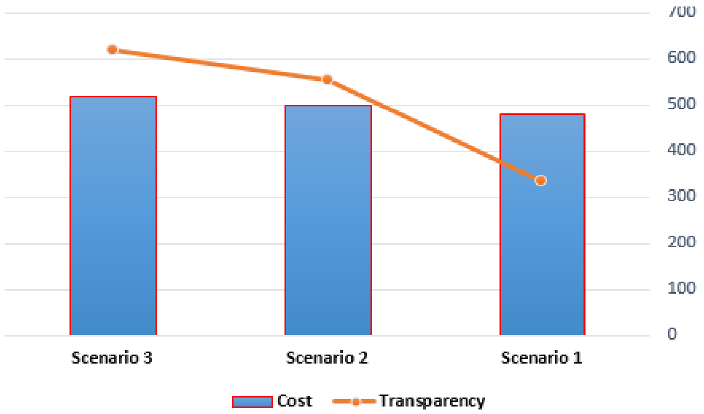

Fig. 4. Total cost and achieved transparency level for different Blockchain integration scenarios

6 | Conclusions

This study has investigated a BC-integrated 4PL network design to enhance synergy and address critical inefficiencies within the supply chains of OSC projects. The proposed bi-objective mathematical model successfully optimizes the trade-off between minimizing total network costs and maximizing operational transparency, providing a comprehensive decision-making framework for stakeholders. The model's outputs include optimal locations for preprocessing centers, selection of 3PL providers based on cost and BC capability, assignment of installation teams, and planning of material flows across the network.

The sensitivity analysis underscored the model's practical viability and strategic value. It was shown that the total network cost is resilient to moderate fluctuations in BC service pricing, easing concerns about cost volatility associated with this emerging technology. Furthermore, the analysis revealed that transparency is a significant competitive factor for logistics providers, as even a modest improvement in a 3PL's transparency score can lead to a substantial increase in its allocated shipment volume. Perhaps most importantly, the scenario comparison offers clear strategic guidance: partial BC integration is highly cost-effective for firms seeking a balance between transparency and expenditure. In contrast, full integration remains a viable option for high-stakes projects where end-to-end traceability is paramount.

The findings affirm that an integrative 4PL model, enabled by BC technology, can significantly reduce logistics costs and project delays while fostering trust and coordination among the diverse, often fragmented actors in the construction industry. This research provides a foundational step towards the adoption of Industry 4.0 paradigms in construction logistics. For future research, directions include extending the model to incorporate uncertainty in key parameters such as demand, capacity, and cost; developing efficient metaheuristic algorithms to solve larger-scale problem instances; and incorporating production sequencing and prerequisite relationships to better reflect real-world manufacturing constraints.

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Data Availability

The data used and analyzed during the current study are available from the corresponding author upon reasonable request.

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Appendix

Sets:

I	A set of suppliers of raw materials.
J	Set of structural manufacturing workshops.
P	Set of project sites.
B	Set of potential 4PL preprocessing center locations.
V	Set of potential 3PL providers under the supervision of 4PL.
M	Set of raw materials.
K	Set of components.
L	A set of structural installation team.
M_p	Set of raw materials of the project p.
K_p	set of components of project p.

Parameters:

des_{ij}	Distance between supplier i and structural manufacturing workshop j.
des'_{ib}	Distance between supplier i and potential preprocessing center b.
des''_{bj}	Distance between potential preprocessing center b and structural manufacturing workshop j.
des'''_{jp}	Distance between the structural manufacturing workshop j and the project site p.
c^{m}_{ijv}	Unit cost of transporting raw material m from supplier i to structural manufacturing workshop j using 3PL v.
c'^{m}_{ibv}	Unit cost of transporting raw material m from supplier i to potential preprocessing center b using 3PL v.
c''^{m}_{bjv}	Unit cost of transporting raw material m from potential preprocessing center b to structural manufacturing workshop j using 3PL v.
c'''^{k}_{jpv}	Unit cost of transporting component type k from structural manufacturing workshop j to project site p using 3PL v.
t^{m}_{ijv}	The transportation time of raw material m from supplier i to structural manufacturing workshop j using 3PL v.
t'^{m}_{ibv}	The transportation time of raw material m from supplier i to potential preprocessing center b using 3PL v.
t''^{m}_{bjv}	The transportation time of raw material m from potential preprocessing center b to structural manufacturing workshop j using 3PL v.
t'''^{k}_{jpv}	The transportation time of component type k from structural manufacturing workshop j to project site p using 3PL s v.
H_b	Fixed cost of installing the preprocessing center at the potential location b.
g_b	Variable cost per unit processed at the potential preprocessing center b.
a_{lp}	Distance between the location of the structural installation team l and the project site p.
r	Coverage radius for assigning the structural installation team to the project site.
ti_{lp}	Duration of the structure's installation at the project site p by the installation team l.

ci_{lp}	Structure installation cost at the project site, p, by the installation team, l.
F_{im}	Maximum supply capacity for supplier i for raw material m.
cap_{b}	Maximum processing capacity in the potential preprocessing center b.
d_{pk}	Demand for project site p from component type k.
e_{mk}	The amount of raw material m required to produce each unit of component type k.
dd_{p}	Final planned completion time of the project site p.
cl_{p}	Unit cost of penalty for late delivery of the project p.
bc^{m}_{ijv}	Unit cost of recording and verifying the flow of raw material m from supplier i to workshop j via 3PL v on the Blockchain.
bc'^{m}_{ibv}	Unit cost of recording and verifying the flow of raw material m from supplier i to potential preprocessing center b via 3PL v on the Blockchain.
bc''^{m}_{bjv}	Unit cost of recording and verifying the flow of raw material m from potential preprocessing center b to workshop j via 3PL v on the Blockchain.
bc'''^{k}_{jpv}	Unit cost of recording and verifying the flow of component k from workshop j to site p via 3PL v on the Blockchain.
tr^{m}_{ijv}	Transparency score coefficient for the flow of raw material m from supplier i to workshop j via 3PL v.
tr'^{m}_{ibv}	Transparency score coefficient for the flow of raw material m from supplier i to potential preprocessing center b via 3PL v.
tr''^{m}_{bjv}	Transparency score coefficient for the flow of raw material m from potential preprocessing center b to workshop j via 3PL v.
tr'''^{k}_{jpv}	Transparency score coefficient for the flow of component k from workshop j to site p via 3PL v.
MM	A relatively big amount.
pc_{im}	Unit price of raw material m of supplier i.
q_{pj}	Total production time of components of structure p in structure workshop j.

Decision variables:

x_{b}	It equals 1 if a potential preprocessing center is located at node b, and 0 otherwise.
y^{m}_{ijv}	It is equal to 1 if 3PL s v is selected to transport raw material m from supplier i to structural manufacturing workshop j, 0 otherwise.
y'^{m}_{ibv}	It equals 1 if 3PL v is selected to transport raw material m from supplier i to the preprocessing center b, and 0 otherwise.
y''^{m}_{bjv}	It equals 1 if 3PL v is selected to transport raw material m from the preprocessing center b to the structural manufacturing workshop j, and 0 otherwise.
y'''^{k}_{jpv}	It is equal to 1, if 3PL v is selected to transport component k from structural manufacturing workshop j to project site p, 0 otherwise.
o_{lp}	It is equal to 1 if the installation team l is assigned to the project site p, and 0 otherwise.
z^{m}_{ijv}	The transport volumes of raw material m from supplier i to structural manufacturing workshop j using 3PL v.
z'^{m}_{ibv}	The transport volumes of raw material m from supplier i to preprocessing center b using 3PL v.
z''^{m}_{bjv}	The transport volumes of raw material m from the preprocessing center b to the structural manufacturing workshop j using 3PL v.
z'''^{k}_{jpv}	The transport volumes of component k from structural manufacturing workshop j to project site p using 3PL v.
ct_{p}	Actual time completion of the project site p.
w_{p}	Tardiness of the project p.
dem_{mp}	Amount of raw material m required in project p.