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# Fourth-Party Logistics in Off-Site Construction: A Synergy-Based Service Strategy

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**Abstract**

The construction Supply Chain (SC) suffers from very low productivity due to the temporary nature of projects, the complexity and extent of communication between actors, and high logistics costs. Therefore, leveraging synergy and interaction, along with the presence of an integrator, can help mitigate these challenges. Fourth-party logistics is one of the drivers that can be considered an integrator in the construction industry, given its successful implementation in other industries. This study presents a mathematical model to investigate the effect of synergy in the construction industry by taking advantage of the integrative potential of a 4PL. It also considers the interaction between contractors and 4PL, pricing for the supply of raw materials, and the choice of transportation method, thereby bringing the problem closer to reality. To validate and demonstrate the efficiency of the proposed model, GAMS, a commercial software package, is used to conduct sensitivity analyses of key variables. The results show that creating a synergistic framework between contractors and leveraging the integrative capabilities of a fourth-party logistics enterprise can significantly reduce project delivery costs and delays, suggesting the proposed model's higher efficiency than those available in the literature on the subject.

**Keywords:** Off-site construction, Multi-project environment, Synergistic logistics, Fourth-party logistics, Integrated management.

## 1 | Introduction

Off-Site Construction (OSC) is a method of construction in which a complete structure is divided into prefabricated parts manufactured in a factory and transported to the construction site for installation [1]. More immediate construction, less construction debris, higher quality, greater safety, and higher sustainability can be considered advantages of OSC over the conventional construction method [2–6].

However, OSC poses some challenges to the construction industry. Given the greater complexity and fragmentation of the Off-Site Construction Supply Chain (OSC-SC) compared to the Supply Chain (SC) of conventional cast-in-situ construction [7], Off-Site Construction Supply Chain Management (OSC-SCM)

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poses a fundamental challenge for the successful delivery of OSC projects [8]. One of the principal reasons for low productivity and increased costs is ineffective management of this complexity [9]. The principles of Supply Chain Management (SCM) have not been successfully applied in the construction industry, particularly OSC [10], and do not enable construction corporations to fully realize their potential in their current state [11]. A deficiency of cooperation among performers in the SC network, as a substantial origin of pauses, mistakes, and business cycle repetitions in projects, is one of its causes [12]. According to the OSC-SC planning and functions, no sufficient SC drivers exist to act as focal coordinators to bring associated performers closer together across the construction network [11], [12]. Another cause is the provisional and project-based nature of construction approaches, which makes the formation of transient SCs common in construction projects [13].

As a multi-echelon SC, the OSC-SC begins by designing the elaborate scheme and purchasing the illustrations of the structure's constituents to be produced in a prefabricated installation. The components are then preserved and transported to the construction sites for installation. Customizing the constituents is conducted to fit the specifications of individual projects. Therefore, producing the constituents by prefabricators is impossible before demands are received. Furthermore, because the constituents are large and difficult to move or carry, contractors cannot maintain their massive buffer supplies to address delayed deliveries [14]. Likewise, the OSC-SC involves considerable risks spread along its phases (i.e., design, production, logistics, and on-site construction) [15]. Any disturbance at earlier steps of the OSC-SC impacts subsequent steps, leading to an unproductive SC. Consequently, investigators have made considerable efforts to examine OSC-SC and enhance its performance through diverse procedures [16].

Business strategies are well incorporated, in line with SCM's primary principles, to enhance OSC-SC's performance [17]. Integrating performers to achieve more satisfactory information sharing is the objective of an efficient OSC-SC, resulting in improved trust and cooperation [18]. To apply SCM principles in OSC project management, logistics re-organization driven by construction owners and/or main contractors must motivate the participation of related CSC actors [11], [17]. In practice, construction managers turn to Logistics Service Providers (LSPs) for logistics re-organization, especially in the context of large construction projects [17]. Companies in other industrial sectors have leveraged the benefits of LSPs, enabling them to focus on their primary business and achieve budget reductions, long-term strategic alliances, and effective logistics reengineering [19]. However, in the construction industry, using logistics service providers is a new phenomenon, and this applies to all related actors, including owners, main contractors, suppliers, building merchants, and transportation providers [17]. Therefore, shareholders must address new interfaces and project parameters when an LSP is considered the coordinator of the CSC network.

Recently, the logistics industry has quickly grown. Given the globalization of business, many corporations have outsourced their logistics services to third-party logistics (3PL) providers to gain a competitive advantage. Many corporations select one or more 3PL providers to enhance customer service and enable resource flexibility. Nevertheless, 3PL also faces limitations, such as limited integration capabilities and inefficient functions [20].

In 1998, Accenture introduced a new concept, fourth-party logistics (4PL), to address the challenges mentioned above. 4PL providers design, create, implement, and supervise comprehensive SC solutions by assessing their own technology capabilities and resources, as well as those of other performers [21]. As the entity in the "organizer" role in the SC, the 4PL provider enables cost reductions, enhanced efficiency, higher-quality logistics services, and greater industry flexibility [22]. For example, "Cainiao Smart Logistics Network Ltd." is a comprehensive 4PL provider in China. It is a subsidiary of the Alibaba Group. It adopts a collaborative approach to logistics, leveraging an innovative, open data platform to improve efficiency and the customer experience for all players along the SC. The 4PL platform integrates over 30 3PL entities to provide an efficient, fast logistics network to meet the demands of the two largest online marketplaces in China, "Taobao.com" and "Tmall.com." Importantly, it plays an essential role in connecting suppliers and customers [23].

*Table 1* briefly reviews and compares the research closest to this current research. Despite the recorded outcomes of the OSC-SC including decreased productivity, increased complexity, and raised expenditures and verified advantages of integrated management approaches in other industries, there's an unexpected shortage of emphasis on this typical research area about the construction SC. The potential of their integration with OSC remains largely unknown, while 4PL enterprises can effectively address these challenges. It offers investigators a great opportunity to bridge the gap and examine how to lead 4PL to optimize OSC projects, ultimately resulting in a widely adopted, more economical construction process.

**Table 1. A brief overview of the related literature.**

| Reference | Supply Chain Decision Levels | | | | | Review Type | | Objective Criteria | | | Suppliers | Supply Chain Coordinator | | | Project-Oriented Decisions | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Supply | Production | Distribution | Transportation | Integrated | Quantitative | Qualitative | Cost | Delay | Other | | Main contractor | Logistics Service Provider: 3PL | Logistics Service Provider: 4PL | Multi-project | Scheduling |
| Aissaoui et al. [24] | ✓ | | | | | | ✓ | ✓ | | | ✓ | ✓ | | | | |
| Said and El-Rayes. [25] | | | | ✓ | | ✓ | | ✓ | | | | ✓ | | | | |
| Plebankiewicz and Kubek [26] | ✓ | | | | | ✓ | | ✓ | | | ✓ | ✓ | | | | |
| Ekeskär and Rudberg [17] | | | | ✓ | | | ✓ | ✓ | | | | | ✓ | | | |
| Liu et al. [27] | | | | ✓ | | ✓ | | ✓ | | ✓ | | ✓ | | | | |
| Choudhari and Tindwani [28] | | | | ✓ | | ✓ | | ✓ | | | | ✓ | | | | |
| Jaśkowski et al. [29] | ✓ | | | ✓ | | ✓ | | ✓ | | | ✓ | ✓ | | | | |
| Hsu et al. [14] | | ✓ | | ✓ | | ✓ | | ✓ | | | | | | | | |
| Deng et al. [30] | ✓ | | | | | ✓ | | ✓ | | | ✓ | ✓ | | | | |
| Nolz [31] | | | | ✓ | | ✓ | | ✓ | | | | ✓ | | | ✓ | ✓ |
| Fredriksson et al. [32] | | | | ✓ | | | ✓ | | | ✓ | | | ✓ | | | |
| Le et al. [33] | ✓ | | | | | ✓ | | ✓ | | | ✓ | | ✓ | | | |
| RezaHoseini et al. [34] | ✓ | | | | | ✓ | | ✓ | ✓ | | ✓ | ✓ | | | ✓ | ✓ |
| Son et al. [35] | ✓ | | | | | ✓ | | ✓ | | | | ✓ | | | | |
| Ekeskär and Rudberg [36] | | | | ✓ | | | ✓ | ✓ | | | | | ✓ | | | |
| Ekeskär et al. [37] | | | | | ✓ | | ✓ | ✓ | | | | | ✓ | | ✓ | |
| Chen and Hammad [38] | | | ✓ | | | ✓ | | | | ✓ | | | ✓ | | | |
| Darabad et al. [39] | | | | | ✓ | ✓ | | | ✓ | ✓ | | ✓ | | | ✓ | |
| Aliahmadi et al. [40] | | | | | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | | | ✓ | ✓ |
| Ghamari et al.[41] | ✓ | | | | | ✓ | | | | ✓ | ✓ | ✓ | | | | |
| Current Study | | | | | ✓ | ✓ | | ✓ | | | ✓ | | | ✓ | ✓ | ✓ |

With the primary aim of addressing existing gaps, the present study proposes a Mixed-Integer Linear Programming (MILP) model for an integrated approach to the supply, production, distribution, and installation of prefabrications in a multiple-project SC, in cooperation with a 4PL enterprise. The suggested model can make the proper decision on whether prefabricated factories should collaborate with a 4PL enterprise to finalize allocated projects at the lowest cost and with the least delivery delay. Thus, it seeks to answer the following research questions to implement an integrated approach to planning in the SC of prefabricated construction projects with high-level productivity as its leading motivation.

I. How can optimal decisions be made regarding a prefabricated factory's logistics actions, whether to self-support or outsource?

II. How can a fourth-party logistics enterprise's capabilities boost the productivity of the prefabricated construction industry?

III. What circumstances make it justifiable for prefabricated factories to receive the services of a fourth-party logistics enterprise?

IV. Under what circumstances does it make sense for a prefabricated factory to partner with a fourth-party logistics enterprise?

V. How can raw materials be purchased in bulk from suppliers, with discounts included in the model?

Considering the justifications above and as a response to the cited research questions, the study aims to adopt an integrated approach to the supply, production, distribution, and installation process of prefabricated construction projects by closely cooperating with a fourth-party logistics enterprise to enhance the harmonious balance between cost and delivery time in a joint multiple-project scheduling benchmark. Thus, substantial contributions can be recognized for the present research as follows:

I. Utilizing the 4PL's logistics capabilities in the prefabricated projects industry through a mathematical programming model.

II. Regarding the capability of selecting prefabricated factories to execute the logistics cycle through self-supporting or outsourcing in a mathematical model.

III. Considering the impact of mass partnership and the cumulative relations of prefabricated factories in diminishing logistics expenses.

The rest of the paper is structured as follows. Section 2 gives the problem statement and develops a mathematical model. Section 3 presents computational outcomes, sensitivity analyses, and management policies. Finally, Section 4 makes valid conclusions and practical recommendations for future studies.

# 2 | Problem Statement and Mathematical Model

In this section, the research problem and related assumptions are first described. We then define the notation used in the mathematical model. Finally, a MILP model will be presented to integrate the supply, manufacturing, distribution, and installation processes of off-site structures in a multi-project environment with 4PL participation.

## 2.1 | Problem Definition

In this problem, there is a network of prefabricated construction projects assigned to contractors operating under a construction holding company. Each structural project requires a range of raw materials, sourced from various suppliers. Also, a 4PL company active in construction projects is considered, which, in exchange for a membership fee from producers as a group, provides various specialized services, including the purchase and procurement of raw materials, pre-processing, transportation, and structure installation. Among the benefits of outsourcing these services to the industry's 4PL company for manufacturers of structures are reduced costs from bulk buying and greater bargaining power, more specialized, cost-effective transportation by 3PLs, and the ability to focus solely on production as their core activity. Of course, the decision to outsource the operation and join an innovative 4PL company in the industry, or to carry out the operation in a self-supporting manner, is the producers' responsibility, and they have the right to choose.

The total demand of each project's activities for a specific raw material represents the project's demand for that raw material. Each raw material can be sourced from a range of suppliers, and it is up to the manufacturer to decide which suppliers to order from for each project (suppliers under contract with 4pl or other suppliers). Each supplier has a specific capacity and supplies raw materials at a specific price. Therefore, to reduce purchase costs, given that each supplier has its own discount function, it has been tried to apply the appropriate discounts through the industry's innovative 4PL company and to aggregate demand for the raw materials producers need.

Suppliers are geographically dispersed. In this matter, to transfer resources from suppliers to producers and reduce the costs of transportation and production for suppliers, three transportation methods have been proposed to increase transportation options and thus enable the selection of the best method. Among the three methods presented, two methods require the presence of 3pl. Of course, these three transportation methods will exist if the structure manufacturer is under contract with 4pl. Otherwise, the only way there will be for transportation is for the manufacturer to completely self-support without using a 3PL.

It should be noted that, in this model, 3PL's dependence on 4PL is justified because 3PL is a party to the contract with 4PL and provides its services to manufacturers under contract with 4PL, including discounts. Of course, if a manufacturer is a member of 4PL and the self-backed transportation method is cheaper for him than the other two methods, he will not have to use 3PL. Below is a full description of each transportation method:

I. Shipping using 3PL is done directly from the supplier to the manufacturer. Manufacturers can benefit from this method if they are under contract with an industry-leading 4PL company.

II. Self-supporting transportation from the supplier to the manufacturer is handled directly by the manufacturer. This transportation method involves the manufacturer transporting purchased raw materials without using a 3PL and in a self-supporting manner. This shipping method can be done with or without the involvement of an industry-leading 4PL company.

III. The transportation of raw materials purchased from the supplier to one of the 4PL company's intermediate warehouses is handled by 3PL, and from the warehouse to the manufacturer is either self-supported or handled by 3PL. This shipping method is suitable when manufacturers want some pre-processing operations, including) performed at a lower cost and in a more specialized manner by a 4PL company so that they can focus only on their main production operations. Manufacturers can take advantage of this method if they are under contract with an industry-leading 4PL company.

After the raw materials arrive at the manufacturing plant, the manufacturers proceed through the stages of the structural production process. Then, using one of the two transportation methods through 3PLs or self-supporting, they transfer the components of the structure to the project site. Finally, after completing all the activities of a project and sending the components of the structures to the project sites, the manufacturers can use its cranes and installation equipment if they are members of the innovative 4pl company, or to rent It should be noted that the time of completion of the installation of the structure is the time of the end of the project and all the steps should be determined in such a way that the total cost of project delays is minimized.

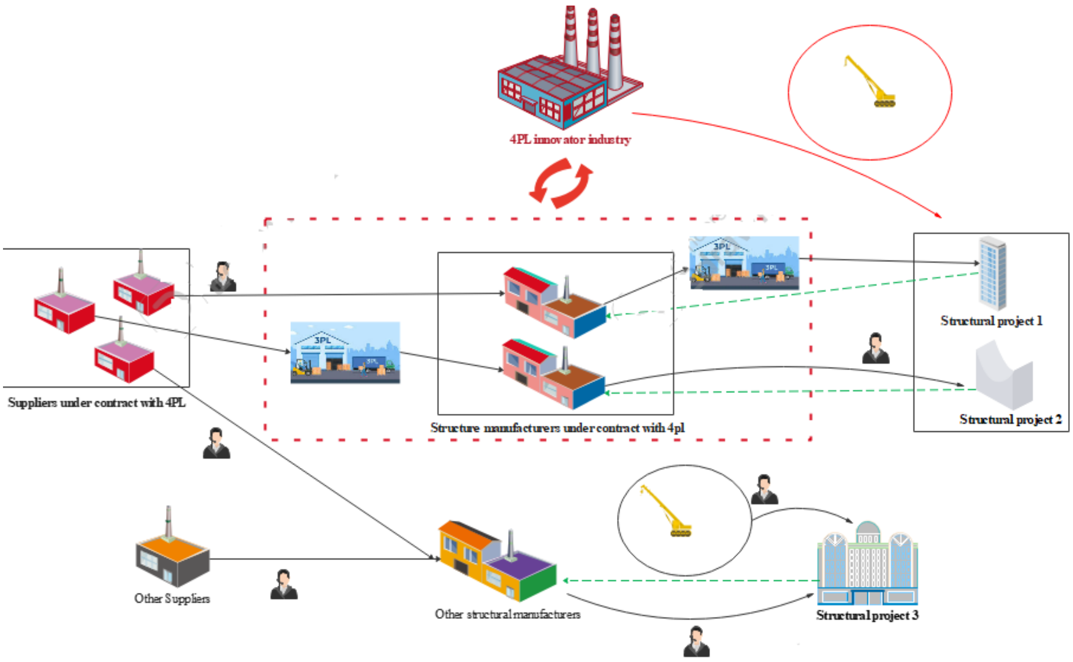


**Fig. 1. Overall structure of the problem environment.**

To summarize, the manufacturers of prefabricated structures must decide between two alternatives: outsourcing to a 4PL or self-supporting production, distribution, and installation, balancing the costs of procurement, production, distribution, and installation. This decision enables them to complete the assigned projects with the least time delay and cost.

## 2.2 | Notations

Notations and symbols used to model the problem are divided into four groups, namely, indices, sets, parameters, and decision variables, as represented as follows:

**Sets and indices**

| | |
|---|---|
| $I$ | Index of suppliers ($i = 1, 2, \dots, I$). |
| $J$ | Index of structure manufacturers ($j = 1, 2, \dots, J$). |
| $P$ | Index of projects ($p = 1,2, \dots, P$). |
| $M$ | Index of raw materials ($m = 1,2, \dots, M$). |
| $V$ | Index of third-party logistics companies ($v = 1,2, \dots, V$). |
| $P$ | Set of projects. |
| $M$ | Set of raw materials. |
| $K$ | Set of components. |
| $I$ | Set of suppliers. |
| $K_p$ | Set of components of project p. |
| $I_m$ | Set of suppliers for raw material m. |
| $J$ | set of structure manufacturers. |
| $V$ | set of third-party logistics companies. |

**Parameters**

| | |
|---|---|
| $pc_{im}$ | Unit price of raw material m of supplier i without discount. |
| $d_{pm}$ | Amount of material m that is required by project j. |
| $c^1_{ijmv}$ | The cost of transporting a unit of raw material m from supplier i to manufacturer j by third-party logistics v under the supervision of the 4PL. |
| $c^2_{ijm}$ | The cost of transporting a unit of raw material m from supplier i to manufacturer j in a self-supporting manner under the supervision of the 4PL. |
| $c^3_{ijm}$ | The cost of transporting a unit of raw material m from supplier i to manufacturer j in a self-supporting manner, independent of the 4PL. |
| $cap_{im}$ | Capacity of supplier k for material m. |
| $DD_p$ | Due date for project j to be closed. |
| $cin^1_p$ | The cost of installing the structure in the project p under the 4PL's supervision. |
| $cin^2_p$ | The cost of installing the structure in the p project is independent of the 4PL. |
| $tin^1_p$ | The duration of the installation of the structure in the p project under the supervision of the 4PL. |
| $tin^2_p$ | The duration of installing the structure in the p project is independent of the 4PL. |
| $MM$ | A relatively big amount. |
| $r_{im}$ | Release time of supplier k for material m. |
| $w_p$ | Tardiness costs per unit time for the project. |
| $f_j$ | The amount of the manufacturer j's membership fee for joining the 4PL. |

**Decision variables**

| | |
|---|---|
| $d^1_{ijm}$ | Demand for raw material m by manufacturer j from supplier i in the case of membership in the 4PL. |
| $d^2_{ijm}$ | Demand for raw material m by manufacturer j from supplier i in the case of independent purchase. |
| $price_{im}$ | The purchase price of each unit of raw material m after the supplier's discount i. |
| $n_{im}$ | The total order amount of raw material m from supplier i. |
| $FL^1_{ijmv}$ | Amount of raw material m transported from supplier i to manufacturer j by third-party logistics v under the supervision of 4PL. |
| $FL^2_{ijm}$ | The amount of raw material m that is transported from supplier i to manufacturer j in a self-supporting manner under the supervision of the 4PL. |
| $FL^3_{ijm}$ | The amount of raw material m that is transported from supplier i to manufacturer j in a self-supporting method independent of the 4PL. |
| $pg_j$ | It equals one if manufacturer j is a member of the 4PL and zero otherwise. |
| $x^1_{ijmv}$ | It equals one if a third-party logistics provider (v) is used to transport raw material (m) from supplier i to manufacturer j under the supervision of a 4PL. |
| $x^2_{ijm}$ | It equals one if a self-supporting method is used to transport the raw material m from supplier i to manufacturer j under the 4PL's supervision. |
| $x^3_{ijm}$ | It equals one if the independent, self-supporting 4PL method is used to transport raw material m from supplier i to manufacturer j. |
| $TD_p$ | Tardiness of project j. |
| $CT_p$ | Completion time of project j. |
| $CS_p$ | The time when the installation of project j is completed (closing time of project j). |
| $\lambda_{jp}$ | It is equal to 1 if project p is assigned to producer j, and zero otherwise. |
| $u_{kp}$ | The amount of the produced component type k for project p. |
| $h_{jim}$ | It equals one if producer j meets its need for raw material m from supplier i, and zero otherwise. |
| $z^1_{kjpv}$ | Structure volume type k shipped from manufacturer j to project site p by third-party logistics v under the supervision of 4PL. |
| $z^2_{kjp}$ | Structure volume type k shipped from the manufacturer j to the project site p in a self-supporting manner under the supervision of the 4PL. |
| $z^3_{kjp}$ | Structure volume type k shipped from the manufacturer j to the project site p in a self-supporting manner, independent of the 4PL. |
| $o^1_{jpv}$ | It equals one if the third-party logistics provider v is used to ship the structure from manufacturer j to the project site p under the 4PL's supervision, and zero otherwise. |
| $o^2_{jp}$ | It is equal to 1 if a self-supporting method under the supervision of 4PL is used to ship the structure from manufacturer j to project site p, and zero otherwise. |
| $o^3_{jp}$ | It equals one if a self-supporting method independent of the 4PL is used to ship the |

| | |
|---|---|
| | structure from manufacturer j to project site p, and zero otherwise. |
| $ins_p$ | It equals one if the method under the supervision of 4pl is used to install project p, and zero otherwise. |
| $ins'_p$ | It equals one if the self-supporting and independent 4PL method is used to install project p, and zero otherwise. |

## 2.3 | Mathematical Model

The mathematical model of the problem is expressed to minimize the total network cost as follows:

$$\begin{aligned}\text{Min obj} = &\sum_j f_j \times pg_j + \sum_j\sum_i\sum_m price_{im} d^1_{ijm} \\ &+ \sum_j\sum_i\sum_m pc_{im} d^2_{ijm} + \sum_i\sum_j\sum_m\sum_v FL^1_{ijmv}\, c^1_{ijmv} + \sum_i\sum_j\sum_m FL^2_{ijm}\, c^2_{ijm} \\ &+ \sum_i\sum_j\sum_m FL^3_{ijm}\, c^3_{ijm} + \\ &+ \sum_k\sum_j\sum_p\sum_v z^1_{kjpv}\, c'^1_{kjpv} + \sum_k\sum_j\sum_p z^2_{kjp}\, c'^2_{kjp} + \sum_k\sum_j\sum_p z'^3_{kjp}\, c^3_{kjp} \\ &+ \sum_p cin^1_p ins_p + \sum_p cin^2_p ins'_p + \sum_p cl_p w_p,\end{aligned} \tag{1}$$

$$\sum_p \lambda_{jp} = p, \text{for all } j, \tag{2}$$

$$\sum_p \beta_p\, \lambda_{jp} \le cap'_j, \text{for all } j, \tag{3}$$

$$D_{jm} = \sum_p d_{pm} y_{jp}\,, \text{for all } j, m, \tag{4}$$

$$D_{jm} = \sum_i d^1_{ijm} + \sum_i d^2_{ijm}\,, \text{for all } j, m, \tag{5}$$

$$\sum_i\sum_m d^i_{ijm} \le pg_j \times MM, \text{for all } j, \tag{6}$$

$$\sum_i\sum_m d^2_{ijm} \le (1 - pg_j) \times MM, \text{for all } j, \tag{7}$$

$$n_{im} \ge \sum_j d^1_{ijm}\, h_{jim} + \sum_j d^2_{ijm}\, h_{jim}, \text{for all } i\,, m, \tag{8}$$

$$n_{im} \le cap_{im}, \text{for all } i\,, m, \tag{9}$$

$$FL^1_{ijmv} \le x^1_{ijmv} \times MM, \text{for all } i\,, j, m, v, \tag{10}$$

$$FL^2_{ijm} \le x^2_{ijm} \times MM, \text{for all } i\,, j, m, v, \tag{11}$$

$$FL^3_{ijm} \le x^3_{ijm} \times MM, \text{for all } i\,, j, m, v, \tag{12}$$

$$\sum_v FL^1_{ijmv} + FL^2_{ijm} = d^1_{ijm}, \text{for all } i\,, j, m, \tag{13}$$

$$FL^3_{ijm} = d^2_{ijm}, \text{for all } i\,, j, m, \tag{14}$$

$$\sum_v x^1_{ijmv} + x^2_{ijm} = pg_j, \text{for all } i\,, j, m, \tag{15}$$

$$x^3_{ijm} = (1 - pg_j), \text{for all } i\,, j, m, \tag{16}$$

$$\sum_{v} x_{ijmv}^{1} + x_{ijm}^{2} + x_{ijm}^{3} = 1, \text{for all } i, j, m, \tag{17}$$

$$tt'_{ijm} = \sum_{v} t_{ijmv}^{1} x_{ijmv}^{1} + t_{ijm}^{2} x_{ijm}^{2} + t_{ijm}^{3} x_{ijm}^{3}, \text{for all } i, j, m, \tag{18}$$

$$l_{j}^{m} = \left(r_{mi} + tt'_{ijm}\right) h_{ijm}, \text{for all } i, j, m, \tag{19}$$

$$price_{im} = \text{Max}\left(price_{im}^{min}, price_{im}^{0} - k\sum_{j} d_{ijm}^{1}\right), \text{for all } i, m, \tag{20}$$

$$u_{kp} y_{jp} = w_{kjp}, \text{for all } k, j, p, \tag{21}$$

$$w_{kjp} = \sum_{v} z_{kjpv}^{1} + z_{kjp}^{2} + z_{kjp}^{3}, \text{for all } k, j, p, \tag{22}$$

$$z_{kjpv}^{1} \le o_{kjpv}^{1} \times MM, \text{for all } k, j, p, v, \tag{23}$$

$$z_{kjp}^{2} \le o_{kjp}^{2} \times MM, \text{for all } k, j, p, \tag{24}$$

$$z_{kjp}^{3} \le o_{kjp}^{3} \times MM, \text{for all } k, j, p, \tag{25}$$

$$\sum_{v} o_{kjpv}^{1} + o_{kjp}^{2} + o_{kjp}^{3} = 1, \text{for all } k, j, p, \tag{26}$$

$$\sum_{v} o_{kjpv}^{1} + o_{kjp}^{2} = pg_{j}, \text{for all } k, j, p, \tag{27}$$

$$o_{kjp}^{3} = (1 - pg_{j}), \text{for all } k, j, p, \tag{28}$$

$$tt''_{kjp} = \sum_{v} t'^{1}_{kjpv} o_{kjpv}^{1} + t'^{2}_{kjp} o_{kjp}^{2} + t'^{3}_{kjp} o_{kjp}^{3}, \text{for all } k, j, p, \tag{29}$$

$$CT_{p} \ge ST_{p} + t_{p} + tt''_{kjp}, \text{for all } k, j, p, \tag{30}$$

$$CS_{p} \ge CT_{p} + INS_{p}, \text{for all } p \in P, \tag{31}$$

$$TD_{p} \ge CS_{p} - DD_{P}, \text{for all } p \in P, \tag{32}$$

$$\lambda_{jp}, ins_{p}, ins'_{p}, o_{jpv}^{1}, o_{jp}^{2}, o_{jp}^{3}, pg_{j}, x_{ijmv}^{1}, x_{ijm}^{2}, x_{ijm}^{3}, h_{jim} \in \{0,1\}, \text{for all } i, j, p, v, m, \tag{33}$$

$$price_{im}, FL_{ijmv}^{1}, FL_{ijm}^{2}, FL_{ijm}^{3}, TD_{p}, z_{kjpv}^{1}, z_{kjp}^{2}, z_{kjp}^{3} \ge 0, \text{for all } i, m, j, v, p, k. \tag{34}$$

According to *Eq. (1)*, the objective function of this model seeks to minimize the total costs of prefabricated projects. The total cost of the network from the sum of the costs of membership in the fourth party logistics company, the cost of supply and cumulative purchase of raw materials and in terms of collective discounts or directly from suppliers, the costs of transporting raw materials from suppliers to structure manufacturers from one of the three methods is the cost of in-house production, as well as the costs of transporting structural components from manufacturers to project sites using one of the three methods, similarly, and the cost of project delays. *Constraint (2)* states that the maximum number of projects that can be assigned to a structure producer is equal to p projects. *Constraint (3)* states that the total number of projects assigned to a structure manufacturer should not exceed the maximum production capacity of that structure. *Constraint (4)* deals with the calculation of the total demand of producer j of each raw material based on the type of projects assigned to it. *Constraint (5)* states that each producer can fulfill her need for raw materials through one of two methods under the 4pl company's supervision, either collectively or independently from suppliers. *Eqs. (6)* and *(7)* show that the delivery of raw material orders under the supervision of a 4pl is possible when the manufacturer has signed a cooperation agreement with that 4pl and has become a member of it. The willingness to use it has a cumulative purchase service. *Eq. (8)* ensures that the order quantity of each raw material from each supplier is at least equal to the total demand of projects in the hands of all manufacturers assigned to that supplier. *Constraint (9)* guarantees that the total order quantity of each raw material from each supplier by all manufacturers must not exceed each supplier's maximum capacity for that raw material. *Constraints (10)-(12)* state that any of the three transportation methods may be used to transport raw materials from the supplier to the manufacturer, who has previously been given the option of transportation. *Constraint*

*(13)* states that if the producer is under contract with and a member of the 4pl company, she can satisfy her demand in one of two ways: by using a third-party logistics company or by self-supporting. *Constraint (14)* states that if the producer is independent of the 4PL company, she must meet her raw-material needs in a self-supporting manner. *Constraints (15)* and *(16)* state that any producer under contract with a 4PL company can use either the first or second transportation method, i.e., third-party logistics or self-supporting. On the other hand, if it is independent of the 4pl company, it should only transport the raw materials from the supplier to the manufacturer on its own. *Constraint (17)* states that each manufacturer may choose only one of three transportation methods: third-party logistics, self-supporting, or affiliated with the 4pl company under supervision, or independent of the 4pl company. *Constraint (18)* calculates the duration of transportation of each raw material from the supplier to the manufacturer, depending on which of the production methods to use. *Constraint (19)* determines the earliest time each raw material becomes available to each producer. In other words, the earliest time of raw material m being available at the disposal of producer j is equal to the sum of the first time raw material m is provided by supplier i and the duration of transportation from the supplier to the producer. *Constraint (20)* deals with the calculation of the price of raw material m of supplier i after applying a discount depending on the ratio of demand to its maximum production capacity. *Constraints (21)* calculate the number of production components of each type needed for each project, as assigned to the manufacturer. *Constraint (22)* states that any dependent manufacturer, whether under contract or a member of the 4pl, can ship the bundled components through one of three methods: using a third-party logistics company, or self-supporting under supervision. 4pl or send independently to the project site. *Restrictions (23)-(25)* state that if it is possible to use any of the three transportation methods to transport structural components from the manufacturer to the project site, which was previously possible, the way is provided. *Constraint (26)* states that each producer may choose only one of three transportation methods: third-party logistics, self-supporting, or affiliated with the 4pl company under supervision, or independent of the 4pl company. *Constraints (27)* and *(28)* state that any manufacturer under contract with a 4PL company can use either the first or second transportation method, i.e., third-party logistics or self-supporting. On the other hand, if it is independent of the 4pl company, it should only transport the structural components from the production site to the project site on its own. Constraint (29) calculates the transportation time for each raw material from the producer to the project site, depending on the Tweed method used. *Constraints (30)-(32)* indicate the completion time and closing time of each project. In addition, it explains how the delay relates to the project's closing time. *Eqs. (33)* and *(34)* place the binary and non-negativity constraints upon the decision variables, respectively.

# 3 | Sensitivity Analysis

In this section, the performance and applicability of the proposed model to improve the productivity of the prefabricated construction SC through integration with fourth-party logistics, and the effects of various variables on the results, are investigated. For this purpose, three types of sensitivity analysis are conducted. Also, it should be noted that the formulated model in subsection 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 with 4.00 GB RAM. *Fig. 2* shows the relationship between 4pl participation/non-participation in the network and the total construction SC cost per allocated project. As shown by the high number of projects, leveraging 4pl's potential for service integration significantly reduces SC costs for construction projects. (The unit of costs is in Rials.)

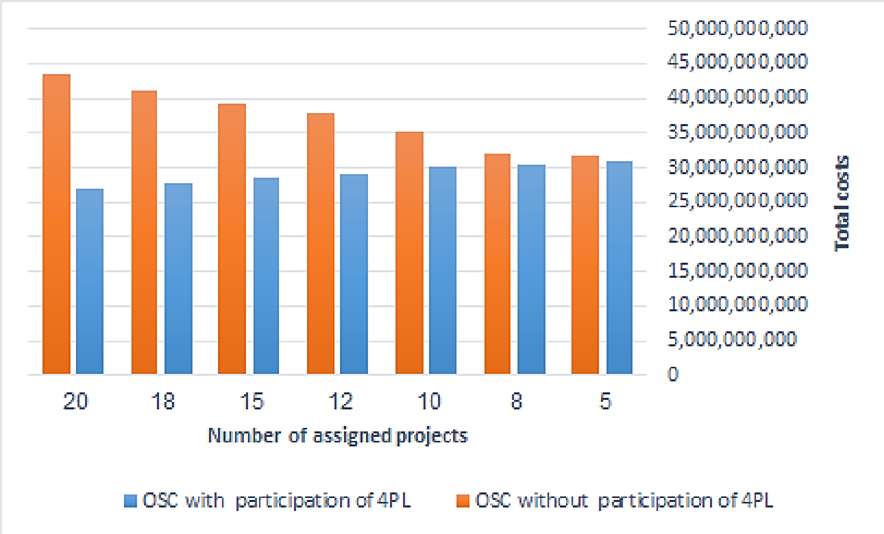


**Fig. 2. Number of assigned projects vs. total construction SC cost with the participation of 4pl and without 4pl.**

*Fig. 3* shows the relationship between the amount of contractors' membership fees in 4pl and the average number of logistics services they receive from 4pl. As shown, when the membership fee is very high, contractors do not receive any services from 4pl. On the contrary, as the membership fee is reduced, the number of services received increases until they receive all the services provided by 4pl (Such as the supply of raw materials from suppliers under contract with 4PL, transportation from the supplier to the factory by 3PLs, transportation from the factory to the project site by 3PLs, and installation at the project site). (The unit of costs is in Rials.)

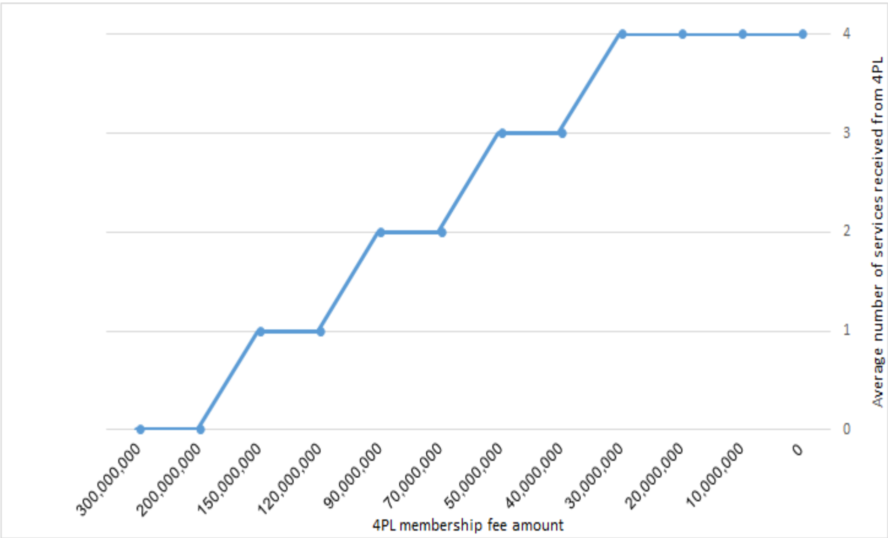


**Fig. 3. 4PL membership fee amount vs. Average number of services received from 4P.**

As shown in *Fig. 4*, as the penalty rate for project delivery delay increases, the rate of 3PL use for transportation between SC levels increases relative to self-supported transportation. (The unit of costs is in Rials.)

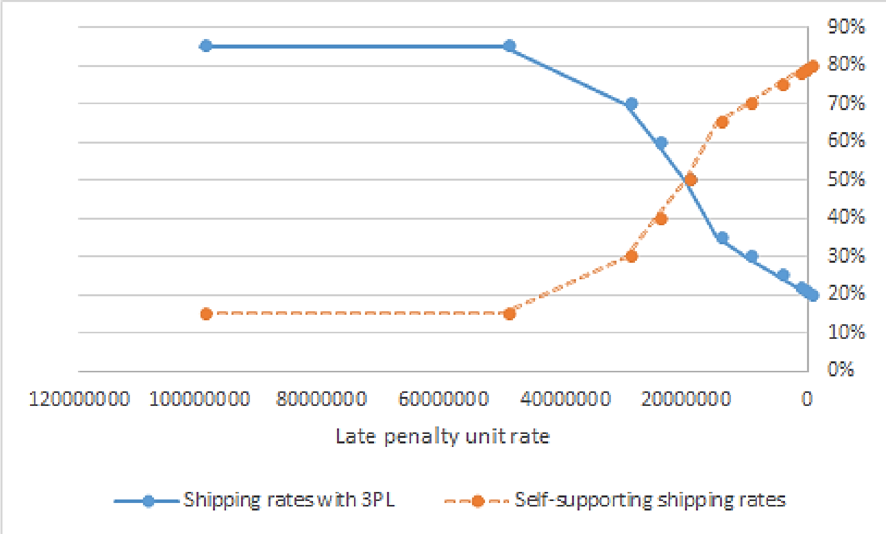


**Fig. 4. Late penalty unit rate vs. Shipping rates with 3PL or Self-supporting.**

# 4 | Conclusions

This study has investigated the issue of synergy among contractors in the OSC-SC through integrative fourth-party logistics, using a mathematical model. Since the construction SC is highly inefficient due to the temporary nature of projects, the complexity of stakeholder communication, and high logistics costs, the main objectives of the construction SC are to reduce costs and delays in project delivery. The results of the sensitivity analysis show that using fourth-party logistics as an integrator and coordinator across the levels of the construction SC can make the proposed model more efficient than previous models, while reducing logistics costs and project delivery delays. Uncertainty about important variables such as capacity, cost, and demand can suggest future research directions. Also, this study adopts a rigorous method to solve the model. Therefore, meta-heuristic and heuristic algorithms are proposed to solve larger problems. Also, considering prerequisite relationships and manufacturing requirements in the production phase will make the model more realistic.

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# Data Availability

The data supporting this study are available from the corresponding author upon reasonable request.

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