

Article

Optimization of Multi-Building Tower Crane Scheduling for Lean Prefabricated Construction

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Abstract

Tower cranes (TCs) as essential lifting equipment in construction engineering, play a critical role in prefabricated buildings (PBs). However, current construction scheduling primarily relies on manual observation and operator experience to execute repetitive tasks, leading to low efficiency, heavy workload, and potential safety risks. In typical PB construction projects, multiple buildings are often constructed in parallel, where each TC is assigned to serve a specific group of buildings independently. This allocation strategy is generally predetermined by the site layout plan to ensure operational safety and avoid inter-crane interference. To enhance lean construction performance and management efficiency in PBs, this study develops a scheduling optimization model that explicitly considers the initial hook position and the specific locations of prefabricated component (PC) supply and demand points. The proposed model is solved and compared using three meta-heuristic algorithms, including Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Artificial Bee Colony (ABC). Numerical results indicate that PSO outperforms GA and ABC in terms of convergence speed and cost minimization performance. After optimization, the operating times of two TCs are reduced by 23.94% and 12.16%, respectively, saving ¥207.29 and ¥293.96 per day in operating costs, and reducing total construction cost by approximately 8.0%. These results demonstrate that the proposed model can effectively improve construction efficiency and support lean management under the considered planning assumptions.

Keywords: tower cranes (TCs); prefabricated buildings (PBs); prefabricated component (PC); scheduling optimization; particle swarm optimization (PSO)

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1. Introduction

The construction industry is a fundamental sector of the national and regional economies, playing a crucial role in driving economic development [1]. However, the traditional construction industry is characterized by slow progress, low productivity, and high resource consumption. These issues pose significant challenges to ecological sustainability, public safety, and long-term sustainable development [2]. For instance, construction activities account for approximately 40% of total construction waste, 32% of resource consumption, and 40% of greenhouse gas emissions, while dust pollution severely impacts

urban residents' quality of life [2–5]. Clearly, conventional construction methods hinder social development, degrade living environments, and impede the construction industry's sustainable growth.

In this context, PBs have attracted increasing attention owing to their advantages in energy efficiency, environmental friendliness, and production efficiency. They are widely regarded as a promising approach for promoting the transformation and upgrading of the construction industry and achieving high-quality development [6–8]. As an emerging construction method, PBs involve transferring a substantial portion of on-site operations—traditionally performed in conventional construction—to factories for mass production. The manufactured PCs are then transported to construction sites for assembly [9]. Extensive studies have demonstrated that PBs offer substantial advantages in environmental and resource efficiency [10]. For instance, Jayawardana et al. [11] reported an approximate 8.06% reduction in greenhouse gas emissions, while Greer et al. [12] further demonstrated a potential reduction from 4% to 20%. In the area of resource conservation and waste reduction, Mao et al. [13] found that material consumption in PBs is only 25% of that in traditional building construction, with additional benefits including minimized waste generation and high recyclability. Similarly, Cao et al. [14] confirmed a 35.82% reduction in resource consumption. Regarding energy consumption, Hong et al. [15] revealed that energy savings of 16% to 24% can be achieved in the recycling phase, while total life-cycle energy consumption can be reduced by 4% to 14%. Concerning comprehensive ecological benefits, Cao et al. [14] further reported that PBs can reduce health damage by 6.61% and ecosystem damage by 3.47%. Currently, PBs have been widely adopted in developed countries, including Germany, the Netherlands, Denmark, and Sweden [12–16]. Nevertheless, systematic analysis and in-depth research on lean management in PBs, particularly regarding on-site scheduling of PCs, remain limited. This is particularly evident in multi-building construction environments where multiple TCs operate independently to serve different building clusters. In such layouts, the operational boundaries of each crane are typically pre-defined by the construction execution plan to minimize collision risks and clarify responsibilities.

Lean construction theory, originally proposed by Professor Koskela [17,18], extends lean manufacturing principles to the construction industry. Its core objective is to minimize waste (e.g., time, resources, and materials) and maximize project value. This approach is now widely regarded as an advanced construction system and project management model [19]. In TC scheduling for PC handling, waste primarily manifests as hook empty load movement (motion waste), idle waiting between tasks (waiting waste), and excessive slewing and luffing due to suboptimal path planning (overprocessing waste). Therefore, minimizing total operating time and cost of TCs can be regarded as an implementation of lean construction principles, where reduced operation time directly reflects waste elimination. Although previous studies have applied lean construction in PBs [20–22], most focus on theoretical frameworks [23,24] and technical implementations [25,26], while comprehensive empirical validation of scheduling optimization remains limited.

Based on the above gap, this study investigates TC scheduling optimization for PC assembly in PBs under a lean construction framework. The main contributions of this study are summarized as follows: (1) development of a simulation-based optimization methodology for PC scheduling in PBs; (2) identification of optimal PC supply locations and TC scheduling strategies; (3) improvement of multi-building construction efficiency under independent TC operation; (4) validation through a case study involving two TCs serving multiple buildings in real PB projects. This study focuses on lean construction management on PC construction sites, contributing positively to improving overall site efficiency and managerial standards.

2. Literature Review

2.1. Lean Construction of PBs

PBs are complex systems comprising four stages—design, production, transportation, and construction—each with stringent requirements. However, persistently prioritizing traditional construction goals (cost management, schedule control, and quality management) makes it difficult to achieve lean construction management objectives for PBs. For instance, the design phase must holistically integrate the needs of production, transportation, and construction for PCs to avoid adverse impacts on subsequent stages. During production and transportation, optimizing assembly-line processes and transportation planning are critical. In the construction phase, prioritizing construction operational efficiency and implementing optimized scheduling plans are essential.

Lean construction aligns with the development philosophy of PBs, aiming to systematically eliminate waste, shorten project cycles, and maximize value throughout the entire process chain [27]. Consequently, PBs are widely regarded as an effective approach for implementing lean principles and have attracted substantial research attention [28]. Regarding lean construction theory, Nahmens et al. [29] highlighted its role in reducing resource waste, accelerating construction cycles, and improving the safety of PBs. Similarly, Zhu et al. [30] emphasized the role of lean practices in enhancing operational performance in complex project delivery systems, fostering stakeholder engagement, and reinforcing sustainability. Regarding lean construction techniques, Niu et al. [31] developed an IoT system leveraging intelligent building objects to enhance supply chain management in PBs. Xu et al. [32] proposed a cloud-based IoT platform designed to improve the delivery efficiency of PCs. Parameswaran et al. [33] investigated the application and impact of lean techniques and tools in precast concrete, identifying Value Stream Mapping (VSM) and Just-in-Time (JIT) production as the most widely adopted lean methods in this field.

Overall, improving lean construction implementation in PBs is generally achieved through optimizing construction plans or establishing tailored management systems. However, most existing studies restrict the perspective of lean optimization to outcomes enabled by technological enhancements or focus exclusively on single-project or phase-specific improvements. In practice, construction enterprises frequently manage multiple PBs simultaneously [34,35]. Nevertheless, issues such as resource coordination and conflict resolution in such multi-building environments have seldom been incorporated into the research framework of lean construction. This limitation is particularly relevant for construction sites with multiple buildings, where each TC operates independently but shares the same supply chain and site resources.

2.2. TCs for PBs

TCs are critical auxiliary equipment on construction sites, their operational efficiency determines the assembly efficiency of PCs and thus governs the overall project schedule. Conventional TC scheduling, which relies on material sequences at supply points and repetitive task assignment based on operator experience, lacks systematic spatial planning and often leads to inefficient transportation paths and low efficiency. Three key factors significantly affect TC operational efficiency and safety: (1) TC selection and layout, (2) supply and demand locations of PCs, (3) TC operation plan and hook runtime.

In response to these challenges, scholars have conducted extensive research. Regarding TC selection and layout, simulation models [36,37] and automated systems [38,39] have been developed to optimize crane positioning, thereby effectively preventing collisions and improving operational efficiency. For operational trajectory and scheduling, methods such as GAs [40–42], mixed-integer linear programming [43,44], and multi-agent simulation [45,46] have been widely adopted to optimize hook trajectories and service sequences [47], as well as to reduce waiting times [48]. Prior research has established a solid foundation for lean construction and TC scheduling in PBs. However, it inadequately addresses TC task allocation and path planning across multiple buildings, especially during construction. Existing scheduling approaches either rely heavily on operator experience (leading to suboptimal efficiency) or depend fully on algorithmic optimization (which often ignores complex on-site conditions, limiting practical applicability). Both scenarios risk wasting time and resources.

In summary, although existing studies have made notable progress in optimizing TC scheduling, several common limitations persist. GAs are prone to premature convergence; mixed-integer programming incurs high computational complexity when handling large-scale problems; multi-agent simulation is highly sensitive to parameter calibration and scenario assumptions. Moreover, implementing these methods for discrete combinatorial scheduling problems tends to be complicated. In contrast, PSO offers advantages such as fewer parameters, fast convergence, and ease of encoding and decoding discrete sequences, making it particularly suitable for the PC sequencing problem involving multiple buildings and tasks in this study. Therefore, in the case study in Chapter 4, we adopt PSO as the solution method and introduce the GA and the ABC algorithm for comparison, aiming to comprehensively validate the effectiveness and superiority of the proposed model and algorithm.

The structure of this study is as follows: Section 1 presents the research background and problem statement; Section 2 reviews the literature; Section 3 describes the practical problems and develops the mathematical framework; Section 4 provides a case study as an illustrative example of applying PSO to multi-building PC scheduling in PBs; Section 5 discusses the research limitations and proposes future research directions; Section 6 concludes the paper.

3. Problem Description

3.1. Description of Construction Scheduling Issues

In PBs, PCs are typically stored within the operating range of TCs or on temporarily parked transport vehicles. Effective scheduling schemes improve construction efficiency, reduce costs, minimize safety risks, and enhance management standards. Conversely, poor scheduling may cause work idling, rework, and even major safety incidents such as TC collisions. It can also lead to frequent crane operations, prolonged waiting times for other equipment, and unnecessary resource consumption, all of which increase project costs. Given the parallel execution of multiple projects and tight schedules, efficient integrated scheduling of PCs within limited time has become a significant challenge for managers. Therefore, developing scheduling strategies based on lean construction theory to address multi-building and multi-scenario demands has emerged as a critical issue in current construction practice.

To analyze the operational process of TCs using scientific methods, it is necessary to decompose their operational paths. When executing construction scheduling tasks, the hook of the TC on the boom completes tangential motion (along the circular arc trajectory of the boom), radial motion (along the straight trajectory of the boom's extension), and vertical motion (vertical lifting trajectory) to transport PCs from supply points to demand points on the standard floor work surface. Figure 1 illustrates the spatial relationship

among the TC, the PC supply point (L), and the demand point (W) in a three-dimensional coordinate system. The specific scheduling process is as follows: Starting from its initial position, the hook transports PC_1 from L_1 to W_1 for positioning and assembly (completing task T_1), then returns to L_1 to transport PC_2 to W_2 , and repeats this cycle until all scheduling tasks for multi-building PCs are completed. The complete motion trajectory of the TC hook is: initial position $\rightarrow L_i (PC_{k+1}) \rightarrow W_j \rightarrow L_i (PC_{k+1}) \rightarrow W_{j+1} \rightarrow \dots \rightarrow$ initial position.

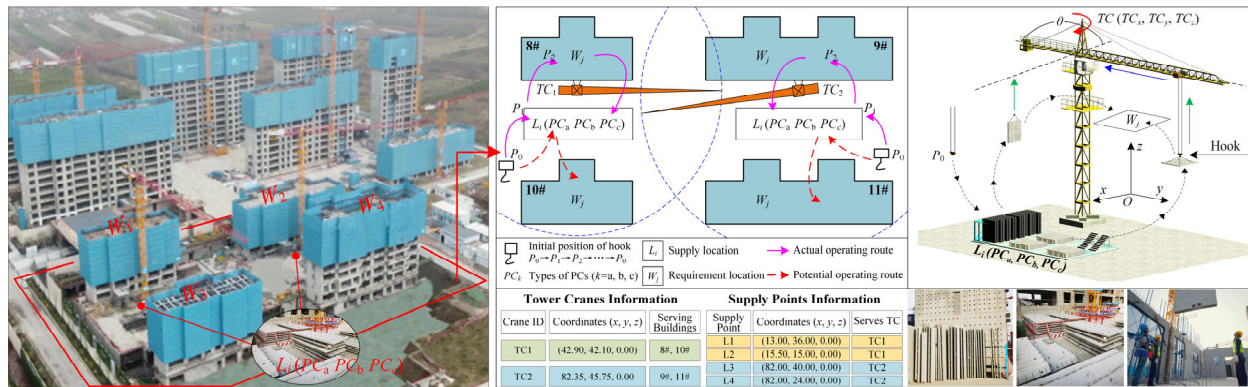


Figure 1. Schematic diagram of the operation path of the construction scheduling of TCs hook.

3.2. Analysis of Construction Scheduling Process

3.2.1. Model Assumptions

To facilitate the development of a mathematical model for multi-building PC construction scheduling in PBs and to ensure that the model accurately reflects lean construction practices, the following assumptions are established:

- (1) The model focuses exclusively on PC scheduling and excludes other materials, such as reinforcing steel and formwork.
- (2) The model does not account for the impact of PC dimensions or site topography on the scheduling process.
- (3) The temporary parking area for PC transport vehicles and the initial positions of TCs are modeled as fixed coordinate points.
- (4) Each PC scheduling task is assigned to a single TC and is performed only once.
- (5) Interactions between concurrently operating TCs (e.g., stopping, waiting, or collision avoidance) are not considered, as each TC is assigned to an independent building cluster without overlapping operational zones.
- (6) TCs operate without interruption until all PC scheduling tasks are completed;
- (7) Owing to site space constraints, the PC transport lanes are modeled as one-way pathways.

It should be noted that the above assumptions are introduced to isolate the effects of scheduling decisions on TC operational efficiency and to maintain model tractability. The proposed model is intended to support planning-level decision making rather than to reproduce all dynamic conditions encountered on construction sites. Factors such as weather disturbances, temporary site congestion, equipment failures, and unexpected task interruptions may influence actual operational performance. Therefore, the optimization results should be interpreted as potential efficiency improvements under controlled construction conditions rather than guaranteed field performance outcomes.

3.2.2. Definition of Model Parameters

The parameter symbols and meanings involved in constructing a mathematical model for the construction scheduling of PCs in PBs are shown in Table 1.

Table 1. Model parameter notation and its description.

NO.	Symbol	Definition
1	L_i	The position of the i th PC supply point, $i \in \{1, 2, \dots, I\}$
2	W_j	The position of the j th PC requirement point, $j \in \{1, 2, \dots, J\}$
3	PC_k	The k th PC, $k \in \{a, b, d, \dots\}$
4	s	The s th transportation task, $s \in \{1, 2, \dots, S\}$
5	P_0	Initial position of hook
6	P_1	The first component supply point position reached by the hook
7	v_1, v_2, v_3	Tangential angular velocity, radial movement velocity, and vertical lifting velocity of TC boom (m/min)
8	T_θ, T_r, T_v	Tangential movement time, radial movement time, and vertical lifting time of TC boom (min)
9	T_{ij}	The time it takes for the PC to move from supply point i to demand point j , where $T_{ij} = T_{ji}$
10	α	The synchronous coordination parameters for the horizontal (tangential and radial) movement of TCs, $\alpha \in [0, 1]$
11	β	The synchronous coordination parameters for the horizontal and vertical movement of TCs, $\beta \in [0, 1]$
12	γ	The difficulty level of hook movement control, $\gamma \in [1, 10]$
13	TC_m	Multi-building m th tower crane performs construction scheduling tasks, $m \in \{1, 2, \dots, M\}$
14	Q_m	The cost incurred by the construction scheduling of the m th TC per unit time per day, $m \in \{1, 2, \dots, M\}$
15	$T_{loading}^k$	The time required to prepare the k th PC for a single lifting operation
16	$T_{unloading}^k$	The time required to assemble the k th PC at the work surface

3.2.3. Kinematic Time Calculation for Hook Operations

In PBs, the primary function of TCs is to transport PCs from supply points to demand points. The motion trajectory can be simplified into three parts. (i) Tangential movement: horizontal rotation of the TC boom along its central axis. (ii) Radial movement: forward-and-backward motion of the hook along the boom. (iii) Vertical movement: up and down motion of the hook along the boom's height. Tangential and radial movements collectively define the horizontal motion trajectory, whereas vertical movement operates independently. The combined horizontal and vertical motion paths are illustrated in Figure 2.

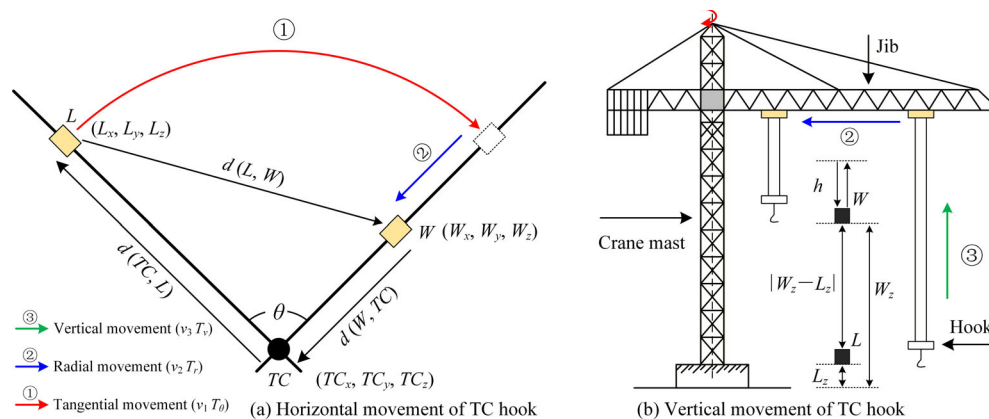


Figure 2. Schematic diagram of horizontal and vertical operation process of TC.

(1) *Horizontal movement time*: In the horizontal direction, the hook moves tangentially with the boom along the motion trajectory shown in Figure 2a. According to relevant studies [49–51], the coordinates of the PC supply point, demand point, and TC origin are denoted as (L_x, L_y, L_z) , (W_x, W_y, W_z) , and (TC_x, TC_y, TC_z) , respectively. The planar distances $d(L, W)$, $d(TC, L)$, and $d(W, TC)$ are calculated as follows:

$$\begin{cases} d(TC, L) = \sqrt{(L_x - TC_x)^2 + (L_y - TC_y)^2} \\ d(L, W) = \sqrt{(L_x - W_x)^2 + (L_y - W_y)^2} \\ d(W, TC) = \sqrt{(W_x - TC_x)^2 + (W_y - TC_y)^2} \end{cases} \quad (1)$$

where $d(TC, L)$ denotes the straight-line distance between the TC origin and the supply point on the same horizontal plane, $d(L, W)$ denotes the straight-line distance between the supply point and the demand point on the same plane, and $d(W, TC)$ denotes the straight-line distance between the demand point and the TC origin on the same plane.

- Assuming the hook moves uniformly in the tangential direction and has an angular velocity of v_1 , the tangential movement angle is θ , and the tangential movement time is $T_\theta = \theta/v_1$. The calculation formula is as follows:

$$T_\theta = \frac{1}{v_1} \arccos \left(\frac{d(W, TC)^2 + d(TC, L)^2 - d(L, W)^2}{2d(W, TC) \cdot d(TC, L)} \right), \quad (0 \leq \arccos(\theta) \leq \pi) \quad (2)$$

- Assuming the hook moves uniformly in the radial direction with a velocity of v_2 , the radial distance traveled by the hook is d_r and the radial movement time is $T_r = d_r/v_2$. The calculation formulas are as follows:

$$d_r = |d(TC, L) - d(W, TC)| = \sqrt{(L_x - TC_x)^2 + (L_y - TC_y)^2} - \sqrt{(W_x - TC_x)^2 + (W_y - TC_y)^2} \quad (3)$$

$$T_r = d_r/v_2 \quad (4)$$

The tangential and radial movements of TCs are interdependent and overlapping, mainly manifested as the TC moving simultaneously in both directions. Therefore, it is necessary to introduce a synchronization coordination parameter α for TC horizontal movement, which is closely related to the professional skill level of the TC operator. The horizontal movement time of the TC hook is calculated as follows:

$$T_h = \max(T_\theta, T_r) + \alpha \min(T_\theta, T_r) \quad (5)$$

where $\alpha \in [0, 1]$ reflects the operator's ability to coordinate tangential and radial motions in the horizontal plane. Its physical interpretation is as follows: when $\alpha = 0$, the two motions are fully synchronized, and the total time equals the longer of the two; when $\alpha = 1$, the two motions are fully sequential, and the total time equals the sum of the two. A smaller α indicates a higher level of operator coordination and thus a shorter total horizontal movement time [50]. Owing to various on-site contingencies (e.g., haze and adverse weather conditions), α is set to 0.25 [42].

(2) *Vertical movement time*: The vertical movement trajectory of the TC hook is shown in Figure 2b. Assuming L and W are the supply and demand points of a PC, respectively, and the vertical coordinates are L_z and W_z . Considering the safe distance h between the TC and the building, the vertical movement trajectory is as follows: the PC ascends from supply point L by a distance of $|W_z - L_z| + h$, then slowly descends by h until the PC reaches demand point W [52]. Assuming the hook moves uniformly in the vertical direction at a speed of v_3 . The vertical lifting height d_z and vertical movement time T_v of the hook are calculated as follows:

$$d_z = |W_z - L_z| + 2h \quad (6)$$

$$T_v = d_z/v_3 \quad (7)$$

(3) *Single transportation time of the hook*: The horizontal and vertical movements of the hook are usually coordinated synchronously when the TC performs a construction scheduling task. Therefore, it is necessary to introduce a synchronization coordination parameter β and a difficulty parameter γ representing the control difficulty caused by uncertain on-site factors [50,52,53]. The total time T_{ij} for the TC hook to move from supply point L to the demand point W is calculated as follows:

$$T_{ij} = \gamma [\max(T_v, T_h) + \beta \min(T_v, T_h)] \quad (8)$$

where $\beta \in [0, 1]$ physically characterizes the degree of coordination between the horizontal and vertical motions of the TC: $\beta = 0$ indicates fully synchronized movements, whereas $\beta = 1$ indicates fully serial movements. The value of β is influenced by spatial constraints, operator visibility, and component type. Based on field tests, Zhang et al. [50] reported that for typical PC hoisting conditions, vertical lifting requires ensuring component stability, resulting in a high degree of serial nature; thus, a β value in the range of 0.8–1.0 is recommended. Considering both construction safety and operational practices, this study adopts a conservative value of $\beta = 1.0$, which is consistent with the findings of Huang et al. [52].

$\gamma \in [1, 10]$, represents the influence of uncontrollable factors (e.g., weather, accidents, obstacles) that may delay TC operating time. The smaller the value of γ , the better the operating conditions of the PC and the easier it is to control. $\gamma = 1.0$ denotes normal operation, whereas $\gamma = 10$ denotes operation under difficult on-site conditions where the hook is tough to control.

(4) *Total time for a single complete transportation*: In a complete construction scheduling task, the following time components must be considered: preparation time $T_{loading}^k$ for starting PC lifting, travel time T_{ij} from supply point to demand point, unloading time $T_{unloading}^k$ for work surface assembly, and return time T_{ji} from demand point back to supply point. The total time for a single complete PC scheduling cycle is calculated as follows:

$$T = T_{loading}^k + T_{ij} + T_{unloading}^k + T_{ji} \quad (9)$$

where $k = a, b, c$ denotes the PC type: prefabricated shear wall (PC_a), laminated panel (PC_b), prefabricated staircase (PC_c). $T_{loading}^k$ and $T_{unloading}^k$ represent the preparatory time for lifting and the on-site assembly time, respectively.

3.3. Mathematical Modeling of Construction Scheduling

The time required for TC construction scheduling consists of two parts. (i) Initial movement time: The duration for the TC hook to travel from its initial position to the first supply point. (ii) Cumulative scheduling time: The cycle time for the hook to move between supply and demand points (supply $\rightarrow$ demand $\rightarrow$ supply). To minimize the total travel time of TCs, a mathematical model is formulated to transform the construction scheduling problem of TCs into a mathematical optimization problem and to maximize the reduction in TC operation time while satisfying PC assembly requirements on the working surface. This model was initially proposed by Zhang et al. [50].

3.3.1. Decision Variables

For the s th construction scheduling task of PCs, x_{ij}^{ks} represents the execution of the s th construction scheduling task from the supply point i to the demand point j for the k th PC. If the task exists, $x_{ij}^{ks} = 1$; otherwise, $x_{ij}^{ks} = 0$.

3.3.2. Objective Function

- Initial movement time. The time it takes for the hook to move from its initial position to the first supply point. Combined with Equation (8), the time T_1 for the TC hook to travel from the initial position to the first supply point is calculated as follows:

$$T_1 = \gamma [\max(T_v^{p_0, p_1}, T_h^{p_0, p_1}) + \beta \min(T_v^{p_0, p_1}, T_h^{p_0, p_1})] \quad (10)$$

- Cumulative scheduling time. The PCs move from supply point to demand point and then back from demand point to supply point within a limited area. Combined with

Equation (9), the cumulative time T_2 for completing the construction scheduling of PC is calculated as follows:

$$T_2 = \sum_{k=1}^K \sum_{i=1}^I \sum_{j=1}^J \sum_{s=1}^S x_{ij}^{ks} (T_{loading}^k + T_{ij} + T_{unloading}^k + T_{ji}) \quad (11)$$

- Construction scheduling objective function. From Equations (10) and (11), the total time T_{total} for PC scheduling in PBs and the total cost C for TC construction scheduling are calculated as follows:

$$T_{total} = \min \sum_{m=1}^M (T_1 + T_2) \quad (12)$$

$$\min C = \min (T_{total} \cdot Q_m) \quad (13)$$

where Q_m represents the cost incurred by the TC per unit of operating time per day.

3.3.3. Constraint Condition

For $\forall s \in \{1, 2, \dots, S\}$, $i \in \{1, 2, \dots, I\}$ there are:

$$\sum_{k=1}^K \sum_{i=1}^I \sum_{j=1}^J \sum_{s=1}^S x_{ij}^{ks} = 1 \quad (14)$$

$$x_i^s = x_i^{s+1} \quad (15)$$

Equations (14) and (15) together ensure that each task starts from a supply point, delivers a PC to a demand point, and returns to the same supply point before the next task.

The above mathematical formulation focuses on the scheduling of a single TC serving multiple supply and demand points within its designated building cluster. In our case study, two TCs (TC₁ and TC₂) are pre-allocated to distinct building groups according to the construction execution plan (TC₁ serves Buildings 8[#] and 10[#]; TC₂ serves Buildings 9[#] and 11[#]) and operate independently. This division of labor is predetermined based on the following engineering principles, which justify its optimality in this specific case: (i) Spatial separation: The substantial distance between the two building clusters exceeds the economical operational radius of a single crane, making collaborative operation inefficient; (ii) Safety considerations: In busy PC sites, establishing clear, non-overlapping operational zones is a standard practice to prevent crane-to-crane collisions and ensure site safety; (iii) Management efficiency: A clear division simplifies task allocation, aligning with lean construction principles by reducing uncertainty and waste. Consequently, the crane-task assignment is treated as a fixed input parameter rather than a decision variable in our optimization model. The total cost and total time are simply the sum of the two independent optimization results. This setup reflects a typical multi-building but non-collaborative scheduling scenario, which aligns with the actual case conditions.

3.4. Coding and Decoding Strategy for PSO

Classical PSO operates in continuous vector spaces, whereas the considered TC scheduling problem is a discrete combinatorial optimization that requires determining the optimal execution sequence of PC transportation tasks. To apply PSO, a random-key based coding and decoding strategy is devised to map continuous particle positions to discrete sequences.

3.4.1. Coding Strategy

For a problem with S tasks, each particle is represented as an S -dimensional continuous position vector $X_i = \{x_{i1}, x_{i2}, \dots, x_{iS}\}$, with each component $x_{id} \in [0, 1]$. This value serves as the priority key of the corresponding task. During iterations, particles update velocities and positions by tracking personal and global best solutions, thereby adjusting these keys.

3.4.2. Decoding Strategy

At each iteration, the continuous position vector is converted into a feasible task sequence. The tasks are sorted in descending order according to their key values. The resulting ordered sequence constitutes a candidate schedule, which is then evaluated using the established mathematical model (Equation (12)) to compute the total travel time T_{total} . This fitness value guides subsequent search. This strategy enables PSO to solve discrete sequencing problems without modifying its original update rules, preserving algorithmic simplicity.

4. Case Study

4.1. Experimental Method Design

Traditional construction scheduling relies primarily on the observational expertise of TC operators and assistants to repeatedly execute scheduling tasks. This approach lacks systematic spatial consideration, often leading to issues such as inefficient paths and redundant transportation. Therefore, this study focuses on multi-building PC scheduling in PBs by establishing a mathematical model and leveraging intelligent algorithms to formulate and solve optimal TC scheduling plans, thereby enhancing lean management of PCs on PB construction site. Research on intelligent algorithms has demonstrated significant advancements. For TC optimization, traditional methods such as linear and dynamic programming remain widely used [54,55], whereas recent studies increasingly employ genetic algorithm hybrids or enhancements [56]. As a meta-heuristic method, PSO can effectively resolve multi-objective scheduling challenges. Jiby et al. [57] applied PSO to multi-resource-constrained project scheduling. Zhu et al. [58] proposed a hybrid PSO-SA meta-heuristic algorithm for automatic lifting path planning of PBs' TCs. Hammad et al. [49] addressed a hook path problem for prefabricated TCs using PSO. Similarly, Zhang et al. [59] and Arboui et al. [57,60] leveraged PSO for resource-constrained scheduling. Therefore, in this study, PSO is adopted for PC scheduling optimization and compared GA and ABC algorithms to validate its efficacy. It should be noted that in our case study, the two TCs serve different building clusters independently (TC₁ for Buildings 8[#] and 10[#], TC₂ for Buildings 9[#] and 11[#]). Thus, the optimization is performed separately for each crane, and the total performance improvement is the aggregate of the two independent optimizations. This represents a typical multi-building independent scheduling scenario rather than a collaborative multi-building one.

Kennedy et al. [57] proposed the concept of PSO in 1995, this robust evolutionary algorithm outperforms other meta-heuristics in computational efficiency, developmental flexibility, and result consistency [61,62]. The calculation formula are as follows:

$$v_{id}(t+1) = wv_{id}(t) + c_1r_1(P_{id}(t) - x_{id}(t)) + c_2r_2(P_{gd}(t) - x_{id}(t)) \quad (16)$$

$$x_{id}(t+1) = v_{id}(t) + x_{id}(t) \quad (17)$$

In Equations (16) and (17), i represents the i th particle, d represents the d th dimension, and w represents the inertia weight (a decimal between 0 and 1); $v_{id}(t)$ represents the d th dimensional flight velocity component of particle i at the i th iteration; c_1 and c_2 are acceleration factors (learning factors); r_1 and r_2 are random numbers in $[0, 1]$; $P_{id}(t)$ represents the individual optimal solution of the i th particle in the d th dimension at the t th iteration;

$P_{gd}(t)$ represents the global optimal solution of the entire particle swarm in the d th dimension at the t th iteration.

Equation (16) defines the updated velocity by combining the particle's previous velocity with its distances to both its individual and global optimal positions, while Equation (17) updates the particle's position using its historical experience, the swarm's collective best experience, and its previous velocity.

4.2. Construction Scheduling Resource Allocation

4.2.1. Layout of TCs

As illustrated in Figure 1, Buildings 8[#] and 10[#] are allocated to and independently served by TC₁, whereas Buildings 9[#] and 11[#] are allocated to TC₂. No resource sharing or operational coordination exists between the two TCs, reflecting a typical multi-building construction layout.

4.2.2. Supply Point Location

The PC transport vehicles and storage yards are modeled as supply points, designated L_1 , L_2 , L_3 , and L_4 . These supply points accommodate three PC types: PC_a , PC_b , and PC_c . The coordinate system was redefined according to the specific layout of the construction site, and the coordinate ranges for the PC supply points are provided in Table 2.

Table 2. Coordinate information of PCs supply points.

TC	Supply Point (L_i)	Supply Points and Regional Coordinates (L_x , L_y , L_z)		
		x	y	z
TC ₁	L_1	13.00 [−2.00, 28.00]	36.00 [33.00, 39.00]	0.00
	L_2	15.50 [0.50, 30.50]	15.00 [12.00, 18.00]	0.00
TC ₂	L_3	82.00 [62.00, 102.00]	40.00 [37.00, 43.00]	0.00
	L_4	82.00 [62.00, 102.00]	24.00 [21.00, 27.00]	0.00

4.3. Solving the Construction Scheduling Model

4.3.1. Supply Demand Plan for PCs

To ensure the stability and reliability of PBs, the first three floors of each building were constructed using the traditional cast-in-place method. Starting from the fourth floor onward, PCs were used. Specifically, the assembly cycle was 20 days for the first floor, 12 days for the second floor, and 10 days for the third floor. Thereafter, the standard floor assembly cycle was reduced to 7 days. The construction timeline and progress plan for the multi-building (Buildings 8[#]–11[#]) are detailed in Table 3.

Table 3. Group building schedule and construction schedule.

Building Number	Floor	Duration (Days)	Time-On	Time-End
8 [#]	4th floor (first floor PC)	20	26 March 2023	14 April 2023
	5th floor	12	15 April 2023	26 April 2023
	6th floor	10	7 April 2023	6 May 2023
	7th–17th floors	77	7 May 2023	22 July 2023
9 [#]	4th floor (first floor PC)	20	28 February 2023	19 March 2023
	5th floor	12	20 March 2023	31 March 2023
	6th floor	10	1 April 2023	10 April 2023
	7th–25th floors	133	11 April 2023	22 September 2023
10 [#]	4th floor (first floor PC)	20	7 April 2023	26 April 2023
	5th floor	12	27 April 2023	8 May 2023
	6th floor	10	9 May 2023	18 May 2023

11 [#]	7th–17th floors	77	19 May 2023	3 August 2023
	4th floor (first floor PC)	20	3 April 2023	22 April 2023
	5th floor	12	23 April 2023	4 May 2023
	6th floor	10	5 May 2023	14 May 2023
	7th–22nd floors	112	15 May 2023	3 September 2023

Based on Table 3, to ensure the construction scheduling of PCs for multi-building during the period of 24 to 30 March 2023, project managers must submit a demand plan to the PC factory one week in advance to prevent supply delays that could affect the project's construction progress. According to the standard floor construction tasks, the demand plan for PCs for 24 to 30 June 2023, is presented in Table 4.

Table 4. Demand plan for PCs of PBs (24th–30th June).

Demands	June 24th	June 25th	June 26th	June 27th	June 28th	June 29th	June 30th
8 [#]	2	10	6	—	—	26	—
9 [#]	16	9	—	—	48	—	4
10 [#]	6	—	—	26	—	2	10
11 [#]	—	4	16	9	—	—	48
Total (block)	24	23	22	35	48	28	62

4.3.2. Construction Scheduling Experiment Data

An analysis of the lean construction scheduling demand for PCs in multi-building was conducted on 30 June 2023. On that date, Building 8[#] had been constructed up to the 14th floor, with PC_b assembled in place. The process involved binding the steel bars of the PC_b , and there were no construction scheduling tasks for PCs. Building 9[#] had reached the 13th floor, involving PC_c assembly, concrete pouring, and four PC_c construction scheduling tasks. Building 10[#] (up to the 13th floor) required surveying, setting out, PC_c assembly, and scheduling for 10 PC_a installations. Building 11[#] had reached the 13th floor for PC_b assembly, requiring scheduling tasks for 48 PC_b installations.

Based on the previous analysis, a construction scheduling study for PCs in multi-building within PBs was conducted using the PC demand on June 30, 2023, as the basis. TC_1 is assigned to manage construction scheduling for Buildings 8[#] and 10[#] at coordinates (12.90, 42.10, 0.00), while TC_2 oversees scheduling for Buildings 9[#] and 11[#] at coordinates (82.35, 45.75, 0.00). After defining the coordinates of the PC supply points, the coordinates of the demand points on the standard working floor surface must be determined. Therefore, the coordinates of the demand points on 30 June 2023, are presented in Table 5.

Table 5. Coordinate information of PCs demand points.

Types of PCs	Demand Points	Coordinate (W_x, W_y, W_z) Unit/m			Types of PCs	Demand Points	Coordinate (W_x, W_y, W_z) Unit/m		
		x	y	z			x	y	z
PC_c	W_1	68.95	61.85	37.68	PC_b	W_{32}	74.50	4.27	37.68
	W_2	70.25	61.85	38.28		W_{33}	77.37	11.40	37.68
	W_3	95.35	61.85	37.68		W_{34}	79.55	11.40	37.68
	W_4	96.65	61.85	38.28		W_{35}	81.82	11.40	37.68
	W_5	0.10	6.25	37.68		W_{36}	77.51	7.50	37.68
	W_6	0.10	3.75	37.68		W_{37}	79.65	7.50	37.68
PC_a	W_7	0.10	1.50	37.68		W_{38}	81.79	7.50	37.68
	W_8	6.40	6.15	37.68		W_{39}	83.77	11.40	37.68
	W_9	6.40	1.67	37.68		W_{40}	86.05	11.40	37.68
	W_{10}	12.40	1.85	37.68		W_{41}	88.22	11.40	37.68
	W_{11}	15.10	4.90	37.68		W_{42}	83.81	7.50	37.68

PC _b	W ₁₂	16.30	4.90	37.68	W ₄₃	85.97	7.50	37.68
	W ₁₃	15.70	4.10	37.68	W ₄₄	88.09	7.50	37.68
	W ₁₄	15.70	1.25	37.68	W ₄₅	93.47	18.52	37.68
	W ₁₅	61.47	11.40	37.68	W ₄₆	93.10	15.95	37.68
	W ₁₆	63.75	11.40	37.68	W ₄₇	90.80	13.85	37.68
	W ₁₇	65.92	11.40	37.68	W ₄₈	94.00	13.85	37.68
	W ₁₈	61.51	7.50	37.68	W ₄₉	91.10	11.64	37.68
	W ₁₉	63.65	7.50	37.68	W ₅₀	95.95	11.64	37.68
	W ₂₀	65.79	7.50	37.68	W ₅₁	91.10	9.00	37.68
	W ₂₁	72.35	18.52	37.68	W ₅₂	95.95	9.00	37.68
	W ₂₂	72.49	15.95	37.68	W ₅₃	91.10	6.36	37.68
	W ₂₃	71.60	13.85	37.68	W ₅₄	95.95	6.36	37.68
	W ₂₄	74.80	13.85	37.68	W ₅₅	91.10	4.27	37.68
	W ₂₅	69.65	11.64	37.68	W ₅₆	95.95	4.27	37.68
	W ₂₆	74.50	11.64	37.68	W ₅₇	99.67	11.40	37.68
	W ₂₇	69.65	8.99	37.68	W ₅₈	101.85	11.40	37.68
	W ₂₈	74.50	9.00	37.68	W ₅₉	104.12	11.40	37.68
	W ₂₉	69.65	6.36	37.68	W ₆₀	99.81	7.50	37.68
	W ₃₀	74.50	6.36	37.68	W ₆₁	101.95	7.50	37.68
	W ₃₁	69.65	4.27	37.68	W ₆₂	104.09	7.50	37.68

4.3.3. Construction Scheduling Parameter Setting

In this study, parameters including the skill level of the TC operator, synchronization coefficients α and β , and on-site environmental conditions were established based on a single-case scenario. For practical engineering applications, these parameters can be flexibly adjusted according to different construction scenarios, thereby ensuring the model's adaptability to a wide range of PC scenarios and enhancing its generalizability and practicality. Experimental simulation were conducted using Matlab 2022b. Two TCs of the same model were configured with an angular velocity $v_1 = 0.7$ rad/min, a radial velocity $v_2 = 100$ m/min, and a vertical velocity $v_3 = 100$ m/min during scheduling. The TC operators had moderate skill levels, with operating coefficients $\alpha = 0.25$ and $\beta = 1$. During TC operation, weather conditions were optimal, and there were no obstacles along the hook movement path between PC supply and demand points. The difficulty coefficient of hook movement control was set to $\gamma = 1.0$. This value corresponds to favorable construction conditions during the observation period, including normal weather, unobstructed lifting paths, adequate visibility, and the absence of unexpected disturbances. According to the calibration principle proposed in Section 3.2.3, the observed transportation times were highly consistent with the theoretical transportation times, resulting in a calibrated γ value close to 1.0. Therefore, $\gamma = 1.0$ was adopted in this case study. The TC had a good field of view, and the safe distance between the TC and the building was $h = 1.5$ m. The daily cost of each TC was 2000 yuan/day, operating for 8 h/day with a unit time cost of 4 yuan/min.

Based on on-site observations, preparation and assembly times were as follows: $T_{loading}^a = T_{unloading}^a = 6$ min, $T_{loading}^b = T_{loading}^c = 3.5$ min, $T_{unloading}^b = T_{unloading}^c = 3$ min. The height of TC₁ was determined by the highest structural elevation of the 14th floor (40.83 m) for Buildings 8[#] and 10[#], while TC₂ was set to the 13th floor's structural elevation (37.68 m) for Buildings 9[#] and 11[#]. The initial hook coordinates were defined as $P_0(\text{TC}_1) = (12.90, 42.10, 45.83)$ and $P_0(\text{TC}_2) = (12.90, 42.10, 42.68)$.

4.4. Results of Construction Scheduling Experiment

4.4.1. Optimal Construction Scheduling Plan and Supply Points

After settings the model algorithm parameters, the population sizes for PSO, GA, and ABC were each set to 100, with a maximum of 400 iterations. The parameters were defined as $c_1 = 2.8$, $c_2 = 1.3$, $w = 0.729$, $P_c = 0.8$, $P_m = 0.2$, and the number of employed bees was set to 100. Based on the construction progress of multi-buildings PBs (Buildings 8[#]–11[#]), TC₁ was responsible only for the construction scheduling of 10 PC_a units in 10[#] on that day, without interference from TC₂. The Gantt chart of the scheduling plans for TC₁ before and after optimization are shown in Figure 3. Comparative analysis shows that time savings are mainly achieved by compressing three links: (a) optimization of no-load return trips: by comparing task intervals in the Gantt chart, we show how the optimized schedule reduces redundant radial movements associated with returning to a fixed initial position; (b) reduction in redundant tangential (slewing) movements: we explain how task batching in the optimized scheme avoids the frequent, large-amplitude slewing angle changes seen in the traditional approach; (c) elimination of idle waiting time: we demonstrate that the optimized logic enables smooth task transitions, eliminating idle periods caused by unreasonable task assignments.

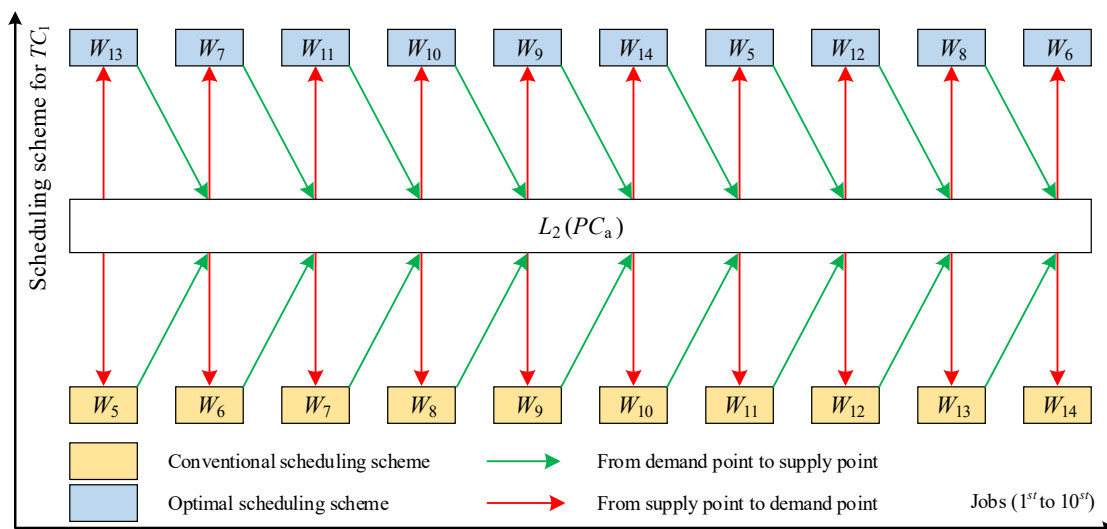


Figure 3. Gantt chart of scheduling scheme for tower crane TC₁ before and after optimization.

According to the construction progress of the multi-buildings PBs, TC₂ was responsible for scheduling 4 PC_c units in Building 9[#] and 48 PC_b units in Building 11[#] on the day. The Gantt chart of the scheduling plans for TC₂ before and after optimization are shown in Figure 4. The time savings are mainly achieved through the following: (a) substantial reduction in no-load travel between buildings: the optimized schedule groups tasks within the same building, significantly reducing the long-distance no-load shuttles (radial movements) that are prevalent in the traditional scheme; (b) optimization of vertical no-load travel: savings in vertical movement time are achieved by rationally sequencing the hoisting of components at different floor levels. Quantitative analysis indicates that the reduction in idle time is the primary reason for the 12.16% decrease in total time.

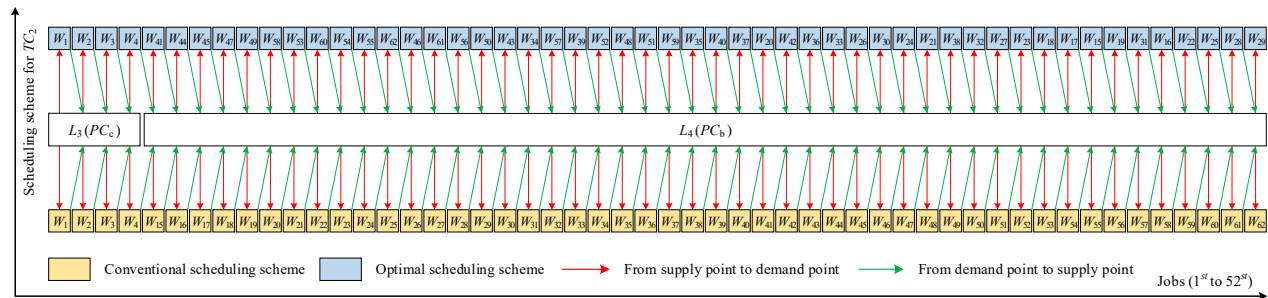


Figure 4. Gantt chart of scheduling scheme for tower crane TC2 before and after optimization.

4.4.2. Minimum Time Cost for Tower Crane Construction

To ensure the effectiveness and reliability of the proposed algorithm, the widely recognized PSO algorithm was employed to simulate and optimize the construction scheduling of PCs in multi-buildings PBs. Additionally, the computational reliability of PSO was compared and analyzed against that of GA and ABC. After 400 iterations, all three algorithms achieved convergence. In contrast to the traditional scheduling approach, which relies primarily on the experience of TC operators and assistants, three distinct optimization algorithms were applied to solve the problem. The cumulative runtimes of TC1 and TC2 after iterative convergence are shown in Figure 5, and the cumulative costs for both TCs are presented in Figure 6. The operational cost convergence curves for TC1 and TC2 are demonstrated in Figure 7.

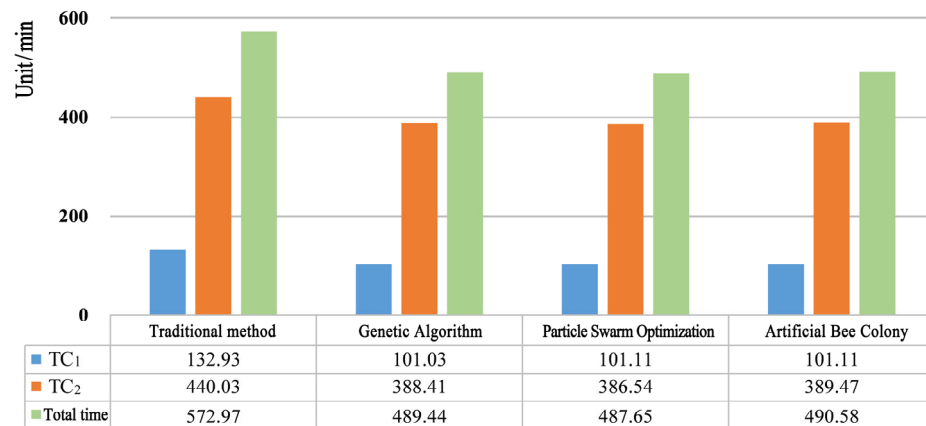


Figure 5. Comparative analysis of operating time between TC1 and TC2.

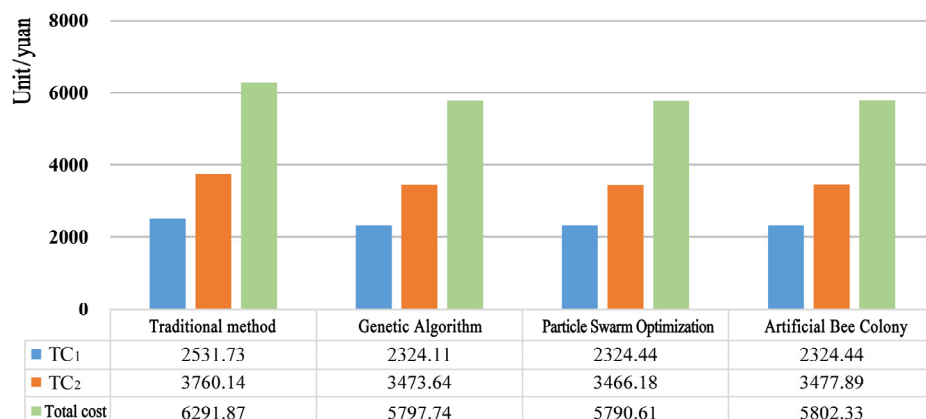


Figure 6. Comparative analysis of operating costs between TC1 and TC2.

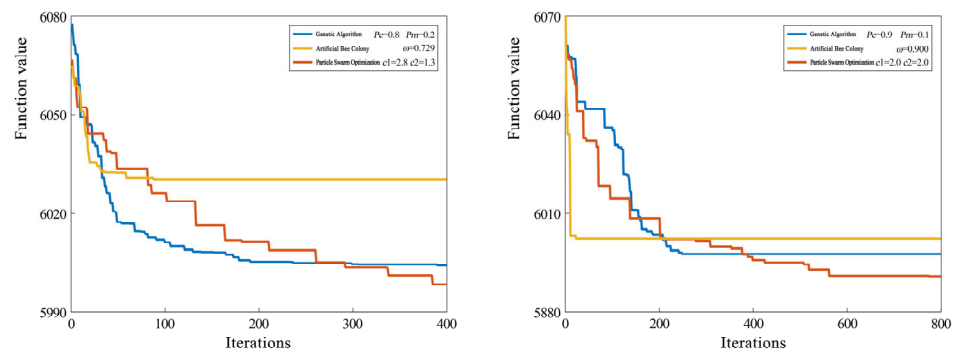


Figure 7. Convergence curve of operating cost fitness for TC₁ and TC₂.

4.4.3. Analysis of Experimental Simulation Results

As shown in Figure 5, the optimization simulation for PC construction scheduling in multiple independent buildings (Buildings 8[#]–11[#]) was conducted to minimize the runtime of each separately. Compared with traditional construction methods, all three optimization algorithms converge, but PSO exhibits superior in performance. In terms of solution quality, PSO achieved the lowest total operating cost (¥5790.61) under the joint scheduling of TC₁ and TC₂. In terms of convergence speed, PSO reached a stable solution after 378 iterations, whereas GA and ABC require more iterations to approach the convergence. Furthermore, repeated experimental results have indicate that PSO demonstrates better stability and robustness. Simultaneously, PSO reduced the runtimes of TC₁ and TC₂ by 23.94% and 12.16%, respectively, and the cumulative daily runtime of the two TCs decreased by 85.31 min (1.4 h).

As shown in Figures 6 and 7, the convergence curves for construction scheduling and operating costs of TCs in multi-buildings PBs (Buildings 8[#]–11[#]) indicate that PSO exhibits superior convergence performance. After 378 iterations, the algorithm achieved a runtime of 31 s and the lowest total runtime cost of ¥5790.61 for both TCs, outperforming GA and ABC. When using traditional scheduling methods, the operating costs for TC₁ and TC₂ were ¥2531.73/day and ¥3760.14/day, respectively. After optimization, the operating cost of TC₁ was reduced by ¥207.29/day, and that of TC₂ was reduced by ¥293.96/day, yielding a total daily savings of ¥501.25 during PC construction scheduling tasks. It should be emphasized that the reported reductions in operating time and cost represent the performance improvement achieved within the defined modeling assumptions. These values should not be interpreted as direct predictions of field productivity gains. In practical projects, external uncertainties and operational constraints may reduce the magnitude of achievable improvements. Nevertheless, the results demonstrate that significant inefficiencies exist in traditional experience-based scheduling and that systematic optimization can provide substantial opportunities for performance enhancement.

In summary, the multi-building PCs scheduling model for PBs proposed in this study significantly reduces time and cost while delivering multifaceted lean benefits. The reduced operational time minimizes idle and non-productive periods for TCs, thereby reducing energy consumption and mechanical wear. Furthermore, the optimized path and supply point planning enhance on-site spatial utilization efficiency and logistics organization, mitigating resource waste and safety risks in PC management. Consequently, the optimization outcomes of this research represent a comprehensive integration of temporal, economic, resource, and safety benefits. The findings provide a scientifically sound and readily applicable analytical method for optimizing management and promoting lean practices in PB processes, offering substantial practical guidance for advancing lean management in construction projects.

5. Discussion and Future Research Directions

5.1. Discussion

The optimization results not only report quantitative improvements but also reveal the underlying mechanisms: the time and cost savings stem from the systematic elimination of “empty travel” and “idle waiting” in the scheduling sequence, which directly embodies the core lean construction principle of waste elimination.

Comparing the Gantt charts before and after optimization (Figures 3 and 4) illustrates the specific improvement pathways for TC₁ and TC₂. For TC₁ (handling 10 PC_a units), traditional experience-based scheduling involved substantial redundant radial movements—operators tended to return to a fixed initial position after each lift rather than dynamically adjusting based on the next task’s supply point. The optimization algorithm re-sequenced the tasks so that the empty hook proceeds directly from the current demand point to the nearest next supply point, thereby eliminating 23.94% of the operating time. For TC₂ (handling 4 PC_c and 48 PC_b units), the main waste came from long-distance no-load shuttles between different buildings and vertical idle travel across floor levels. The optimized scheme batches tasks within the same building and sequences lifts according to floor height, significantly reducing cross-building non-productive movements and achieving a 12.16% time saving.

From a lean construction perspective, these improvements correspond to the reduction in three types of waste: (a) motion waste: optimized path planning reduces unnecessary slewing and luffing; (b) waiting waste: rational task sequencing eliminates idle hook periods caused by unreasonable assignments; (c) overprocessing waste: avoids repeated selection of suboptimal supply points. The daily cost saving of ¥501.25 serves as a monetary measure of this waste elimination.

It should be emphasized that the optimized results are obtained under a predefined independent scheduling mode (TC₁ serves Buildings 8[#] and 10[#]; TC₂ serves Buildings 9[#] and 11[#]). This division is based on safety and management efficiency considerations of the site layout. However, in practical projects where crane operational zones overlap, collaborative anti-collision mechanisms would need to be incorporated. Moreover, while the model parameters (α , β , γ) capture operator skill and environmental complexity, dynamic disturbances such as extreme weather or equipment failures may still affect field execution. Therefore, the reported efficiency improvements should be interpreted as achievable optimization potential under controlled construction conditions, rather than exact predictions of field performance.

In summary, this study uncovers the structural sources of hidden waste in conventional experience-based scheduling via mathematical optimization, providing a quantifiable and replicable lean management pathway for multi-building PCs.

5.2. Research Limitations and Future Research Directions

Notwithstanding the demonstrated efficacy and reliability of the multi-building TCs scheduling model and optimization algorithm for PBs developed in this study, several limitations warrant acknowledgment, as delineated below:

- (1) Collaborative scheduling and collision avoidance. A primary limitation is the preset division of labor among TCs, which is treated as a fixed input rather than an optimization variable. Although we have justified the optimality of the current assignment in this specific case based on spatial separation, safety, and management efficiency principles, this presupposition restricts the model’s generalizability to scenarios requiring collaborative operation. In practice, cranes’ service ranges may overlap dynamically, and the optimal task allocation itself becomes a critical decision variable. Therefore, incorporating automatic task allocation—i.e., collaborative multi-crane

scheduling—into the optimization model is a crucial direction for future research. Furthermore, as TCs are critical mechanical equipment in PBs, their operation safety should not be overlooked. This study deliberately omits potential spatial interference and collision risks among multiple TCs operating simultaneously. In practical engineering applications, factors including safety distances between cranes, overlapping operational zones, and conflicts in jib rotation trajectories fundamentally impact scheduling safety and efficiency. Future research should integrate anti-collision algorithms with real-time positioning systems to establish collaborative scheduling mechanisms capable of dynamic obstacle avoidance. Additionally, while the current model idealizes dynamic site conditions (e.g., weather changes, temporary obstacles) by addressing them holistically via parameter γ , this simplification provides valuable insights for developing more sophisticated real-time response models. Moreover, the human-factor executability of the optimized schedules has not yet been validated through long-term field observations. Future studies could integrate TC operation logs, Building Information Modeling (BIM) platforms, and real-time positioning technologies to investigate operators' compliance with optimized schedules, their adaptive behaviors, and deviations from planned sequences, thereby enhancing the engineering applicability of the proposed approach.

- (2) Multi-plant supply chain coordination. For PC construction scheduling in PBs, this study fully incorporates practical conditions but is limited to scenarios where a single prefabricated plant supplies multiple PBs, without addressing the collaborative supply and transportation scheduling among multiple prefabricated plants. As the scale of PBs expands, cross-plant and cross-project collaborative scheduling will become crucial for enhancing the efficiency of the overall supply chain. As evidenced by studies such as Song [63] and Cui [64], which focus on collaborative scheduling involving multiple prefabricated plants, future research should aim to develop multi-plant–multi-building collaborative scheduling models. Such models would integrate transportation resources and lifting plans to achieve seamless coordination between the supply chain and on-site construction processes.
- (3) Dynamic adaptability. Although the optimization model adopted in this study demonstrates satisfactory performance in static environments, it still exhibits limitations in addressing dynamic on-site variations (e.g., task priority adjustments, equipment failures, and emergent task insertions). Future research should prioritize the development of dynamic adaptive scheduling mechanisms by integrating digital twins, Internet of Things (IoT), and real-time data fusion technologies to achieve a transition from “pre-planning” to “real-time response”.
- (4) Practical usability and visualization. Current research outcomes remain predominantly focused on theoretical models and algorithms, lacking user-friendly visual interfaces and interactive systems for on-site management personnel. Enhanced efforts should be directed toward developing human–machine collaborative decision-support systems that translate optimized results into graphical and instructional construction guidance, thereby improving the practical applicability and scalability of research achievements.
- (5) Validation across diverse projects. The proposed scheduling model and solution algorithm are primarily validated using a single PB (four buildings, two tower cranes). Although three metaheuristic algorithms (PSO, GA, ABC) are compared to demonstrate relative performance, a rigorous cross-project and multi-case validation procedure is lacking. Consequently, the generalizability and robustness of the model across different project scales, building layouts, component types, and site operation conditions remain to be further assessed. Future research should systematically evaluate the proposed approach by collecting diverse prefabricated construction cases

with varying types and scales, and by integrating simulation and digital twin technologies. Such efforts would enhance the model's transferability and reliability in real-world engineering applications.

In light of the aforementioned limitations, future research will be closely aligned with practical industry demands, focusing on the following directions:

- (1) Develop an intelligent collaborative scheduling platform that integrates safety constraints. This platform will deeply integrate TC collision avoidance algorithms, real-time positioning and scheduling models, and constructs a multi TC collaborative operating system with security warning, obstacle avoidance, and dynamic adjustment functions. Combining UWB/GPS/IoT sensors to real-time sense the angle of the crane arm and the position of the lifted object, automatically decelerate, stop or replan in case of conflict, and forming a two-layer architecture of "offline pre-planning + online correction" with offline optimization models to achieve a balance between efficiency and safety.
- (2) Construct an integrated "supply chain-construction" scheduling model. Expanding the research scope to integrate multiple PCs factories, transportation fleets, and on-site TCs resources, a cross-factory, multi-building, and full-process collaborative scheduling model will be developed to enhance the overall efficiency of construction industrialization.
- (3) Investigate data-driven dynamic adaptive scheduling mechanisms. To address the rapidly changing conditions on construction sites, future research will explore the use of technologies such as the Internet of Things (IoT) and digital twins. This will enable the scheduling system to perceive dynamic information, including equipment status, weather changes, and task progress, in real time, and respond quickly with rescheduling. The goal is to transition from static, pre-planned scheduling to dynamic, adaptive real-time scheduling, significantly improving the system's robustness in real-world environments.
- (4) Promote the practicality and operability of algorithmic outcomes. Recognizing that even the most advanced algorithms may fail to be implemented if they are not understood and accepted by on-site personnel, we will strive to optimize the visualization of scheduling results and human-computer interaction design. By developing intuitive graphical interfaces and simplified operational instructions, complex optimization results will be transformed into specific guidance that is easy for on-site managers and tower crane operators to understand and execute. This will fundamentally enhance the practical applicability and operational feasibility of the research outcomes.
- (5) Address the validation limitation of a single project case. Future research will systematically apply the proposed scheduling model to multi-building with different building layouts, tower crane configurations, and component supply conditions. Combined with simulation and digital twin technologies, the model's generalizability and robustness will be rigorously tested, thereby providing a stronger evidence base for practical adoption in diverse engineering settings.

6. Conclusions

This study makes innovative contributions to the theory, methodology, and practice of TC scheduling in multi-building PCs: (i) Theoretical. For the first time, a collaborative optimization model is developed for the "multi-building, multi-crane, independent scheduling" scenario, revealing the coupling savings mechanism between supply point locations and hoisting sequences, thus filling a theoretical gap in joint decision-making. (ii) Methodological. A discrete sequence coding and decoding strategy using PSO is proposed, alongside an adjustable parameter system (α, β, γ) that captures operator skills and

site conditions, greatly enhancing the model's adaptability and robustness in dynamic environments. (iii) Practical. Validated through a case study, the model reduces the daily operating time of two TCs by 23.94% and 12.16%, respectively, achieving an overall cost saving of approximately 8.0%, thereby providing a quantifiable decision-support tool and lean management strategy for similar multi-building. The main conclusions are as follows:

- (1) The proposed model addresses the lack of systematic spatial planning in PC scheduling within lean construction. A mathematical model was established that considers the initial hook position, coordinates of supply and demand points, and three-dimensional motion times, accurately describing the tangential, radial, and vertical movements of the TC. The optimization results show that under independent scheduling, the total daily operating times of two TCs (TC₁ and TC₂) are reduced by 23.94% and 12.16%, respectively, compared with traditional experience-based scheduling, representing a total saving of 1.4 h. This method provides a quantifiable decision-making tool for lean scheduling in multi-building parallel construction scenarios.
- (2) The proposed model solves the combinatorial optimization problem of multi-task sequencing and path planning. The PSO algorithm was employed to solve the scheduling sequence, with comparative validation against GA and ABC. PSO achieved convergence after 378 iterations, demonstrating faster convergence speed and better stability. After optimization, the total daily operating cost of the two TCs decreased from ¥6291.87 to ¥5790.61, saving ¥501.25, which corresponds to an overall construction cost reduction of approximately 8.0%. This algorithmic framework can flexibly adapt to different operator skill levels (parameters α , β) and on-site environmental complexity (parameter γ), offering good scalability.
- (3) The proposed model achieves collaborative optimization of supply point locations and scheduling schemes. It simultaneously determines the optimal PC supply point coordinates and the hoisting task execution sequence, effectively reducing no-load movements and idle waiting time. The daily operating cost saving of ¥501.25 directly reflects the core lean construction principle of waste elimination. The methods and results presented in this study provide replicable and transferable management strategies and optimization bases for similar PBs involving multi-building parallel operations and multi-tower-crane independent scheduling.

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Abbreviations

The following abbreviations are used in this manuscript:

TC	Tower Crane
PBs	Prefabricated Buildings
PSO	Particle Swarm Optimization
PC	Prefabricated Component
GA	Genetic Algorithm
ABC	Artificial Bee Colony

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