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RESEARCH ARTICLE

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Intelligent planning of safe and economical construction sites: Theory and practice of hybrid multi objective decision making

Abstract Construction site layout planning (CSLP) involves strategically placing various facilities to optimize a project. However, real construction sites are complex, making it challenging to consider all construction activities and facilities comprehensively. Addressing multi-objective layout optimization is crucial for CSLP. Previous optimization results often lacked precision, imposed stringent boundary constraints, and had limited applications in prefabricated construction. Traditional heuristic algorithms still require improvements in region search strategies and computational efficiency when tackling multi-objective optimization problems. This paper optimizes the prefabricated component construction site layout planning (PCCSLP) by treating construction efficiency and safety risk as objectives within a multi-objective CSLP model. A novel heuristic algorithm, the Hybrid Multi-Strategy Improvement Dung Beetle Optimizer (HMSIDBO), was applied to solve the model due to its balanced capabilities in global exploration and local development. The practicality and effectiveness of this approach were validated through a case study in prefabricated residential construction. The research findings indicate that the HMSIDBO-PCCSLP optimization scheme improved each objective by 18% to 75% compared to the original layout. Compared to Genetic Algorithm (GA), the HMSIDBO demonstrates significantly faster computational speed and higher resolution accuracy. Additionally, in comparison with the Dung Beetle Optimizer (DBO), Particle Swarm Optimization (PSO), and Whale Optimization Algorithm (WOA), HMSIDBO exhibits superior iterative speed and an enhanced ability for global exploration. This paper completes the framework from data collection to multi-objective optimization in-site layout, laying the foundation for implementing intelligent construction site layout practices.

Keywords prefabricated construction, prefabricated component construction site layout planning (PCCSLP), construction efficiency, safety risk, hybrid multi-strategy improvement dung beetle optimizer (HMSIDBO)

1 Introduction

Prefabricated construction involves manufacturing prefabricated components in a factory, as opposed to traditional cast-in-place construction. This is followed by transporting and assembling the entire component or semi-assembled parts at the construction site (Tam et al., 2007). Currently, prefabricated construction offers advantages such as reduced construction waste, improved quality control, noise and dust reduction, higher health and safety standards, time and cost savings, decreased labor requirements, and lower resource consumption. It has been suggested as a primary method to achieve China's national urbanization goals (Monahan and Powell, 2011; The State Council, 2014). It is common for prefabricated construction projects to have limited spatial characteristics, with lifting equipment and prefabricated components occupying most of the construction site's space. This

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poses challenges in designing construction layout schemes. Inadequate layout and lifting of prefabricated components on the construction site can lead to disorganized construction operations, impacting construction efficiency, causing project delays, and potentially resulting in financial losses and safety risks (Yang et al., 2021a; Tatari, 2023; Zhang et al., 2023).

It is of utmost importance to carefully plan construction site layouts based on construction efficiency and safety risk. Construction site layout planning (CSLP) involves the strategic allocation of relevant facilities to enhance construction efficiency and reduce safety risks (Ning et al., 2019c). In the case of prefabricated assembly construction sites, the lifting of prefabricated components is a frequent and hazardous operation, often involving large-sized components with lifting weights ranging from 7 to 10 tons (Cao et al., 2015). Studies have shown that accidents commonly occur during the assembly phase of these prefabricated elements, accounting for a staggering 57% of accidents (Fard et al., 2017). Therefore, effective control of moving prefabricated components is crucial in mitigating safety risks. On actual construction sites, multiple tower cranes are often involved in simultaneous lifting operations. Given the repetitive nature of these tasks, even slight discrepancies in lifting operations can have significant impacts on both construction efficiency and safety. Consequently, considering the unique characteristics of prefabricated assembly construction sites, the establishment of a comprehensive Prefabricated Component Construction Site Layout Planning (PCCSLP) is of utmost importance in optimizing on-site construction management.

Scholars have extensively explored the layout challenges of prefabricated construction sites. Solutions to the CSLP problem are mainly categorized into mathematical programming methods and heuristic algorithms. However, mathematical programming methods are complex, time-consuming, and not suitable for large-scale projects and practical engineering applications (Aydemir et al., 2020). In contrast, heuristic algorithms rely on experience- and intuition-based problem-solving strategies, aiming to find optimal solutions without exhaustively exploring all possibilities. Their excellent generality, stability, and rapid convergence have made them increasingly popular in engineering applications. Recent research has focused on continuously improving various heuristic algorithms to determine the optimal layout of prefabricated component construction sites under multi-objective and multi-constraint conditions.

This study aims to enhance the planning of prefabricated modular construction sites by proposing a comprehensive framework for the spatial organization of prefabricated components and the arrangement of tower cranes. The objective of this initiative is to address the challenges associated with repetitive operations in the lifting process of prefabricated elements. To significantly reduce lifting duration and minimize risks associated with the hoisting of prefabricated components, a mathematical model has been developed. This model includes three objective functions and seven constraints. Additionally, an innovative heuristic algorithm has been utilized to optimize the placement of facilities, showcasing its effectiveness in densely populated sites where space is limited. The proposed methodology facilitates the integration of more realistic considerations in line with the actual progress of the project.

2 Literature review

2.1 Research on the layout of traditional cast-in-place construction sites

Over the past few decades, numerous researchers have focused on issues related to construction site layout planning. Site planning and layout are crucial tasks that involve determining the positions, sizes, and shapes of temporary facilities on-site (Tommelein et al., 1992). The primary principles guiding construction site layout planning are safety risks and construction efficiency (Xu and Li, 2012; Zhang and Hammad, 2012; Huang and Wong, 2015). In the context of traditional cast-in-place buildings, extensive research has been conducted to address the layout of temporary facilities and material stacking on construction sites. Sanad et al. (2008) proposed the use of actual route distances to measure distances between on-site facilities, taking into consideration safety and environmental factors. Ning et al. (2018a) developed a safety risk assessment model that involves factor identification, categorization, factor analysis, and assessment function design to assist site managers in accurately and comprehensively evaluating different site layout scenarios. Wang et al. (2015) focused on construction efficiency and developed a C-Building Information Model (BIM) mathematical model to determine construction site layout schemes that minimize transportation times.

2.2 Research on the layout of prefabricated construction sites

The lifting operations of prefabricated components are a crucial factor that greatly affects the efficiency of prefabricated construction (Hong et al., 2014). Therefore, the construction efficiency at prefabricated building sites is closely related to the positioning of tower cranes and prefabricated component supply points. The placement of the supply points and tower cranes is of utmost importance in the domain of prefabricated construction sites due to the significant hoisting operations involved with prefabricated components. A careful arrangement of tower crane locations helps prevent potential collisions between cranes, surrounding structures, mechanical vehicles, and laborers during lifting, slewing, and trolleying operations (Hwang, 2012). In terms of CSLP issues in prefabricated construction, a rational layout plan for the construction site is crucial for the safe operation of all on-site facilities. Tower cranes, being subject to more restrictions, are typically positioned first before allocating space for other facilities (Li et al., 2023), while the positioning of prefabricated component supply points at the construction site can be optimized using a lifting time model.

Studying CSLP issues solely from the perspectives of construction efficiency or safety risk fails to adequately address the complex and ever-changing conditions found on construction sites. In recent years, some researchers have begun to incorporate both construction efficiency and safety risk into multi-objective optimization studies. However, current research on CSLP primarily focuses on determining the layout of temporary facilities during the pre-construction phase of cast-in-place construction. There is limited research on the storing and inventory phase of prefabricated components in assembly construction, which accounts for only 11% of the studies reviewed (Wang et al., 2019). Additionally, objective methods are rarely used to define the stacking locations and installation of prefabricated components in prefabricated construction.

In the domain of site planning for modular construction, various researchers have made notable contributions. Lu and Zhu (2021) used the NSGA-II algorithm to explore site layout optimization, considering hoisting efficiency, safety risks, and transportation costs. Yang et al. (2022) developed an integrated framework for modular construction site layout that combines BIM and optimization strategies using the Dynamo visual programming platform. This approach, validated through the application of Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) algorithms, resulted in reductions in transportation and time costs. Zhang and Yu (2021) addressed dynamic layout challenges of prefabricated component sites, utilizing the PSO algorithm within an optimization framework to minimize project duration. Yao et al. (2023) improved the effectiveness of the heuristic algorithm in tackling modular construction site layout problems by introducing an enhanced multi-population constrained MPC-NSGA-II algorithm. However, a review of the literature reveals a significant research gap in understanding the relative positioning of different types of modular prefabricated components and tower cranes. Previous research primarily focuses on temporary facilities on prefabricated construction sites, overlooking the impact of prefabricated components on overall construction efficiency and safety. Furthermore, the combination of site constraints, component constraints, construction efficiency, and safety risk is not adequately addressed in existing studies on PCCSLP.

Building upon previous literature reviews, it is evident that few scholars have examined the distinctions of prefabricated construction sites and conducted research on the PCCSLP. This paper contributes to prior research on CSLP for traditional construction sites by integrating a model that optimizes lifting times at prefabricated component supply points, along with a safety risk model, into the framework of the PCCSLP. Setting itself apart from earlier studies, this work introduces the concept of overlapping work areas of multiple tower cranes as a crucial factor in evaluating safety risks. It also represents the first application of the Hybrid Multi-Strategy Improvement Dung Beetle Optimizer (HMSIDBO) algorithm for heuristic algorithm selection, enabling precise arrangement of various prefabricated components's stacking positions within the site's temporary facilities layout. Consequently, it addresses a significant research gap. The proposed model focuses on the effects of different choices of prefabricated component supply points on the overall construction layout in prefabricated construction sites.

2.3 Research on heuristic algorithms for solving CSLP problems

The challenge posed by construction site layout issues falls under the category of non-deterministic polynomial (NP) complexity problems (Ning and Liu, 2011; Kaveh et al., 2018). Previous research has commonly relied on GIS methods, mathematical planning models (Yi et al., 2018), integer programming approaches (De Santis et al., 2020; Ji and Leite, 2020; Riga et al., 2020), linear programming (Aydemir et al., 2020), and traditional heuristic algorithms such as genetic algorithms (Said and El-Rayes, 2013), artificial bee colony algorithms (Yahya and Saka, 2014), Whale Optimization Algorithm (Zavari et al., 2022), and particle swarm optimization algorithms (Yang et al., 2022). These methods are used to accurately solve single-objective or multi-objective optimization functions and generate feasible layout solutions. Taking into account the global search space and regional search strategies, the enhanced Dung Beetle Optimizer (DBO) algorithm is applied to the PCCSLP problem due to its faster convergence speed, stronger solution precision, and more balanced global search capabilities.

To address the deficiencies in existing research and tackle the PCCSLP problem, this paper explores the integration of construction efficiency and safety risks of prefabricated components into the study of assembly construction site layout. The objective is to enhance the layout of prefabricated construction sites. The paper begins by analyzing the safety risks, construction efficiency, and dynamic constraints associated with PCCSLP, establishing the theoretical foundation for this problem. Next, the paper proposes the HMSIDBO-PCCSLP model, based on an improved DBO algorithm. This model incorporates three minimization objectives: the horizontal transportation time of tower cranes, the horizontal path length of component lifting, and the overlapping working areas of multiple tower cranes. Additionally, the paper outlines four boundary constraints and three overlapping constraints to define the conditions of the proposed model. The model is designed to consider site constraints and component constraints, with the aim of reducing construction risks while maximizing construction efficiency. To demonstrate the viability of the proposed method for addressing PCCSLP, a case study is presented in the final part of the paper. This study contributes significantly to the field by offering mathematical modeling and algorithmic developments for solving the HMSIDBO-PCCSLP problem. The approach presented in this paper focuses on maximizing project construction efficiency while simultaneously minimizing safety risks, harnessing the advantages of prefabricated construction through effective on-site coordination and layout.

In most cases, compliance with relevant technical standards is necessary for the arrangement of construction sites. Project managers typically organize the layout of temporary facilities based on their practical knowledge. However, such planning often struggles to accurately predict construction efficiency, safety risks, and spatial utilization in actual project operations. This can result in disorganized storage, overcrowded site layouts, and subsequent delays to the overall construction schedule. Existing literature rarely considers the distinctions of modular construction sites or investigates the PCCSLP. Building upon previous research on the CSLP, this paper proposes a model that integrates an optimization model for the hoisting time of prefabricated component supply points with a safety risk model into the PCCSLP. The proposed model focuses on the impact of different choices for the locations of prefabricated component supply points and tower cranes on the overall layout of modular construction sites, aiming to address the research gap in the layout of prefabricated building construction sites. The development of a PCCSLP model, tailored for scenarios prevalent in prefabricated construction and characterized by a high volume of on-site prefabricated component lifting operations, represents a new approach in theory. In practice, the model's effectiveness was validated through its application to two prefabricated residential projects, and the solution provided by the HMSIDBO algorithm demonstrates the feasibility of the model.

3 Methodology

In the layout planning of prefabricated construction sites, the high frequency of component storage yards and the utilization of vertical transportation machinery can amplify differences in distance, cost, and safety risks, even when the placement positions are very close. This amplification occurs due to the repetitive operations of high-frequency processes, ultimately affecting the project's schedule and profitability. This chapter establishes a theoretical framework for balancing construction safety and efficiency in the on-site storage of prefabricated components based on the principles of construction efficiency, safety risks, and facility boundary constraints. It combines an HMSIDBO algorithm that is more suitable for the PCCSLP problem.

3.1 Theory of PCCSLP model

3.1.1 Construction efficiency

The efficiency of material transport, personnel mobility, and information dissemination on construction sites has a direct impact on production effectiveness and profitability. In relation to the CSLP, there are three factors that are crucial to construction efficiency: the transportation of production materials, the efficient flow of personnel, and production efficiency. In the context of prefabricated construction sites, the efficiency of tower crane hoisting significantly affects the construction efficiency of prefabricated components (Hong et al., 2014). This efficiency primarily depends on the duration of the hoisting process. During the assembly process, prefabricated components are horizontally shifted to their designated assembly positions using tower crane hoisting and then vertically assembled to meet specific requirements. Furthermore, the determination of vertical transport time is based on the difference in component stacking height and the height of the target installation point, as well as the difference in distance to the target installation point. Vertical transport time is strongly correlated with elevation difference and is not influenced by planar position coordinates. The positioning of component storage yards determines the initial transport position of the tower crane and also governs the time within the horizontal range of movement. During the construction process, it is possible to break down the hoisting motion. The mathematical model developed by Choi and Harris (1991) divides the entire hoisting motion into vertical and horizontal motions, as shown in Eqs. (1) and (2):

$$T_n = T_{\mathrm{vn}} + T_{\mathrm{hn}}, \tag{1}$$

$$T_{vn} = T_{\mathrm{uvn}} + T_{\mathrm{lvn}}, \tag{2}$$

where T_n = the time taken by tower crane n to hoist prefabricated components between the supply point and the demand point; T_{hn} = the horizontal transportation time of tower crane n; T_{vn} = the vertical transportation time of tower crane n; T_{uvn} = The vertical hoisting time when tower crane n is unloading; and T_{lvn} = the vertical lifting time when tower crane n is loading.

3.1.2 Safety risk

The limited space at the construction site necessitates careful utilization and layout considerations to prevent collisions among workers, materials, and machinery or to minimize on-site disturbances. Therefore, when planning the layout of the prefabricated component storage area, it is essential to take into account the other facilities within the construction site and strive to minimize congestion while maintaining a specified safety distance. The vertical lifting speed of the tower crane is closely related to the lifting capacity, which, in turn, correlates with the lifting radius (Hu et al., 2023). For example, when the load radius is less than a certain distance, the tower crane maintains a favorable load state. However, when the load radius exceeds a certain distance, the crane's load state gradually deteriorates, indicating an increased safety risk during hoisting operations (Jiang and Jiang, 2023). Additionally, as the overlapping working areas of multiple tower cranes increase, there is a higher likelihood of collisions during crane lifting, slewing, and luffing processes. The risk zones for multi-tower crane operations are outlined as shown in Fig. 1. The "L" region is defined as the area situated behind the tower crane, designated as a low-risk zone. Conversely, the "M" region represents the operational area of each crane, identified as a medium-risk zone. The "H" region outlines areas where the operational zones of multiple cranes intersect, marking these as high risk (El-Rayes and Khalafallah, 2005; Huang et al., 2021).

Accidents tend to occur while hoisting prefabricated components in prefabricated construction (Fard et al., 2017). The precarious conditions of prefabricated components during the hoisting process also pose significant safety risks, potentially arising from operational errors by construction personnel, which lead to an inadequate support system for these components. Such deficiencies can cause safety incidents, including slippage or compression of the components during lifting or transportation. Tower cranes serve as the pivotal link connecting various facilities at the construction site, and the higher the frequency of crane hoisting, the greater the potential for conflicts or collisions among materials, personnel, and equipment. Longer travel distances between facilities increase the likelihood of accidents, such as falls from heights and collisions between multiple tower cranes. Therefore, the control of travel distances for resource transport is of significant importance in reducing safety risks in prefabricated construction. When planning the storage yard, it is recommended to minimize the lifting paths that cross transportation routes or work areas and to reduce the extent of hazardous zones to the greatest possible degree. The travel distance for resource transport is related to the overlapping working area of multiple tower cranes, as expressed in Eqs. (3) and (4):

$$D_n = D_w + D_r, \tag{3}$$

$$S_o = S_1 \cap S_2, \tag{4}$$

where D_n is the travel distance for resource transport; D_w is the rotation distance of the jib; D_r is the travel distance of the trolley; S_o is the overlapping working area of multiple tower cranes; S_1 is the working area of the first tower crane; S_2 is the working area of the second tower crane.

3.1.3 Facility boundary constraints and overlap constraints

In the prefabricated construction process, various components are transported from factories to the construction

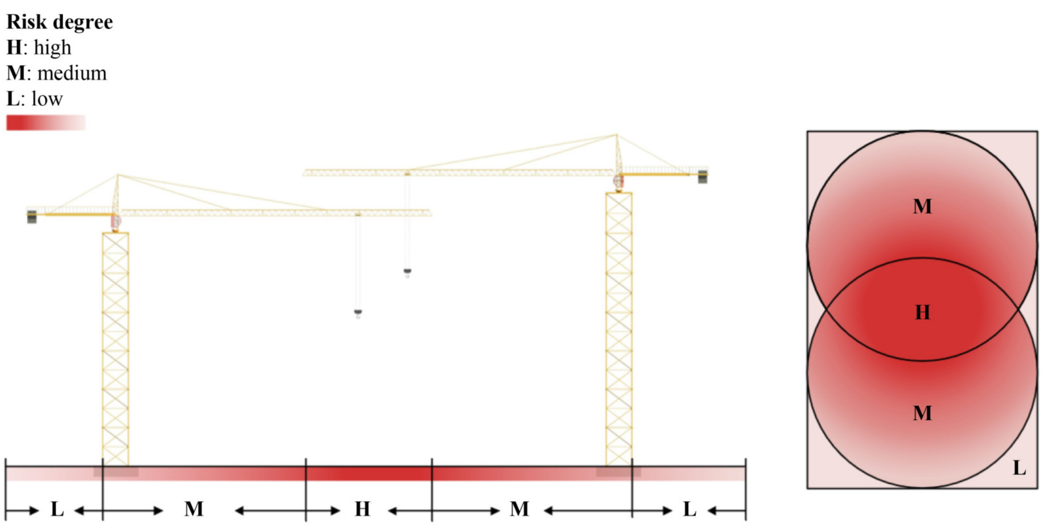


Fig. 1 The risk zones for multi-tower crane operations.

site. When loading and transporting these components, it is important to consider the dimensions of the transport vehicles and their maximum payload capacity. Upon arrival at the construction site, efforts must be made to minimize storage space while arranging everything in a rational manner. To achieve this, certain optimization rules should be followed. Additionally, the storage yard should be treated as a temporary warehouse, with all facilities and equipment integrated within a fixed space. These facilities should be placed at reasonable distances from each other and should not overlap. Figure 2 demonstrates examples of layout situations that do not comply with boundary constraints and overlapping constraints. Figure 2(a) shows scenarios where temporary facilities overlap, Fig. 2(b) depicts intersections between temporary facilities and the main structure under construction, and Fig. 2(c) displays instances where temporary facilities extend beyond the boundaries of the construction site. The internal layout directly impacts the size of the warehouse, the efficiency of loading and unloading goods, and ultimately, the overall spatial utilization of the construction site. Equation (5) can be used to restrict the placement of facilities within the construction site:

$$E_1, E_2, E_3, \ldots, E_n \subseteq S_c, \tag{5}$$

$$E_i \cap E_n = \varnothing, \tag{6}$$

where $E_1, E_2, E_3, \ldots, E_i, E_n$ denote all facilities within the construction site and S_c denotes the extent of the construction site.

3.2 DBO Algorithm Improvement

The DBO algorithm is employed to solve complex combinatorial problems and is a population-based general search technique. Inspired by the behaviors of dung beetles, such as rolling balls, dancing, foraging, stealing, and reproducing (Zhang and Zhu, 2023), this algorithm has been successfully applied to various engineering design issues by Xue and Shen (2023), validating its practical applicability. Experimental results confirm that the DBO algorithm effectively addresses real-world application problems. Therefore, utilizing the DBO algorithm to solve the CSLP problem under multi-objective functions is a well-founded research endeavor with significant potential.

However, despite its powerful optimization capability and fast convergence speed, the DBO algorithm has a drawback in terms of an imbalance between global exploration and local exploitation. This makes it susceptible to local optima and results in relatively weak global exploration ability. To enhance the search performance of DBO, this chapter introduces three strategies for improving the algorithm, resulting in the HMSIDBO algorithm. The original DBO algorithm struggles to achieve a harmonious balance between exploration and exploitation phases. HMSIDBO addresses this imbalance by incorporating the Bernoulli mapping strategy, integrating the Levy flight strategy (Cui et al., 2022), and introducing the T-distribution perturbation strategy (Yang et al., 2021b). This section will provide specific details about these strategies.

3.2.1 Bernoulli mapping strategy

Research conducted by Saito and Yamaguchi (2016) has demonstrated that the Bernoulli mapping exhibits uniform traversal and convergence properties, making it suitable for initializing chaotic populations. Through well-designed experiments, they have shown that the Bernoulli

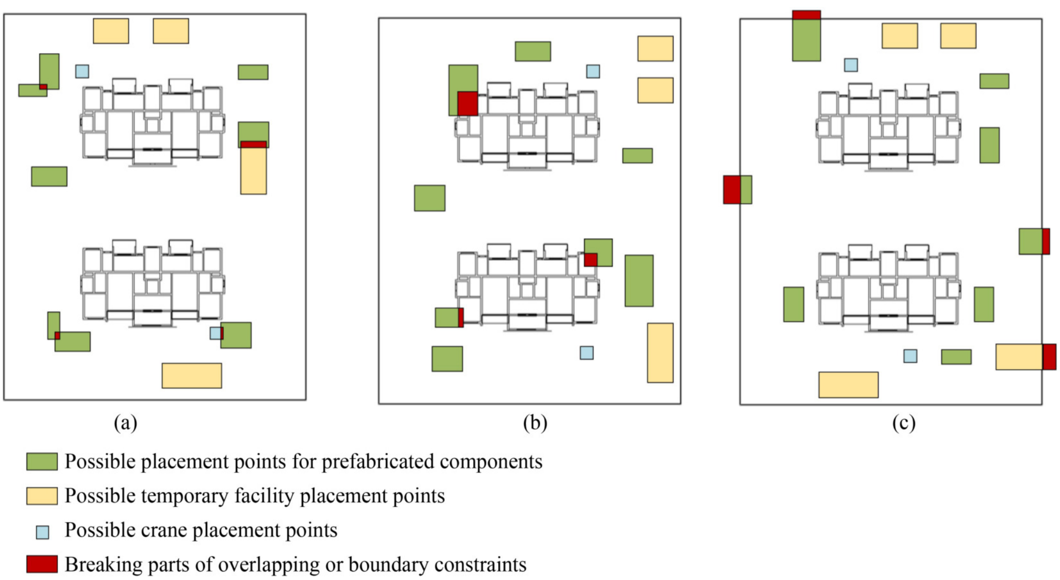


Fig. 2 Layout situations that do not meet boundary and overlapping constraints.

mapping can be utilized to generate initial populations for optimization algorithms. This paper employs the Bernoulli mapping to initialize the positions of the dung beetle individuals. Initially, the obtained values are projected into the chaotic variable space using the Bernoulli mapping relationship. Subsequently, the generated chaotic values are mapped to the initial algorithm space by linear transformation, and the beetle position shown in Fig. 3 is initialized. The specific expression of the Bernoulli mapping is given by Eq. (7):

$$Z_{k+1} = \begin{cases} \dfrac{Z_k}{1-\rho} & 0 \leqslant Z_k \leqslant 1-\rho, \\ \dfrac{Z_k - 1 + \rho}{\rho} & 1-\rho \leqslant Z_k \leqslant 1, \end{cases} \tag{7}$$

where Z_k represents the current value generated for the k-th generation of the chaotic sequence, ρ is the mapping parameter, and $\rho \in (0,1)$. Through experimentation in this paper, it has been observed that when ρ is situated near 0.5, better traversal properties can be achieved.

3.2.2 Levy flight strategy

In the later iterations of the original DBO algorithm, the rapid assimilation of dung beetle individuals leads to the quick convergence of the population around the current best position, with values close to the optimal solution. Consequently, if the current best position is not the global optimum, the dung beetle population clusters around it for searching, preventing the discovery of the true global optimum and causing search stagnation. To address this issue, after updating the positions of dung beetle individuals, a Levy flight is performed to update the individual positions once again. This involves calculating the objective function values for candidate individual positions, aiming to break free from local optima and enhance search capabilities. The expression for the Levy flight update position is given by Eq. (8):

$$X(k+1) = X(k) + \alpha \oplus \text{Levy}(\lambda), \tag{8}$$

where α is the step size control factor, which is set to 1; $\oplus$ represents vector operations; and $\text{Levy}(\lambda)$ denotes step sizes following the Levy distribution.

3.2.3 *t* distribution perturbation strategy

In the *t* distribution, as the degrees of freedom (n) decrease, the shape of the curve becomes flatter, the central part of the curve becomes lower, and the tails on both sides of the curve become more pronounced. Utilizing the *t*-distribution perturbation to modify the positions of dung beetle individuals introduces variability in the population. Subsequently, the objective function values for the perturbed dung beetle individuals are updated, and the updated values are compared to the best function value from the previous generation. If the results are superior, the current best value is updated. The expression for the T-distribution perturbation is provided by Eq. (9):

$$x_i^t = x_i + x_i \cdot t(iter), \tag{9}$$

where x_i^t is the new position of the *i*-th dung beetle in the perturbed population; x_i is the position of the individual before perturbation; $t(iter)$ is the value from the *t*-distribution, with degrees of freedom equal to the iteration count. During the early stages of algorithm iteration, when the *iter* value is small, the results generated by the *t*-distribution function closely approximate Cauchy perturbation. This yields strong global search capabilities. In the later stages, when the *iter* value is relatively large, the perturbation becomes similar to Gaussian perturbation, which provides effective local search capabilities. The

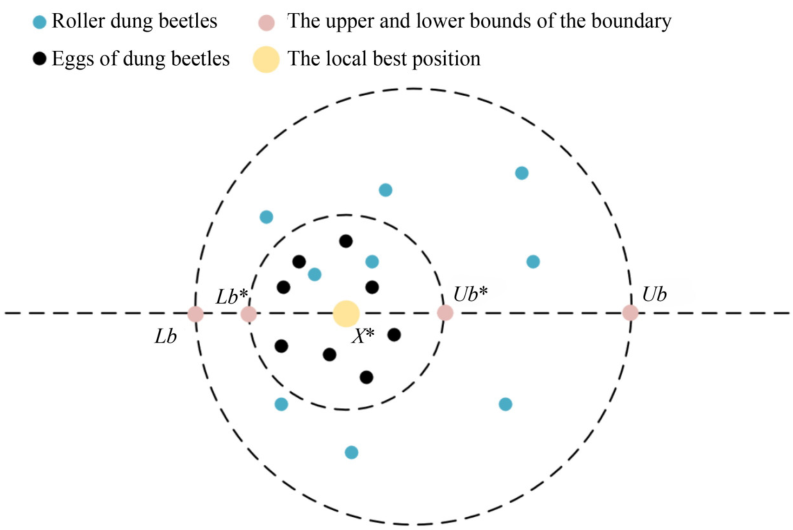


Fig. 3 Bernoulli mapping strategy initializes the position of dung beetles.

search mode combining Levy flight and T-distribution perturbation strategy is shown in Fig. 4. This refinement enhances the algorithm's search precision.

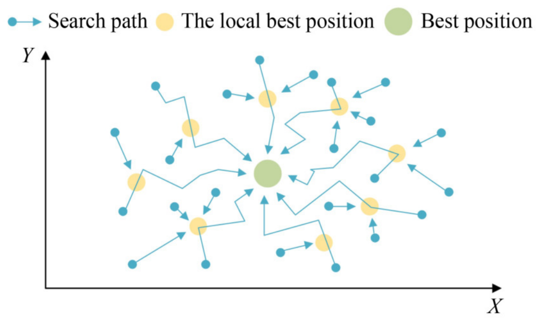


Fig. 4 The search mode of combining Levy flight with *t*-distribution perturbation strategy.

The HMSIDBO algorithm's specific flowchart is visually presented in Fig. 5.

4 HMSIDBO-PCCSLP modeling

In accordance with the methodological analysis presented in the previous chapter, this study proposes the multi-objective layout system framework for prefabricated components construction site layout planning based on the HMSIDBO algorithm, as shown in Fig. 6. The framework consists of three main components: the PCCSLP methodology, the HMSIDBO-PCCSLP mathematical model, and the application of the HMSIDBO-PCCSLP optimization process.

Within this framework, the initial step involves constructing the methodological analysis for factors influencing PCCLSP construction efficiency, safety risks, and facility boundary constraints. A parameterized modeling approach is employed to establish the PCCSLP model. The HMSIDBO algorithm is utilized to balance global exploration and local exploitation capabilities. The quantification of factors and constraints is carried out to align with the specific needs of prefabricated construction, resulting in the establishment of the mathematical model for HMSIDBO-PCCSLP.

4.1 Assumption

The following assumptions are considered when developing a CSLP model for application in prefabricated construction.

1) It is assumed that the construction of components is carried out using pre-designed buildings, temporary facilities, and roads in a well-planned layout. There are no spatial conflicts among these elements, and there is sufficient space on the site to store prefabricated components.

2) The demand levels for each respective demand area and supply area are predetermined. For instance, the total number of elevators, the number of elevators per batch, maximum loading capacity, and unloading delays are all known in advance.

3) To strike a balance between practicality and computational complexity, all facilities are assumed to have regular rectangular shapes that can be defined using center point coordinates, length, and width.

4) Each tower crane is allocated to only one pair of demand and supply areas, and prefabricated components must be situated within the permissible weight radius determined by the crane's jib length and lifting capacity.

5) To ensure computational consistency, all distances between facilities are calculated using the Euclidean algorithm.

4.2 Minimum running time of the hook

The process of lifting prefabricated components primarily involves hoisting, placing, connecting, or securing the elements. The installation of each prefabricated component typically comprises three stages. The first stage involves component preparation, such as bundling and hooking, prior to being lifted by the tower crane. The second stage includes the actual hoisting process, during which the tower crane vertically lifts and horizontally moves the component. The final stage occurs after the component has been lifted to its designated point, and involves placing, connecting, and securing the component.

A mathematical model has been developed to minimize the hoisting time for prefabricated components, based on an analysis of the construction layout on-site. The spatial dimensions of prefabricated component supply points and demand points can be extracted from architectural and construction site design drawings or BIM. Factors such as site size, tower crane arm length, their capacity radii, and other relevant conditions can guide the selection of suitable locations for storage yards.

The objective of the mathematical model in this study is to calculate the locations of supply points and cranes, starting from predetermined points, in order to determine the shortest time required for hook transportation. Equations (10)–(12) outline the total hoisting time and the associated constraints, where F_1 represents the minimum time required for lifting all components from supply point j to demand point l through crane n.

$$F_1 = \min TC = \min \sum_{n=1}^{N} \sum_{j=1}^{J} \sum_{l=1}^{L} T_{jl}^{n} Q_{jl}^{n}, \tag{10}$$

$$\sum_{n=1}^{N} \sum_{j=1}^{J} Q_{jl}^{n} \leqslant Q_{S_j}, \tag{11}$$

$$\sum_{n=1}^{N} \sum_{j=1}^{J} Q_{jl} = Q_{D_l}, \tag{12}$$

where TC is the total crane time; N is the number of tower cranes; J is the number of supply points; L is the

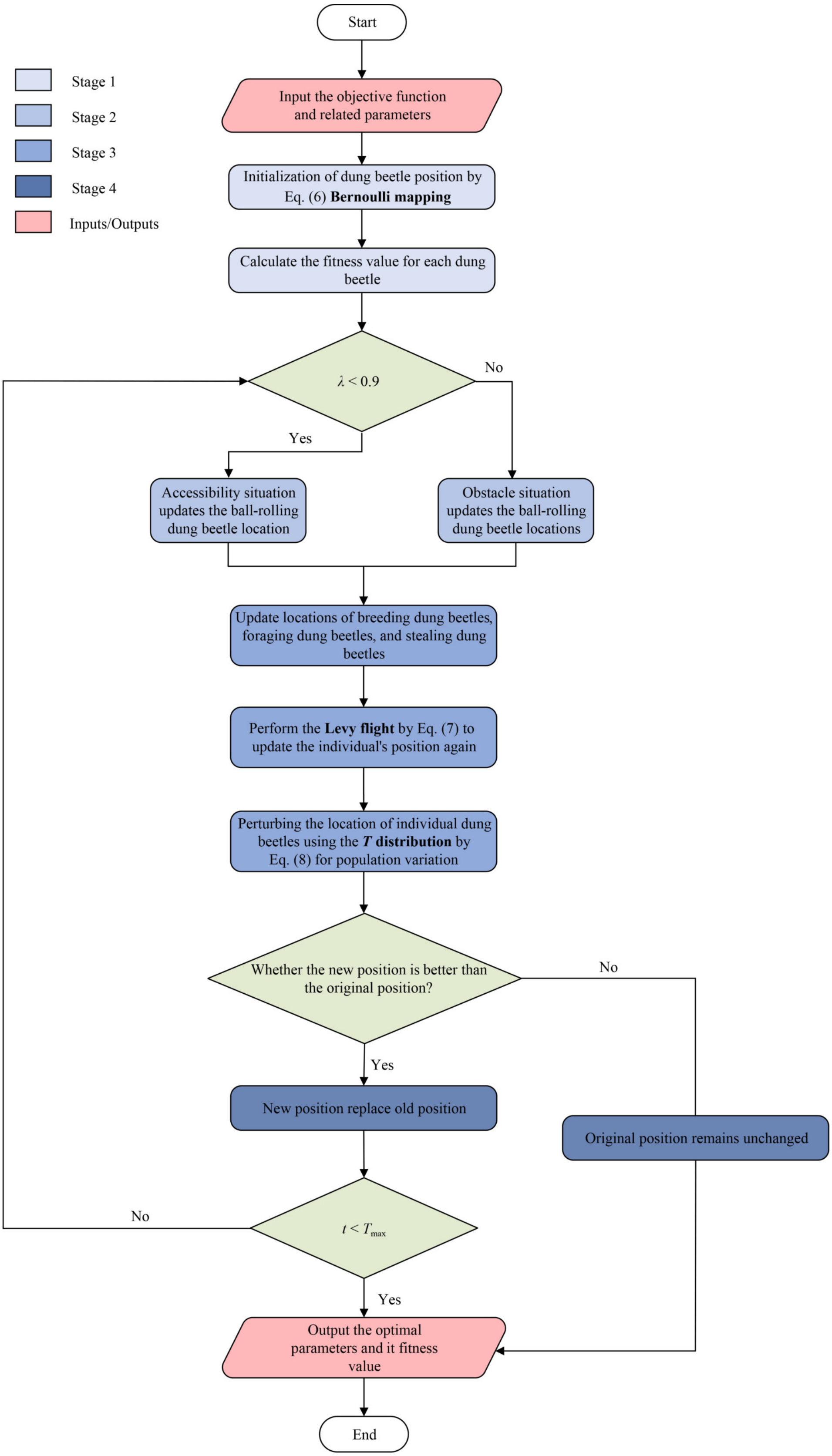


Fig. 5 Diagram of the HMSIDBO algorithm.

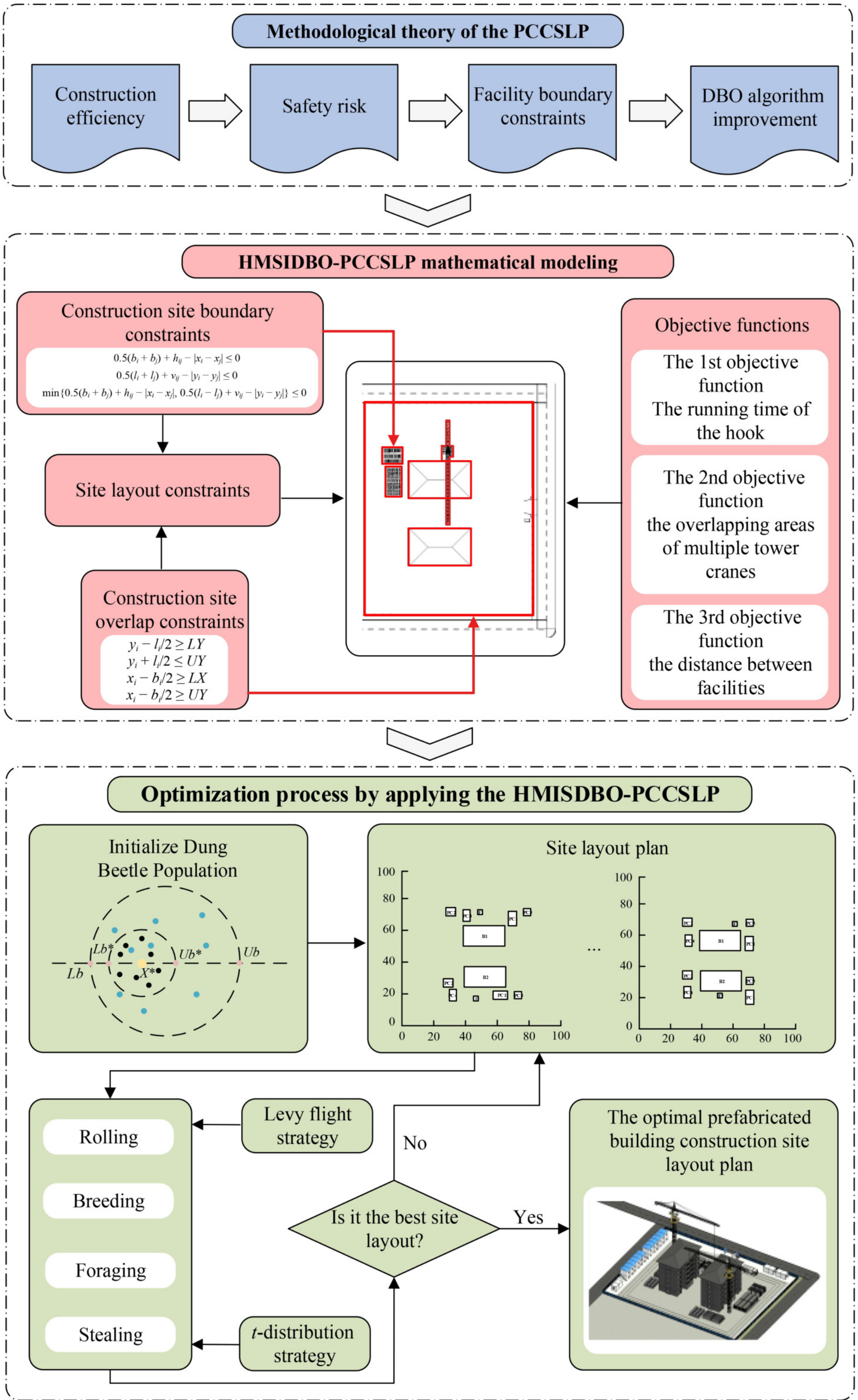


Fig. 6 Framework of multi-objective layout system based on HMSIDBO-PCCSLP.

number of demand points; T_{jl}^{n} is the travel time of the nth crane from the jth supply point (S_j) to the lth demand point (D_l); Q_{jl}^{n} is the material flow quantity from S_j to D_l for the nth tower crane; Q_{S_j} is the total supply capacity of S_j; Q_{D_l} is the total demand for D_l.

The process of hoisting a prefabricated component from a supply point to a demand point using a tower crane involves vertical lifting, horizontal transportation, loading at the supply point, and unloading at the demand point. Figures 7 and 8 depict the horizontal, vertical, and

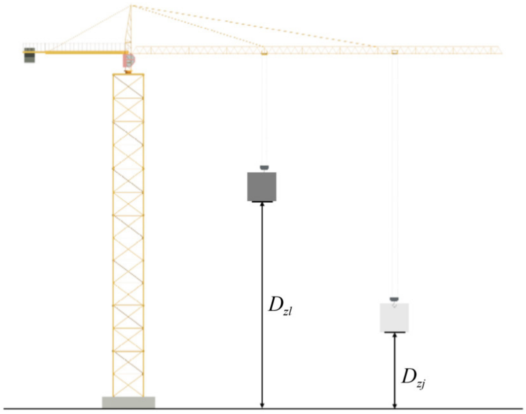


Fig. 7 Vertical transportation distance of the hook.

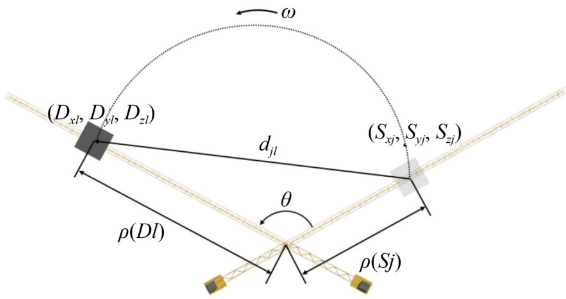


Fig. 8 Movement of the hook during transportation.

radial movements of the hoist hook, which collectively determine the total time required to complete all hoisting tasks. Here, (S_{xj}, S_{yj}, S_{zj}) and (D_{xl}, D_{yl}, D_{zl}) respectively denote the locations of the prefabricated component supply point and the prefabricated component demand point for a given task. The tower crane's position is symbolized by (C_{xn}, C_{yn}, C_{zn}). The comprehensive hoisting time for each prefabricated component can be calculated using an adjusted mathematical model that takes into account specific site conditions and skills. Equations (13)–(23) outline the hoisting time for a prefabricated component from supply point j to demand point l using tower crane n.

$$\rho(Dl) = \sqrt{(D_{xl} - C_{xn})^2 + (D_{yl} - C_{yn})^2}, \tag{13}$$

$$\rho(Sj) = \sqrt{(S_{xj} - C_{xn})^2 + (S_{yj} - C_{yn})^2}, \tag{14}$$

$$d_{jl} = \sqrt{(D_{xl} - S_{xj})^2 + (D_{yl} - S_{yj})^2}, \tag{15}$$

$$0 \leqslant \arccos\theta \leqslant \pi,$$

$$T_w^n = \frac{1}{V_w^n} \cdot \arccos\left[\frac{d_{jl}^2 - \rho(Dl)^2 - \rho(Sj)^2}{2 \cdot \rho(Dl) \cdot \rho(Sj)}\right], \tag{16}$$

$$T_\alpha^n = \frac{|\rho(S_j) - \rho(D_l)|}{V_\alpha^n}, \tag{17}$$

$$T_z^n = \frac{|D_{zj} - D_{zl}|}{V_z^n}, \tag{18}$$

$$T_\beta^n = \max(T_\alpha^n, T_w^n) + \alpha \cdot \min(T_\alpha^n, T_w^n), \tag{19}$$

$$T_{jl}^n = \max(T_\beta^n, T_z^n) + \beta \cdot \min(T_\beta^n, T_z^n), \tag{20}$$

$$T_{jl}^{n'} = \max(T_\beta^n, T_z^n) + \beta \cdot \min(T_\beta^n, T_z^n) + T_P + T_U, \tag{21}$$

$$Q_{jl}^n = \frac{Q_l}{P_j}, \tag{22}$$

$$TC = \sum_{n=1}^{N} \sum_{j=1}^{J} \sum_{l=1}^{L} T_{jl}^{n'} Q_{jl}^n, \tag{23}$$

where $\rho(Dl)$: the distance in the horizontal direction from tower crane n to component demand point l;

$\rho(S_j)$: the distance in the horizontal direction from tower crane n to component supply point j;

d_{jl}: the horizontal distance from component demand point l to component supply point j;

T_w^n: the duration for the tower crane's trolley to move tangentially;

T_α^n: the time required for the trolley of the tower crane to perform radial motion;

T_z^n: the vertical lifting time of the hook when lifting the component from supply point j to demand point l using tower crane n;

T_β^n: the horizontal movement time of the hook when lifting the component from supply point j to demand point$l$ using tower crane n;

T_{jl}^n: the horizontal movement time required to lift the component from the pre-placed supply point j to demand point l using tower crane n;

$T_{jl}^{n'}$: the hoisting time required to lift the component from the pre-placed supply point j to demand point l using tower crane n;

T_P: the loading time for hoisting the component from supply point j using tower crane n;

T_U: the total unloading time for hoisting the component at demand point l using tower crane n;

Q_{jl}^n: the number of hoisting operations required to lift the component from the pre-placed supply point j to demand point l using tower crane n;

Q_l: the total quantity of components at demand point l;

P_j: the single hoisting capacity.

4.3 Security risk minimization objective

The hazards associated with prefabricated construction include falling objects from heights, inadequate safety protection systems, unsafe prefabricated components, and equipment malfunctions (Liu and Cui, 2020). To enhance the safety of tower cranes during the hoisting process and reduce the risk of accidents involving multiple tower cranes and falling objects, this study establishes a safety risk model. The purpose of this model is to determine the optimal positions for prefabricated components and tower cranes, aiming to minimize the occurrence of collisions between tower cranes and falling objects during hoisting. The model consists primarily of two parts: the overlapping working areas of multiple tower cranes and the horizontal path length for component lifting.

To avoid collisions between cranes during lifting, slewing, and rotation, it is crucial to minimize the overlapping working areas of the tower cranes in multi-tower crane construction. The Eq. (24) represents the overlapping areas of multiple tower cranes:

$$F_2 = \min \sum_{n=1}^{N} \sum_{m=1}^{M} S_{nm}, \tag{24}$$

where S_{nm} is the overlapping working area between tower crane n and tower crane m.

Interactions among temporary facilities in the construction site layout have a considerable influence on the safety risk level of the site (Ning et al., 2018b). Therefore, it is essential to consider the influence of component transportation on the movement of personnel and equipment. Increased hoisting frequency of tower cranes raises the likelihood of conflicts or collisions involving materials, personnel, and equipment (Xu and Li, 2012). As the transportation distance for hoisting prefabricated components increases, the number of intersections and overlapping points along the travel route also increases. Consequently, the intersections or overlaps depend on the movement distances between facilities at the demand points and supply points (El-Rayes and Khalafallah, 2005). Figure 9 illustrates the potential areas for falling objects during the process of hoisting and transportation of prefabricated components.

There is a positive correlation between the risk level and the distance between facilities. Equations (25)–(28) depict this relationship:

$$F_3 = \min \sum_{j=1}^{J} \sum_{l=1}^{L} d_{jl}, \tag{25}$$

$$d_{kj} = d_w + d_r, \tag{26}$$

$$d_r = \sqrt{(D_{xl} - S_{xj})^2 + (D_{yl} - S_{yj})^2}, \tag{27}$$

$$d_w = \min(\rho(Dl), \rho(Sj)) \cdot \arccos\left(\frac{d_r^2 - \rho(Dl)^2 - \rho(Sj)^2}{2 \cdot \rho(Dl)^2 \cdot \rho(Sj)^2}\right), \tag{28}$$

where d_{kjj} refers to the horizontal transport distance from storage yard location j (material supply point S) to position l (material demand point D), which can be divided into the jib rotation distance (d_w) and trolley movement distance (d_r).

4.4 Boundary and overlap constraints

To ensure that temporary facilities do not overlap with each other or with the planned construction, the generated solutions are subjected to boundary constraints and overlap constraints (El-Rayes and Khalafallah, 2005).

1) Boundary constraints: In this model, boundary constraints are implemented to ensure that all facilities operating within the construction site are located within the site's boundaries. The following boundary conditions are established based on Eqs. (29)–(32):

$$\frac{y_i - l_i}{2} \geqslant LY, \tag{29}$$

$$\frac{y_i + l_i}{2} \leqslant UY, \tag{30}$$

$$\frac{x_i - b_i}{2} \geqslant LX, \tag{31}$$

$$\frac{x_i + b_i}{2} \leqslant UX, \tag{32}$$

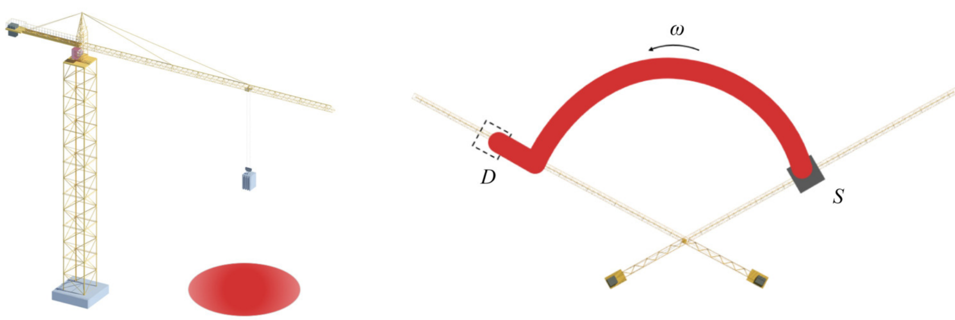


Fig. 9 Hazardous area for falling objects under the lifting path.

where x_i and y_i are the coordinates of each facility, UY and LY represent the upper and lower boundaries of the construction site on the Y-axis, and UX and LX represent the upper and lower boundaries of the construction site on the X-axis. b_i and l_i are the horizontal and vertical dimensions of facility i.

2) Overlap constraints: The following constraints are set from Eqs. (33)–(35) for overlap constraints.

$$0.5(b_i + b_j) + h_{ij} - |x_i - x_j| \leqslant 0, \tag{33}$$

$$0.5(l_i + l_j) + v_{ij} - |y_i - y_j| \leqslant 0, \tag{34}$$

$$\min\{0.5(b_i - b_j) + h_{ij} - |x_i - x_j|, 0.5(l_i - l_j) + v_{ij} - |y_i - y_j|\} \leqslant 0. \tag{35}$$

Equations (33) and (34) impose horizontal and vertical constraints on the facilities, while Eq. (35) ensures that only one of the two constraints will hold. h_{ij} and v_{ij} represent the minimum allowable horizontal and vertical distances between facility i and j.

5 Case study

To validate the practicality and efficiency of the proposed modeling method for prefabricated buildings, two real-world projects were chosen to show the multi-objective layout system framework for stacking prefabricated components at construction sites, utilizing the HMSIDBO algorithm. This study primarily focuses on the layout challenges faced by construction sites with multiple tower crane operations. Therefore, both projects will be executed using the multi-tower crane lifting method. This section provides a description and representation of the projects, as well as the output results from the HMSIDBO algorithm, along with a comparison to the results obtained from the DBO, GA, PSO, and Whale Optimization Algorithm (WOA) .

5.1 Representation of case problems

Two assembly-based architectural projects located in Sanya, China, were selected to illustrate and validate the multi-objective layout planning approach based on HMSIDBO-PCCSLP. The first project involves the third phase of a residential complex, comprising two six-story buildings, with an assembly rate of 52.16%. Adjacent to the construction site, there is a 10-m-wide thoroughfare to the east. Taking into account the conditions of the surrounding road network, vehicular and mechanical access is permitted through the eastern gateway. The second project pertains to the fourth phase of the same residential development, situated west of the third phase. This location allows for vehicular and machinery access to the construction site through the main route on the west side. The locations and dimensions of various facilities within the construction site, as well as the installation positions for the four types of prefabricated components, have been retrieved from the BIM of the two buildings. An overview of the site layout is presented in Fig. 10.

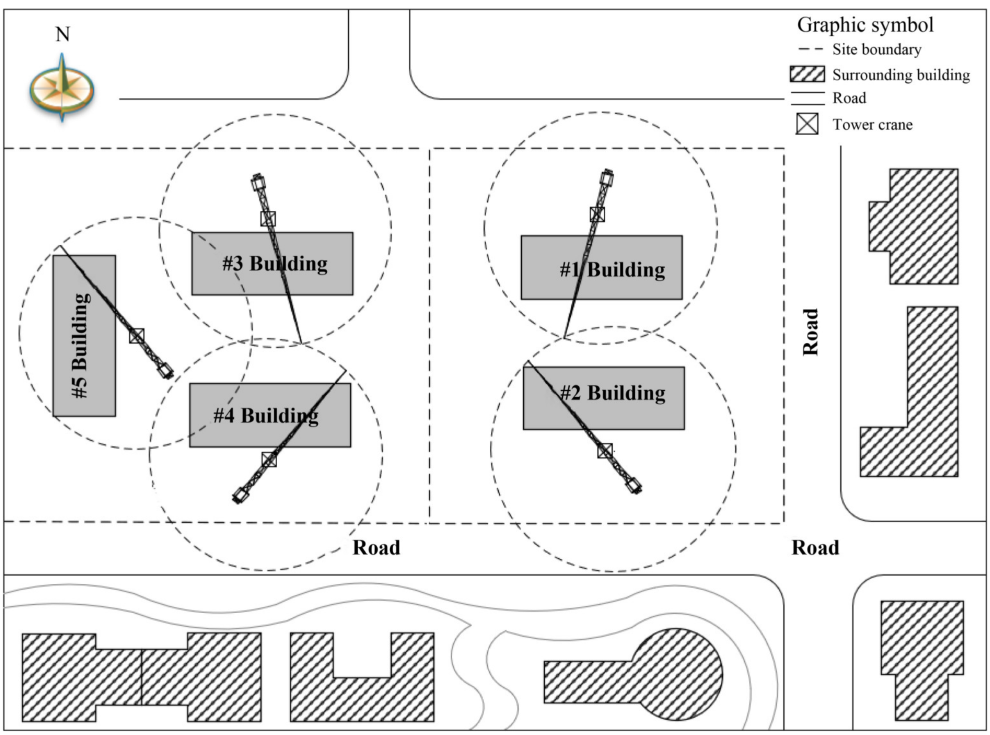


Fig. 10 Schematic diagram of the geographical conditions of the construction site.

This study focuses on the initial investigation of site layout strategies for the construction phase of prefabricated assembly-based structural elements in building construction. The main load-bearing structure utilizes cast-in situ concrete construction, including core walls, internal load-bearing walls, and exterior wall edge nodes. The prefabricated components of the building consist of prefabricated beams, panels, stairs, and internal partition walls. The dimensions and annotations for temporary construction site facilities, based on the scale, form, and progress of construction, are provided in Table 1. Each building has four prefabricated component supply points and six prefabricated component demand points. The quantities of prefabricated components to be hoisted for each demand area are indicated in Table 2 and Table 3.

Considering practical considerations, the estimated weight for each prefabricated component during lifting is approximately 2 tons. Taking into account the use of special steel beams as lifting tools for prefabricated components, the lifting weight increases to 3 tons. To accommodate this, an independent tower crane QTZ80(5513) has been deployed, with a maximum lifting capacity of 8 tons and a nominal lifting moment of 800 KN.m. Detailed specifications for the QTZ80(5513) crane can be found in Table 4. Based on the parameters of QTZ80(5513), a 2-fold working condition is applied to prefabricated components weighing between 3 and 7 tons. The lifting characteristics of the 28-m jib length can effectively meet the requirements of these two projects.

Each prospective building consists of six construction units, and the construction process progresses from the center toward both sides to minimize floor disparities. Each construction unit is treated as a cohesive entity, and the specific data regarding the central coordinate points of the prefabricated component demand points for each construction unit are detailed in Table 5. Although the

Table 1 Construction site temporary facilities

Symbol	Facility name	Length (m)	Width (m)
Prefabricated components			
PC1	Prefabricated panels	13.00	8.00
PC2	Prefabricated stairs	7.00	6.00
PC3	Prefabricated internal partition walls	7.00	7.00
PC4	Prefabricated beams	10.00	6.00
Facilities to be constructed			
B1	#1 Building	22.96	13.88
B2	#2 Building	22.96	13.88
B3	#3 Building	22.40	13.35
B4	#4 Building	22.40	13.35
B5	#5 Building	22.40	13.35
Main types of machinery on-site			
F1	#1 Tower crane	6.00	6.00
F2	#2 Tower crane	6.00	6.00
F3	#3 Tower crane	6.00	6.00
F4	#4 Tower crane	6.00	6.00
F5	#5 Tower crane	6.00	6.00
F6	Mobile crane	–	–
F7	Trucks	–	–
Temporary facilities			
T1	#1 prefab house	20.00	4.50
T2	#2 prefab house	6.00	3.00

Table 2 Number of prefabricated components lifted from the construction site for Project 1

	PC1(t)	PC2(t)	PC3(t)	PC4(t)
D1	26.59	0.00	74.06	36.43
D2	28.32	14.16	51.29	37.45
D3	25.32	0.00	77.26	35.23
D4	23.26	0.00	53.05	54.35
D5	27.31	0.00	49.33	38.56
D6	27.83	0.00	54.52	56.32
D7	25.39	0.00	72.96	37.23
D8	27.14	15.34	53.47	36.34
D9	29.33	0.00	77.13	37.35
D10	22.25	0.00	51.38	52.56
D11	28.41	0.00	52.01	39.13
D12	26.43	0.00	53.93	56.12

Table 3 Number of prefabricated components lifted from the construction site for Project 2

	PC1(t)	PC2(t)	PC3(t)	PC4(t)
D13	27.54	0.00	73.58	37.48
D14	28.15	15.43	51.36	37.77
D15	25.26	0.00	77.48	35.67
D16	23.79	0.00	53.07	54.26
D17	27.47	0.00	49.23	38.93
D18	27.67	0.00	54.52	56.73
D19	25.64	0.00	72.93	37.12
D20	27.24	15.69	53.01	36.57
D21	29.73	0.00	77.93	37.13
D22	22.43	0.00	51.05	52.68
D23	28.25	0.00	53.67	39.25
D24	26.56	0.00	53.58	56.37
D25	30.64	0.00	76.83	42.58
D26	32.24	20.69	77.94	43.23
D27	27.26	0.00	53.05	41.67
D28	29.75	0.00	55.26	57.32
D29	33.43	0.00	60.52	45.84
D30	32.19	0.00	57.49	61.68

Table 4 Main parameters of QTZ80(5513) tower crane

Parameter	Value
Operating radius (maximum)	55 m
Operating radius (minimum)	2.5 m
Weight of load (maximum)	8 t
Weight of load (minimum)	1.5 t
Rotation speed	0.6 r/min
Nominal lifting torque	800 kN·m

simplified hoisting times, following the aforementioned simplification, may slightly deviate from actual times, this method ensures the integrity of the simulation, optimizing computational efficiency while reducing complexity.

5.2 HMSIDBO algorithm to solve the problem

In alignment with the content presented in Section 4, the prefabricated building construction site layout model incorporates three optimization objectives. These objectives, although somewhat conflicting, necessitate a delicate balance. The HMSIDBO algorithm, in comparison to other algorithms, employs the Bernoulli mapping to initialize the positions of dung beetle individuals, applies Levy flights to update individual positions, and utilizes t-distribution perturbations to modify beetle positions, thereby introducing variability in the population. This algorithm effectively combines global exploration and local refinement, demonstrating characteristics of rapid convergence and high solution precision. Consequently, the HMSIDBO algorithm is employed in this study to

Table 5 Simplified coordinates of demand points

Building number	Symbol	Coordinate (X) (mm)	Coordinate (Y) (mm)	Coordinate (Z) (mm)	X-axis length (mm)	Y-axis length (mm)
#1 Building	D1	43607	58947	9300	7700	6900
	D2	51254	58949	9300	7700	6900
	D3	58911	58946	9300	7700	6900
	D4	43600	52001	9300	7700	6900
	D5	51257	52007	9300	7700	6900
	D6	58911	52005	9300	7700	6900
#2 Building	D7	43619	33601	9300	7700	6900
	D8	51272	33601	9300	7700	6900
	D9	58926	33601	9300	7700	6900
	D10	43616	26658	9300	7700	6900
	D11	51271	26660	9300	7700	6900
	D12	58925	26660	9300	7700	6900
#3 Building	D13	−14898	58882	9200	7500	7000
	D14	−7296	58790	9200	7500	7000
	D15	351	58869	9200	7500	7000
	D16	−14788	51918	9200	7500	7000
	D17	−7344	51956	9200	7500	7000
	D18	271	51953	9200	7500	7000
#4 Building	D19	−14913	33566	9200	7500	7000
	D20	−7323	33463	9200	7500	7000
	D21	269	33491	9200	7500	7000
	D22	−14802	26612	9200	7500	7000
	D23	−7368	26633	9200	7500	7000
	D24	219	26649	9200	7500	7000
#5 Building	D25	−40153	50491	9200	7500	7000
	D26	−33192	50596	9200	7500	7000
	D27	−40119	43045	9200	7500	7000
	D28	−33288	43000	9200	7500	7000
	D29	−40121	35428	9200	7500	7000
	D30	−33002	35048	9200	7500	7000

address this issue. The core operation process of HMSIDBO is presented in Fig. 11.

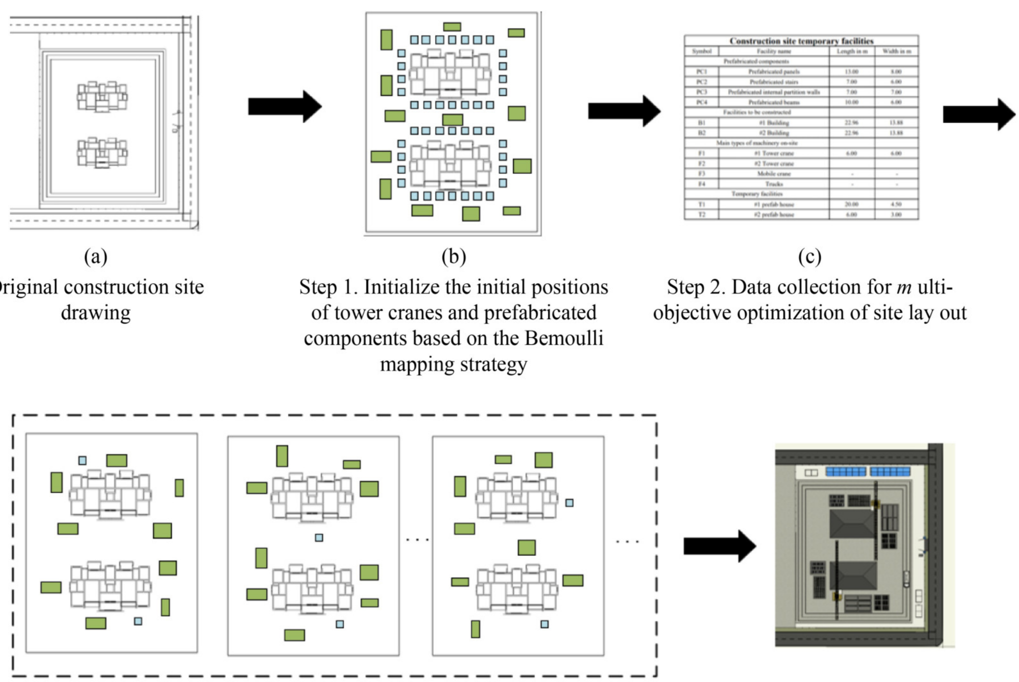
Furthermore, GA, PSO, and WOA are well-established swarm intelligence algorithms frequently utilized in solving CSLP problems, producing favorable results. To verify the reliability of the HMSIDBO algorithm, it is crucial to compare its computational timing results with these algorithms across multiple dimensions. To minimize the influence of incidental factors, ten simulation experiments were conducted, and the optimal results were selected for comparison. Subsequently, the superiority of the HMSIDBO algorithm was confirmed.

The speed data for the tower crane's movements are as follows: V_a (radial movement speed of the crane trolley) $\leqslant$ 55 m/min; V_w (rotation speed of the crane jib) = 0.6 rad/min. The α value (coordination of the hook's movements in the vertical and horizontal planes) is set to 0.25, and the β value (coordination of the hook's radial and tangential movements in the horizontal plane) is set to 1. In addition, the following parameters are employed in executing the HMSIDBO algorithm: population size (popsize) = 80, maximum number of iterations (maxgen) = 100. The computer configuration utilized in this case study consists of a 12th Gen Intel(R) Core(TM) i7-12700H processor, 8.00 GB of RAM, and a 64-bit operating system, running the MATLAB2022b software.

Based on the aforementioned parameters, the MATLAB code for the HMSIDBO algorithm was executed and compared with GA, DBO, PSO, and WOA. The comparative results are presented in Table 6. Figures 12 and 13 depict the iteration curves of these algorithms when evaluating the three objective functions.

6 Discussion on the optimal construction site layout plan

According to the test results from Tables 6 and 7, as well as Fig. 13, it is evident that the HMSIDBO algorithm demonstrates higher computational efficiency, faster convergence, and superior quality. In terms of computational time, the HMSIDBO algorithm has an average runtime of 257s, while the GA algorithm averages 454s. This means that the HMSIDBO algorithm requires only 43.4% of the computational time compared to the GA algorithm. Additionally, when computing the final solution, the optimal solution obtained by the HMSIDBO algorithm surpasses the best solution obtained by the GA algorithm. When compared to three other algorithms, the HMSIDBO algorithm shows an approximate 9.5% improvement in computational time and a roughly 52.3% enhancement in iteration speed, with a computational result error margin of approximately 1.5%. This highlights the accuracy of the algorithm's computational outcomes. Consequently, with its superior computational efficiency, the HMSIDBO algorithm yields a more optimal solution.



(a) Original construction site drawing

(b) Step 1. Initialize the initial positions of tower cranes and prefabricated components based on the Bemoulli mapping strategy

(c) Step 2. Data collection for *m* ulti-objective optimization of site lay out

(d) Step 3. The seard mode combining Levy flight and T-distributed penturbation strategy iteratively finds the global optimal construction site layout

(e) Step 4. Output final construction site layout

Fig. 11 The core operation process of HMSIDBO.

Table 6 Comparison of outcomes from executing various algorithms in Project 1

	TC1 (min)	TC2 (min)	F2 (m^2)	F3 (m)	Calculation time (s)
HMSIDBO	2655	2681	20	20873	203
DBO	2784	2620	23	21205	219
GA	3032	2759	99	27210	432
PSO	2588	2826	24	21304	224
WOA	2558	2884	24	21464	237

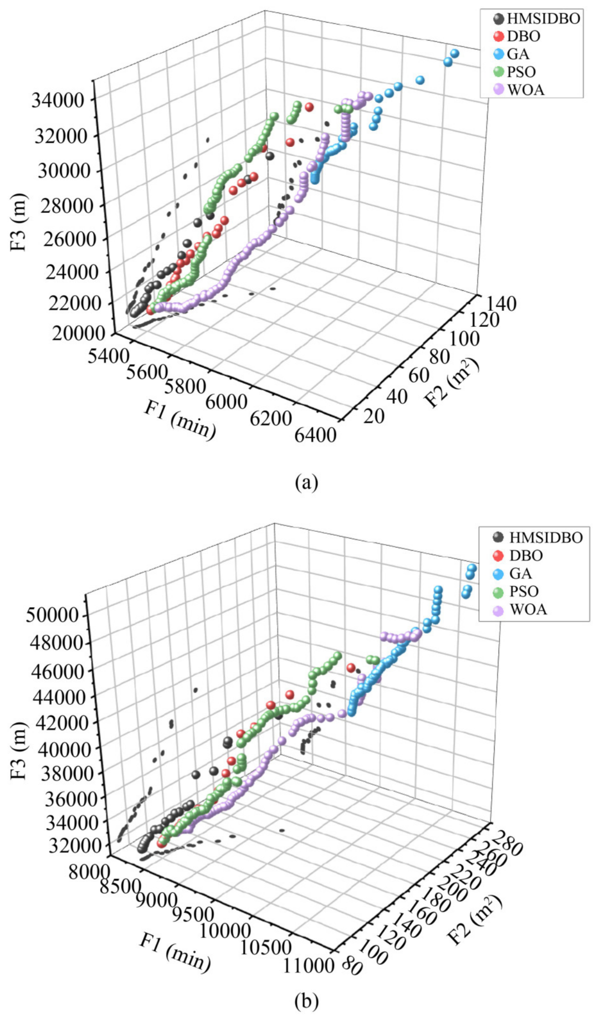


Fig. 12 Optimization iteration results of dual-objective functions F1, F2, and F3: (a) Project 1; (b) Project 2.

Figures 14–16 respectively depict the original construction site layout, the construction site layout generated by the GA algorithm, and the construction site layout produced by the HMSIDBO-PCCSLP. To provide a more precise understanding of the decision-making process of the model, this section selects and comparatively discusses three representative layout schemes, ultimately concluding with the identification of the optimal layout solution.

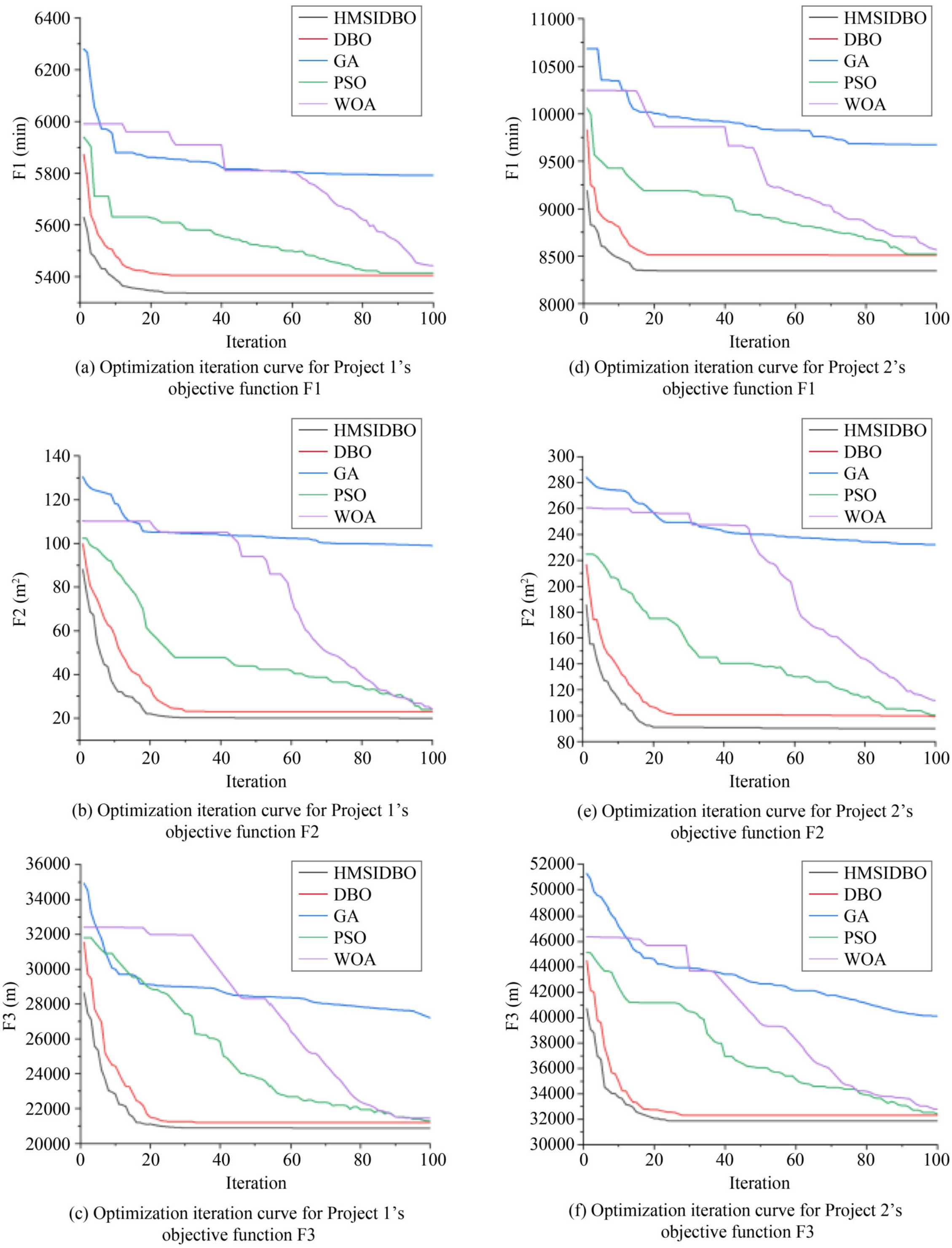
The original layout scheme primarily relies on the project manager's extensive practical experience to organize the site layout. This approach ensures that all essential facilities are accommodated within the site boundaries, while also allocating sufficient operational space and passages for the convenient transport and handling of equipment. In Project 1, the original layout scheme required 6025 min of tower crane operating time to cover an area of 30638 m where the risk of prefabricated component falling impacts is present. It should be noted that: 1) The distance between the prefabricated component stacking area and the buildings is relatively far, increasing horizontal transportation distances and significantly extending the construction duration. 2) The overlapping working areas of multiple tower cranes, totaling 134 m^2, greatly reduce the safety performance level of the site.

The GA layout scheme is designed to strike a balance between tower crane operating time and construction safety. When considering hoisting efficiency, the main difference in hoisting time is found in the horizontal direction. This indicates that the arrangement of supply and demand points for prefabricated components in an arc can reduce hoisting time. Additionally, the two main factors that influence construction safety risks are the overlapping working areas of multiple tower cranes and the selection of stacking locations for prefabricated components. In Project 1, compared to the traditional approach, the placement of PC3 and PC4 on both sides of the tower crane, closer to the prefabricated component demand area, improves hoisting efficiency by 4%. However, the placement of PC2 far from the buildings increases construction safety risks, making it a hazardous choice. In Project 2, modifications to the crane positions have reduced the area of overlapping work zones, thereby mitigating safety risks to a certain extent.

The HMSIDBO-PCCSLP layout approach, which has been designed to cater to diverse optimization goals, begins by formulating a mathematical model that revolves around said objectives. Subsequently, the DBO algorithm is refined and implemented in accordance with the model's features to derive solutions. Throughout the computational process, the Bernoulli mapping strategy is employed to initialize the positions of tower cranes and prefabricated components. A search mechanism that merges Levy flights with T-distribution perturbations is then used to iteratively refine the placement of tower cranes and the stacking locations of prefabricated components across the construction site, with the aim of identifying the globally optimal layout.

The HMSIDBO-PCCSLP layout scheme has demonstrated the shortest installation time and the highest level of safety performance among the three available options. Let us analyze these schemes from both an efficiency and safety risks perspective. From a safety risks standpoint:

1) Various prefabricated components are positioned in proximity to the component demand area, without hindering the movement of equipment within the site. In both



(a) Optimization iteration curve for Project 1’s objective function F1

(d) Optimization iteration curve for Project 2’s objective function F1

(b) Optimization iteration curve for Project 1’s objective function F2

(e) Optimization iteration curve for Project 2’s objective function F2

(c) Optimization iteration curve for Project 1’s objective function F3

(f) Optimization iteration curve for Project 2’s objective function F3

Fig. 13 Optimization iteration curves for the dual-project objective functions F1, F2, and F3.

projects, while meeting operational coverage requirements, the placement of tower cranes has effectively reduced the overlapping work zones to 20m^2 and 90m^2, respectively.

2) The hazardous areas affected by the potential falling of prefabricated components have been minimized to 20873m and 31868m, respectively, representing an average reduction of 21.8% compared to the GA layout scheme.

3) Larger prefabricated components are strategically placed within the minimum radius of the tower crane, thereby mitigating the lifting pressure on the crane (Hebiba, 2020).

From an installation efficiency perspective, both the

Table 7 Comparison of outcomes from executing various algorithms in Project 2

	TC1 (min)	TC2 (min)	TC3 (min)	F2 (m^2)	F3 (m)	Calculation time (s)
HMSIDBO	2739	2672	2932	90	31868	315
DBO	2782	2658	3069	99	32312	331
GA	2846	3274	3554	232	40132	485
PSO	2774	2703	3043	100	32424	348
WOA	2895	2639	2992	112	32792	357

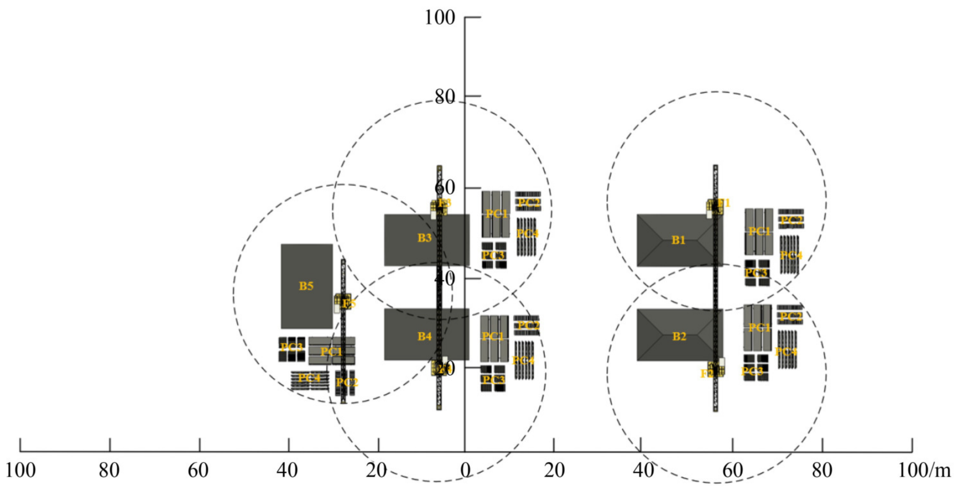


Fig. 14 The original layout scheme.

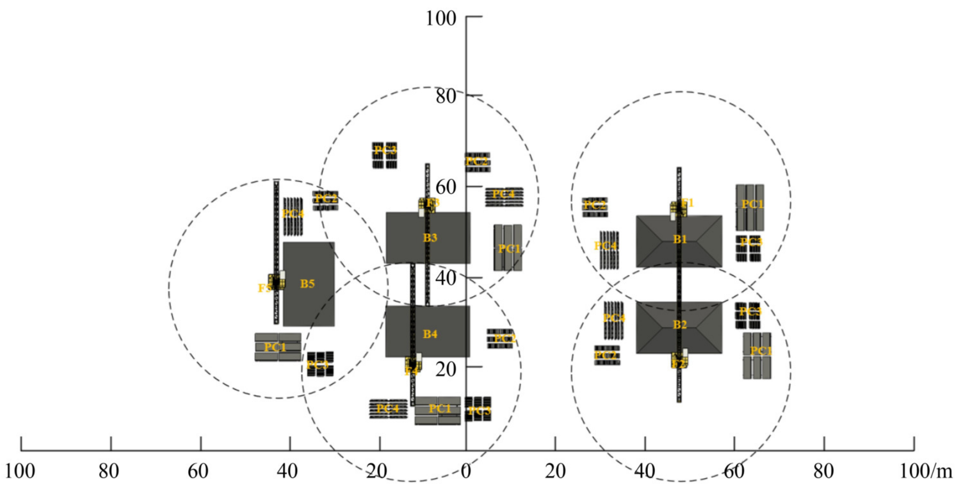


Fig. 15 The GA layout scheme.

HMSIDBO-PCCSLP and GA schemes have managed to locate prefabricated component supply points, tower crane positions, and building locations in closer proximity to one another compared to the traditional scheme. This proximity results in shorter installation times for both the HMSIDBO-PCCSLP and GA schemes. In the HMSIDBO-PCCSLP scheme, the prefabricated component supply point is even closer to the tower crane and the building, leading to higher installation efficiency and lower transportation costs (Lin et al., 2020). Considering safety risks and installation efficiency, the HMSIDBO construction site layout scheme appears to be more suitable and rational for on-site management personnel. Please refer to Fig. 17 for the operational outcomes of the PCCSLP frameworks in each scheme.

The HMSIDBO-PCCSLP scheme positions the prefabricated component stacking point in close proximity to both the crane and the building, resulting in improved lifting efficiency. The prefabricated component stacking point is conveniently located near the on-site road, reducing

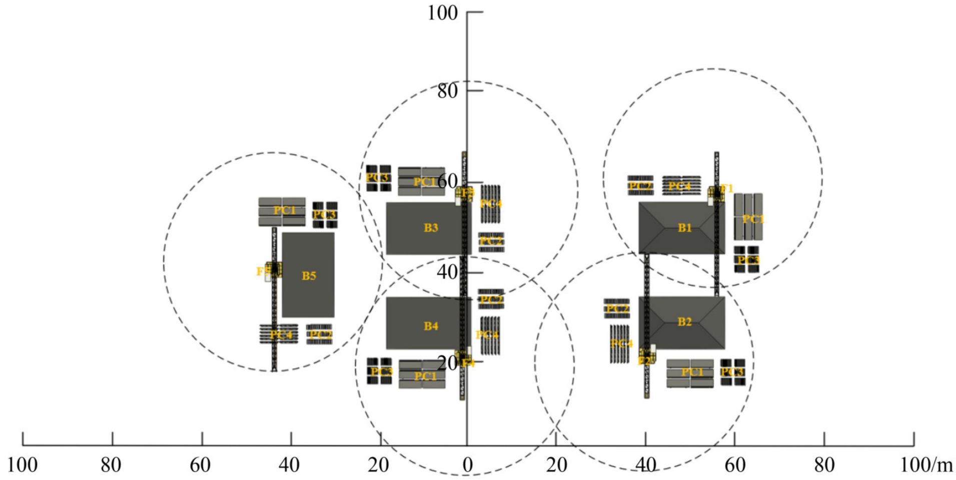


Fig. 16 The HMSIDBO-PCCSLP layout scheme.

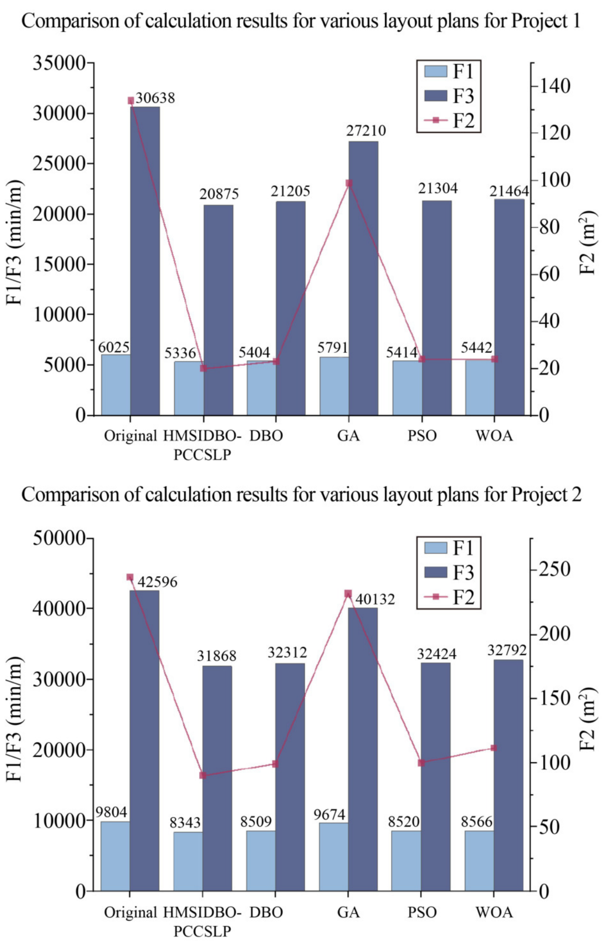


Fig. 17 The results of HMSIDBO-PCCSLP framework operation for each solution.

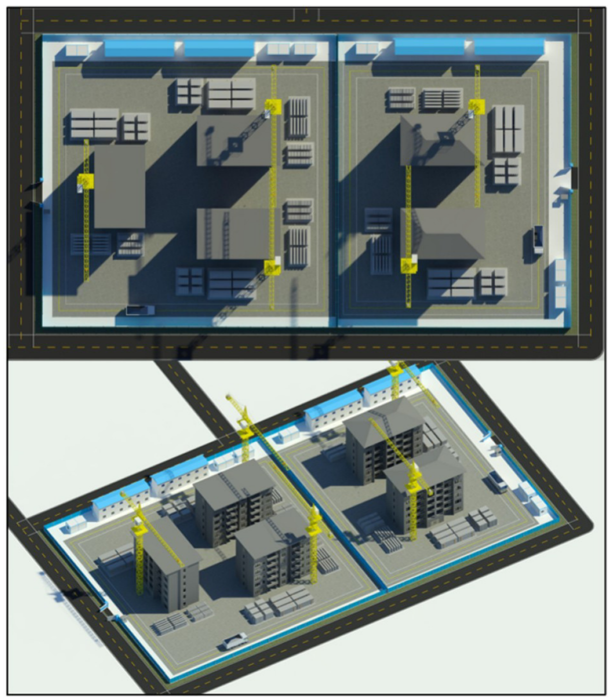


Fig. 18 The layout results of HMSIDBO-PCCSLP.

component handling time and ultimately reducing overall installation time. As a result, this scheme's optimal site layout strikes the best balance between construction efficiency and safety risk. The final site layout plans for these two projects are depicted in Fig. 18.

7 Conclusions

7.1 Research findings

Based on the construction layout of prefabricated building projects, this article establishes a comprehensive multi-constraint CSLP model for prefabricated components to optimize both construction efficiency and safety risk. It presents a mathematical model for minimizing both the hook's running time and safety risks in the PCCSLP, with the addition of the overlapping working area of tower cranes to the objective function for the first time.

To address the multi-objective optimization problem, the HMSIDBO algorithm is employed, demonstrating faster computation speed and higher solution accuracy compared to the GA algorithm. The HMSIDBO algorithm also exhibits a higher iteration speed and enhanced global exploration capabilities when compared to the DBO, PSO, and WOA. Finally, the effectiveness of this model is illustrated through two case studies involving a modular residential construction site project.

The contributions of this paper are as follows:

1) The determination of the layout is made more scientifically, avoiding the common practice of project managers making layout decisions based on personal preferences.

2) The introduction of the HMSIDBO algorithm improves the balance between global exploration and local exploitation capabilities. This is achieved through the use of the Bernoulli mapping strategy, the integration of the Levy flight strategy, and the T-distribution perturbation strategy. These enhancements address the tendency of the prefabricated component supply points and tower crane placement points to fall into local optima under constraint conditions, resulting in improved global exploration capabilities.

3) The establishment of a multi-objective optimization model for HMSIDBO-PCCSLP, along with quantitative calculation formulas. This model considers the characteristics of PCCSLP, decomposes the lifting process, and computes horizontal and vertical operation times, enabling the quantification of the lifting duration function.

4) By utilizing real modular construction project cases with detailed component information and site layout plans, the model incorporates three optimization objectives and constraints. The iterative process reveals regular patterns, and the results indicate significant improvements. Specifically, the average horizontal transportation time for tower cranes was reduced by 18.3%, the hazardous areas affected by falling prefabricated components were reduced by an average of 23.4%, and the overlapping work areas of multiple tower cranes were decreased by an average of 74.3%. These findings verify the effectiveness and feasibility of the model, demonstrating the applicability of the HMSIDBO algorithm from both efficiency and safety perspectives.

7.2 Limitations of the model

The following sections discuss the constraints of the study and offer insights into future research directions. First, it is important to note that construction projects are dynamic, and the layout of prefabricated component sites and boundaries could change over time. Thus, future research should consider various on-site factors for real-time dynamic monitoring and change management. Secondly, a more detailed model is required to analyze the impact of multiple tower cranes overlapping workspace on construction efficiency. Lastly, the proposed model did not consider irregular transport routes, which adds complexity to the transportation of components to stacking points. To address this, future research can provide a more comprehensive set of objective functions that consider distance, obstacles, and available space, thereby addressing more complex optimization problems.

In the future, it is recommended to integrate advanced technologies such as the Internet of Things (IoTs) into the supervision and management of prefabricated components. This integration will comprehensively address both the transportation of prefabricated components and the hoisting operations of tower cranes at the construction site, leading to a more efficient and secure approach to construction management for the entire project.

Competing Interests The authors declare that they have no competing interests.

References

Aydemir E, Yılmaz G, Oruc K O (2020). A grey production planning model on a ready-mixed concrete plant. Engineering Optimization, 52(5): 817–831

Cao X, Li X, Zhu Y, Zhang Z (2015). A comparative study of environmental performance between prefabricated and traditional residential buildings in China. Journal of Cleaner Production, 109: 131–143

Choi C W, Harris F C (1991). A model for determining optimum crane position. Proceedings—Institution of Civil Engineers, 90(3): 627–634

Cui Y, Shi RH, Dong J (2022). CLTSA: A novel tunicate swarm algorithm based on chaotic-levy flight strategy for solving optimization problems. Mathematics, 10(18)

De Santis M, Grani G, Palagi L (2020). Branching with hyperplanes in the criterion space: The frontier partitioner algorithm for biobjective integer programming. European Journal of Operational Research, 283(1): 57–69

El-Rayes K, Khalafallah A (2005). Trade-off between safety and cost in planning construction site layouts. Journal of Construction Engineering and Management, 131(11): 1186–1195

Fard M M, Terouhid S A, Kibert C J, Hakim H (2017). Safety concerns related to modular/prefabricated building construction. International Journal of Injury Control and Safety Promotion, 24(1): 10–23

Hebiba A (2020). Wind-wise automated decision support tool for tower crane type selection and location. Dissertation for the Master Degree. Concordia University (in Canadian)

Hong W K, Lee G, Lee S, Kim S (2014). Algorithms for *in-situ* production layout of composite precast concrete members. Automation in Construction, 41: 50–59

Hu S, Fang Y, Moehler R (2023). Estimating and visualizing the exposure to tower crane operation hazards on construction sites. Safety

Science, 160: 106044
Huang C, Li W, Lu W, Xue F, Liu M, Liu Z (2021). Optimization of multiple-crane service schedules in overlapping areas through consideration of transportation efficiency and operational safety. Automation in Construction, 127: 103716
Huang C, Wong C K (2015). Optimisation of site layout planning for multiple construction stages with safety considerations and requirements. Automation in Construction, 53: 58–68
Hwang S (2012). Ultra-wide band technology experiments for real-time prevention of tower crane collisions. Automation in Construction, 22: 545–553
Ji Y, Leite F (2020). Optimized planning approach for multiple tower cranes and material supply points using mixed-integer programming. Journal of Construction Engineering and Management, 146(3): 04020007
Jiang H, Jiang X (2023). Fatigue life prediction for tower cranes under moving load. Journal of Mechanical Science and Technology, 37(12): 6461–6466
Kaveh A, Khanzadi M, Moghaddam M R, Rezazadeh M (2018). Charged system search and magnetic charged system search algorithms for construction site layout planning optimization. periodica polytechnica. Civil Engineering, 62(4): 841–850
Li R Y, Chi H L, Peng Z Y, Li X, Chan A P C (2023). Automatic tower crane layout planning system for high-rise building construction using generative adversarial network. Advanced Engineering Informatics, 58: 102202
Lin J, Fu Y, Li R, Lai W (2020), An algorithm for optimizing the location and type selection of attached tower cranes based on value engineering. In: 2020 International Conference on Construction and Real Estate Management: Intelligent Construction and Sustainable Buildings, 106–117
Liu Y, Cui J (2020). Identification of hazard sources in prefabricated building construction by entropy weight method. In: 2020 4th International Conference on Water Conservancy, Hydropower and Building Engineering, 560(1)
Lu Y, Zhu Y (2021). Integrating hoisting efficiency into construction site layout plan model for prefabricated construction. Journal of Construction Engineering and Management, 147(10): 04021130
Monahan J, Powell J C (2011). An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. Energy and Building, 43(1): 179–188
Ning X, Liu W H (2011). Max-min Ant system approach for solving construction site layout. In: International Conference on Mechatronics and Materials Processing. Advanced Materials Research, 328–330
Ning X, Qi J, Wu C (2018a). A quantitative safety risk assessment model for construction site layout planning. Safety Science, 104: 246–259
Ning X, Qi J, Wu C, Wang W (2018b). A tri-objective ant colony optimization based model for planning safe construction site layout. Automation in Construction, 89: 1–12
Ning X, Qi J, Wu C, Wang W (2019c). Reducing noise pollution by planning construction site layout via a multi-objective optimization model. Journal of Cleaner Production, 222: 218–230
Riga K, Jahr K, Thielen C, Borrmann A (2020). Mixed integer programming for dynamic tower crane and storage area optimization on construction sites. Automation in Construction, 120: 103259
Said H, El-Rayes K (2013). Performance of global optimization models for dynamic site layout planning of construction projects. Automation in Construction, 36: 71–78
Saito A, Yamaguchi A (2016). Pseudorandom number generation using chaotic true orbits of the Bernoulli map. Chaos, 26(6): 063122
Sanad H M, Ammar M A, Ibrahim M E (2008). Optimal construction site layout considering safety and environmental aspects. Journal of Construction Engineering and Management, 134(7): 536–544
Tam V W Y, Tam C M, Zeng S X, Ng W C Y (2007). Towards adoption of prefabrication in construction. Building and Environment, 42(10): 3642–3654
Tatari A (2023). Simulating Cost risks for prefabricated construction in developing countries using bayesian networks. Journal of Construction Engineering and Management, 149(6): 04023037
The State Council (2014). China’s National New Urbanization Plan 2014–2020, The State Council, Beijing. Available at: https://www.gov.cn/zhengce/2014-03/16/content_2640075.htm, 2023-12-21
Tommelein I D, Levitt R E, Hayes-Roth B (1992). Site layout modeling: how can artificial intelligence help? Journal of Construction Engineering and Management, 118(3): 594–611
Wang J, Zhang X, Shou W, Wang X, Xu B, Kim M J, Wu P (2015). A BIM-based approach for automated tower crane layout planning. Automation in Construction, 59: 168–178
Wang Z, Hu H, Gong J, Ma X, Xiong W (2019). Precast supply chain management in off-site construction: A critical literature review. Journal of Cleaner Production, 232: 1204–1217
Xu J, Li Z (2012). Multi-objective dynamic construction site layout planning in fuzzy random environment. Automation in Construction, 27: 155–169
Xue J, Shen B (2023). Dung beetle optimizer: A new meta-heuristic algorithm for global optimization. Journal of Supercomputing, 79(7): 7305–7336
Yahya M, Saka M P (2014). Construction site layout planning using multi-objective artificial bee colony algorithm with Levy flights. Automation in Construction, 38: 14–29
Yang B, Fang T, Luo X, Liu B, Dong M (2022). A BIM-based approach to automated prefabricated building construction site layout planning. KSCE Journal of Civil Engineering, 26(4): 1535–1552
Yang B, Liu B, Xiao J, Zhang B, Wang Z, Dong M (2021a). A novel construction scheduling framework for a mixed construction process of precast components and cast-in-place parts in prefabricated buildings. Journal of Building Engineering, 43: 103181
Yang X, Liu J, Liu Y, Xu P, Yu L, Zhu L, Chen H, Deng W (2021b). A novel adaptive sparrow search algorithm based on chaotic mapping and T-Distribution mutation. Applied Sciences, 11(23): 11192
Yao G, Li R, Yang Y (2023). An improved multi-objective optimization and decision-making method on construction sites layout of prefabricated buildings. Sustainability, 15(7): 6279
Yi W, Chi H L, Wang S (2018). Mathematical programming models for construction site layout problems. Automation in Construction, 85: 241–248

Zavari M, Shahhosseini V, Ardeshir A, Sebt M H (2022). Multi-objective optimization of dynamic construction site layout using BIM and GIS. Journal of Building Engineering, 52: 104518

Zhang C, Hammad A (2012). Improving lifting motion planning and re-planning of cranes with consideration for safety and efficiency. Advanced Engineering Informatics, 26(2): 396–410

Zhang H, Yu L (2021). Site layout planning for prefabricated components subject to dynamic and interactive constraints. Automation in Construction, 126: 103693

Zhang R, Zhu Y (2023). Predicting the mechanical properties of heat-treated woods using optimization-algorithm-based BPNN. Forests, 14(5–34): 935

Zhang W, Zhang H, Yu L (2023). Collaborative planning for stacking and installation of prefabricated building components regarding crane-collision avoidance. Journal of Construction Engineering and Management, 149(6): 04023029