Resources, Conservation & Recycling Advances 30 (2026) 200334

Contents lists available at ScienceDirect

Resources, Conservation & Recycling Advances

journal homepage: www.sciencedirect.com/journal/Resources-Conservation-and-Recycling-Advances

Bi-objective optimization of low-carbon, low-cost scaffolding design using bamboo and steel with a study in China

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ARTICLE INFO

Keywords:
Bamboo-steel hybrid scaffolding
Bi-objective optimization
Net-zero energy building
Sustainable construction
Life cycle analysis

ABSTRACT

Sustainable structures in construction are increasingly promoted, yet sustainable temporary structures such as scaffolding remain underexamined. Conventional scaffolding is predominantly constructed with either bamboo or steel. Bamboo has low carbon emissions but raises regulatory and safety challenges sometimes. Steel ensures high strength but produces high emissions. This paper proposes a low-carbon, low-cost bamboo-steel hybrid scaffolding (BSHS) that leverages the environmental benefits of bamboo with the safety advantages of steel. A bi-objective optimization model is formulated to minimize life cycle carbon emissions and total cost subjecting to constraints of overweighted safety regulations; the baseline solver is Non-Dominated Sorting Genetic Algorithm II (NSGA-II). A case study in Shenzhen, China, demonstrated that BSHS can reduce scaffolding-related carbon emissions by up to 99.6 % compared to the baseline steelwork solution at a 4.7 % cost increase, while confidently satisfying all safety requirements. Our findings also confirmed that the slight cost overrun will be offset and eventually result in cost savings through the scale effect and easier learning curves, once the technology is widely adopted. The contribution of this paper is two-fold. First, it formulates a bi-objective optimization framework for sustainable scaffolding design. Secondly, the findings provided empirical evidence that BSHS reduces life cycle carbon footprint while maintaining cost-effectiveness and regulatory compliance.

1. Introduction

Sustainable development is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987). Rapid urbanization has created multiple challenges in the built environment, such as increased construction waste, carbon emissions, and resource depletion. The United Nations proposed 17 Sustainable Development Goals (SDGs), comprising 169 specific targets (UN 2015). Goal 11 “Sustainable Cities and Communities” issues an urgent call to action in the construction industry to advance sustainable development.

The energy consumption and associated carbon footprint throughout a building’s life cycle are central to sustainable development in the construction industry (Sizirici et al., 2021). The built environment contributes over 37 % of global energy-related carbon emissions (UNEP 2023). Buildings emit carbon across all stages, from construction, operation, maintenance, to demolition (Chen et al., 2022). Some buildings achieve carbon neutrality in operation and maintenance through optimized designs (Lu et al., 2024), energy models (Meng et al., 2026), advanced technologies, and green retrofitting (Rayegan et al., 2024). Yet, other stages still produce a heavy carbon footprint.

Scaffolding is a critical yet often overlooked component of sustainable construction. Scaffolding contributes about 10–25 % of total construction costs and 18–30 % of on-site labor (Yin and Caldas, 2022), while the global scaffolding market was projected to reach USD 75 billion by 2030 (Tejas, 2025). However, carbon footprint of scaffolding receives less attention than permanent structures in both practice and literature. One possible reason is that scaffold designs were often excluded from architectural and tender drawings (Kim and Teizer, 2014). Another possible reason was outsourcing of scaffolding to specialized small firms relying on single-material systems, regardless of site-specific conditions, scaffolding efficiency, and carbon emissions. Sustainable scaffolding systems, thus, will be meaningful for achieving net-zero energy building targets (Ibrahim et al., 2024).

Steel and bamboo are the two predominant scaffolding materials. Bamboo scaffolds have prevailed in South and East Asia and Africa (Sanni-Anibire et al., 2022), while steel dominates in the rest of the world (Amede et al., 2022). Fig. 1 shows that bamboo’s sustainability

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https://doi.org/10.1016/j.rcradv.2026.200334

Available online 1 April 2026

advantages, as it grows rapidly in 3–5 years and sequesters carbon as about 50 % of dry weight (Sujarwo, 2016). After service life in site, reuse in wastewater treatment or gardening applications can further reduce the carbon footprint (Chang et al., 2018; Choy et al., 2005). In contrast, steelwork generates notably more carbon emissions across stages: mining, smelting, manufacturing, transportation, and recycling. Therefore, in Hong Kong, bamboo scaffolding temporarily remains dominant under local codes (HKLD 2024). While its use is declining due to safety concerns, new regulations, and insufficient training programs for bamboo scaffolders (HKDevB 2025).

Multi-objective optimization (MOO) methods optimize conflicting goals simultaneously (Gunantara, 2018). MOO/BOO can provide theoretical computational approaches for studying bamboo-steel hybrid scaffolding (BSHS), in order to integrate the advantages with regard to structural safety and environmental sustainability.

This paper presents a modular, low-carbon BSHS design and its BOO formulation. The objectives to minimize are life cycle carbon footprint and total cost with constraints of minimum structural strength and given site conditions, whereas the variables to determine include framework configuration and material properties. Typical MOO algorithms, such as Non-dominated Sorting Genetic Algorithm II (NSGA-II), can solve this BOO problem for each site.

Contribution of this paper is two-fold. First, the BOO formulation of BSHS quantifies sustainability and cost goals of bi-material scaffolding. Second, the BOO results confirmed that BSHS considerably reduces life cycle carbon footprint and maintains cost efficiency and safety compliance.

2. Literature review

2.1. Bamboo scaffolding

Bamboo scaffolding has been widely used across South and East Asia and parts of Africa, particularly in China and India, with abundant bamboo resources. Fig. 2. shows historical records of bamboo proto-scaffolding in China's Sui and Tang dynasties (581–907 CE) (Li and Kobayashi, 2004; Shi et al., 2013). The Northern Song dynasty (960–1127 CE) marked systematic use of bamboo poles and wooden rods for temporary architectural elements (Dlamini et al., 2022).

The use of bamboo in construction has decreased due to industrialization. China's governments have restricted bamboo scaffolding since 2000s due to its limitations, including insufficient material strength, lack of standardization, decay, and flammability (Liu et al., 2022; Ramanathan, 2008). The Ministry of Housing and Urban-Rural Development (MOHURD) (2021) prohibited bamboo and timber scaffolding for projects exceeding CNY 600,000 (approximately USD 84,000). However, increased reliance on steel accelerates carbon emissions throughout construction. For instance, China produced 1.005 billion tons of crude steel in 2024, which is more than half of the world (Cai and Zhu, 2025).

On the contrary, bamboo scaffolding was used in over 95 % of Buildings Department-registered projects in Hong Kong in 1990s, including large developments such as the Hong Kong Convention and Exhibition Centre (Chang and Yu, 2002). Even though part of the large-scale public projects has been shifted to steelworks in recent years, bamboo remains a main scaffolding material in Hong Kong, India, Nigeria, and several other regions. The Hong Kong Buildings Department possesses detailed regulatory codes regarding the installation, use, maintenance, and dismantling of bamboo scaffolding.

Bamboo scaffolding has several key advantages in Hong Kong. First, Hong Kong is adjacent to bamboo sources of Guangdong and Guangxi provinces (Fang et al., 2004). Bamboo's light weight also reduces transportation, installation, and dismantling costs compared with steelwork (Amede et al., 2021). Additionally, its flexibility also suits Hong Kong's dense urban environment. Licensed scaffolders can do on-site adjustments in length and positioning (Crolla, 2018). Bamboo scaffolding is also time-saving due to its rapid assembly, requiring only one-sixth the time of steelwork (Gebremariam et al., 2024).

2.2. Bamboo-steel hybrid applications in construction

Bamboo-steel hybrid materials have been applied to the construction field to enhance sustainability. Bamboo's carbon sequestration rate is 6–13 mg/ha/yr (Nath et al., 2015), which sheds light for a carbon-efficient bamboo-steel hybrid structure (Zhang et al., 2021). Although natural bamboo has a limited and varied service life in scaffolds, some processed bamboo building components, such as floor tiles, can achieve a lifespan of 30–40 years (Gichohi, 2014).

The bamboo-steel hybrid composition can also provide considerable structural strength. These hybrids can withstand compressive stresses of up to 3656 kg/cm^2 (358.53 MPa) (Paudel, 2008). Bamboo's tensile strength reaches approximately 28,000 N/m^2 (0.028 MPa) (Nurdiah, 2016). Bamboo provides significant weight reduction while maintains high structural strength for lightweight construction projects (Adier et al., 2023).

2.3. Optimization in scaffolding design

Optimization algorithms, along with deep learning technologies driven by optimization, have been applied in scaffolding engineering to

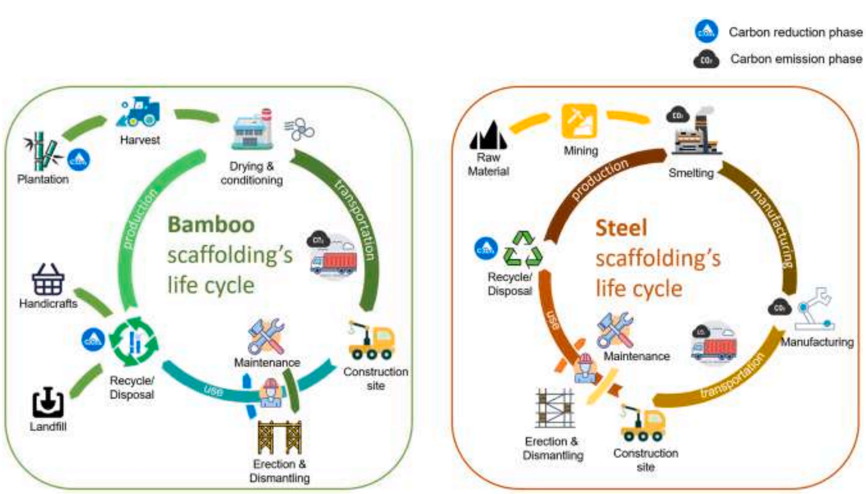

Fig. 1. Life cycle comparison of bamboo and steel scaffolding.

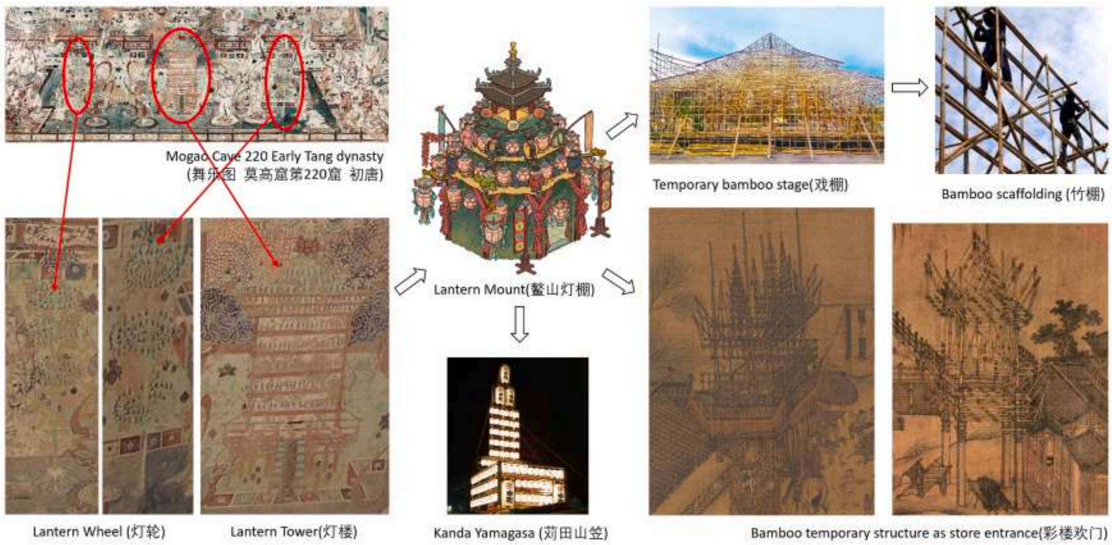

Fig. 2. The history of bamboo scaffolding in China and Japan.

improve construction safety and management efficiency. Dzeng et al. (2024) developed an automated system that leverages the YOLO algorithm and augmented reality devices to detect defects in scaffolding installations. Johansson and Jernek (2022) incorporated a multi-objective genetic algorithm and linear programming to solve constrained optimization problems in the scaffolding industry against various building shapes and plot sizes. Takva et al. (2023) conducted a cost analysis of H-frame façade scaffolding configurations about horizontal and vertical dimensions. Blockchain technology has also been applied in scaffolding project management (Yang et al., 2022; Kong et al., 2025).

3. Research methods

Fig. 3 illustrates the four phases of the BSHS approach proposed in this paper. Section 3.1 describes the site analysis phase. A construction site in Shenzhen was selected, and the regional scaffolding codes under the China's National Standards (GB) were reviewed.

Section 3.2 defines the formulation phase. Structural safety clauses from relevant regulations were quantified as material ratio constraints (steel-to-bamboo) for the BSHS system. The life cycle carbon footprint and total cost were modeled as the two optimization objectives.

Section 3.3 presents the optimization phase. Key variables—such as structural framework configuration and material properties—were parameterized. The NSGA-II algorithm, together with Grasshopper and Wallacei X software, was used for iterative computation to generate the pareto frontier.

3.1. Site selection and analysis

The selected case site was an office building developed by China Vanke Co., Ltd., as shown in Fig. 4. The site was located in Bao'an District, Shenzhen, Guangdong Province. For this site, steel scaffolding served as the primary type. The selected steel pipe type is $\Phi 48 \times 3$, with an outer diameter of 48 mm and a wall thickness of 3 mm. The weight of this pipe type was approximately 3.329 kg/m. The bamboo pipes used on this site followed the local technical code (MOHURD 2012), and employed Moso bamboo (*Phyllostachys edulis*) with an average weight of approximately 1.5 kg/m.

3.2. BOO formulation definition

For all the pipes within the original scaffolding, define set $U = \{u_1, u_2, \ldots, u_k\}$, $k = |U|$, u_i is a single pipe position within the original scaffolding design. For all the possible positions of pipe that can be replaced by bamboo poles, define set $\mathbb{X} = \{x_1, x_2, \ldots, x_n\}, n = |\mathbb{X}|$, and x_i is one pole.

The BOO formulation consists of two objectives, as shown in Eq. (1).

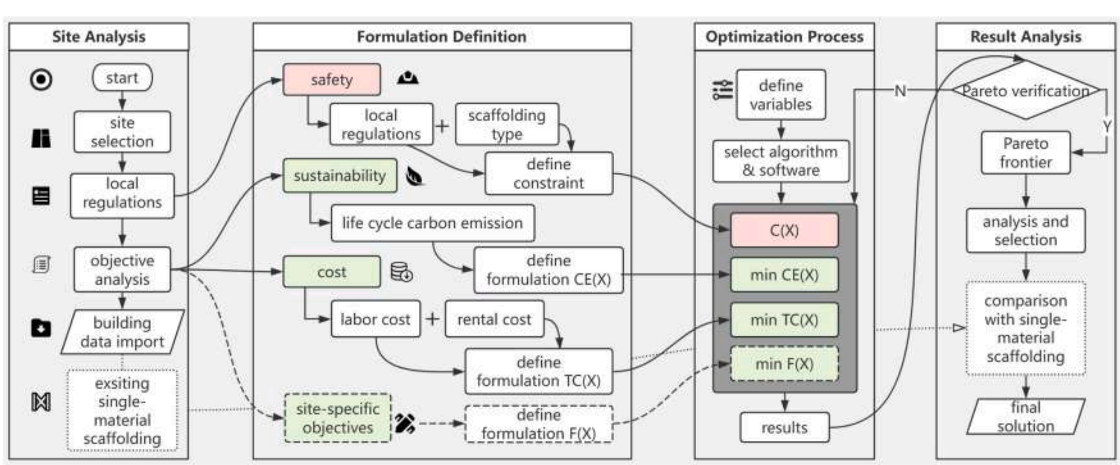

Fig. 3. Research method.

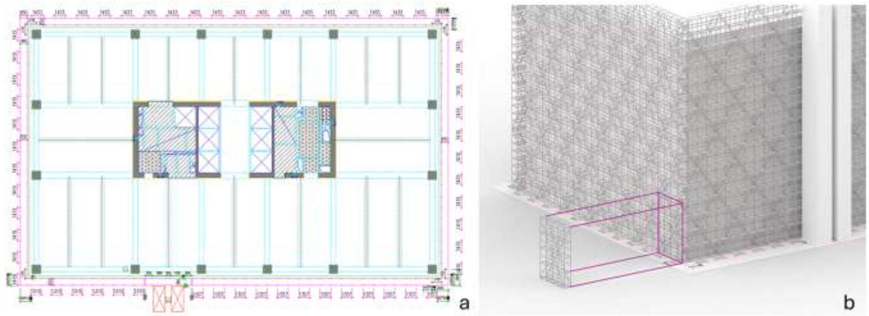

Fig. 4. Case site information (a) Building plan with scaffolding scheme. (b) Module of the scaffolding scheme.

$$\textbf{optimized } F(X) = \textbf{min } CE(X),\ TC(X) \quad \textbf{subject to } X = \{x_1, x_2, \ldots, x_y\},\ x_i \in \mathbb{X},\ \text{and } 1 \le i \le y \le n,\ \boldsymbol{C}(X) \ge 0 \tag{1}$$

where $X \subseteq \mathbf{X}$ is a subset of bamboo poles; $x \in \mathbf{X}$ represents a bamboo pole; $CE(X)$ and $TC(X)$ are the two objective functions regarding carbon emissions and total cost, respectively; and $y = |X|$ is the quantity of bamboo poles in the design. The generalized constraints, $C(X)$, represent a series of mandatory requirements that must be satisfied. Define that the distances from the case site to the steel scaffolding factory and the bamboo scaffolding factory are d_1 and d_2, respectively. The weight of all the bamboo poles in X is w_1, and the weight of all steel pipes in U-X is w_2, respectively. To calculate the total weight of the two materials based on the member lengths, overlapping factors (OFs) are necessary due to the overlapping lengths requirement at the lashing nodes of components intersections. According to the report from the Occupational safety and Health Council of Hong Kong (2016), the OF for bamboo members is 1.5, which means the effective length of a bamboo pole per unit length requires 1.5 times the actual bamboo poles length. Similarly, the OF for steel pipes is 1.16. Due to the different frame densities of bamboo scaffolding and steel scaffolding, after replacing the steel pipes, the density of bamboo needs to be increased at the replacement location to ensure the rigidity of the structural strength.

3.2.1. Formulation for sustainability

The primary objective of this paper is to optimize the carbon footprint across the life cycle of scaffolding. A cradle-to-grave Life Cycle Assessment (LCA) typically consists of four stages: production, transportation, use, and disposal (Asdrubali et al., 2024; Laleicke et al., 2015). In calculating carbon emissions, only those generated from resource and energy consumption are considered, while human factors are excluded. During the production stage, the carbon emission of steel material $\boldsymbol{C_{p1}}$ is:

$$C_{p1} = e_{p1} \cdot w_1 \tag{2}$$

where $\boldsymbol{e_{p1}}$ is the carbon emission factor (CEF) of steel, and $\boldsymbol{w_1}$ is the weight of all the bamboo poles in X.

As the steel pipe type is $\Phi 48 \times 3$ carbon steel, the value of $\boldsymbol{e_{p1}}$ should be 2310kgCO_2e/t according to the standard *GB-T51366–2019* (MOHURD 2019). The carbon emissions of bamboo material $\boldsymbol{C_{p2}}$ is:

$$C_{p2} = e_{p2} \cdot w_2 \tag{3}$$

where $\boldsymbol{e_{p2}}$ is the CEF of bamboo scaffolding, $\boldsymbol{w_2}$ is the weight of all steel pipes in U-X.

The value of $\boldsymbol{e_{p2}}$ is 327 kgCO_2e/t (Zhang et al., 2023). Meanwhile, during the growth phase of bamboo, the carbon sequestration process must also be accounted for alongside carbon emissions. The carbon sequestration of bamboo material $\boldsymbol{S_{p2}}$ is:

$$S_{p2} = e_{sp2} \cdot w_2 \tag{4}$$

where $\boldsymbol{e_{sp2}}$ is the carbon sink factor (CSF) of bamboo.

$\boldsymbol{e_{sp2}}$ can be inferred from (Lv et al., 2025). In the transportation stage, carbon emissions are primarily determined by vehicle energy consumption, which includes direct emissions from the combustion of gasoline and diesel, as well as indirect emissions from fuel production. These two components of emissions are typically combined into emission factors. The carbon emission of BSHS from transportation stage $\boldsymbol{C_t}$ is:

$$C_t = e_t \cdot (d_1 \cdot w_1 + d_2 \cdot w_2) \tag{5}$$

where e_t is the transport carbon emission factor per unit weight-distance, d_1 the distance from case site to steel scaffolding factory, and d_2 the distance from case site to bamboo scaffolding factory.

$\boldsymbol{e_t}$ is mainly determined by the types of different transport vehicles according to the standard *GB-T51366–2019*. Within this case site context, the value of $\boldsymbol{e_t}$ is 0.179 kgCO_{2}e /(t*km). At disposal phase, common practices for steelwork involve smelting and recycling, which saves carbon emissions from raw material extraction and processing. Therefore, the carbon reduction benefits of steel recycling can be quantified as $\boldsymbol{S_{p1}}$:

$$S_{p1} = e_{sp1} \cdot w_1 \tag{6}$$

where e_{sp1} is the carbon sink factor (CSF) of steel material.

e_{sp1} of steel is about 1280 kg CO_2e/t (Wang et al., 2024). Common disposal methods for bamboo include landfill, incineration for power generation, recycling and reuse, and composting. When bamboo is landfilled, it produces methane as a by-product. According to the IPCC model, the carbon emissions from bamboo landfill ($\boldsymbol{e_l}$) are about 0.75 kg CO2e/kg (Ximenes et al., 2018). Incineration for power generation can substitute coal combustion, resulting in net emission reduction for the whole process. The carbon emissions ($\boldsymbol{e_r}$) for this disposal method is about −0.4 kg CO2e/kg (Phuangchik et al., 2023). Recycling contains sorting bamboo for reuse in construction or processing into furniture or handicrafts, etc., which can extend the carbon storage duration. Carbon emissions from composting are similar to landfill because of the reduction in emissions from chemical fertilizer production.

Bamboo scaffolding currently only accounts for a low proportion in Shenzhen's construction industry. The specialized statistics on bamboo disposal are thus lacking. This paper adopts a simplified calculation model based on Hong Kong's patterns (Hossain et al., 2016) and Shenzhen's current construction waste classification and incineration (Zhang et al., 2024; Yi et al., 2024). The disposal proportions are: 60 % incineration for power generation, 20 % recycling and reuse, and 20 % landfill treatment (Liang, 2022; Yu et al., 2020). Therefore, the carbon emissions of BSHS from disposal stage $\boldsymbol{C_d}$ is:

$$C_d = w_2 \cdot (0.2 \cdot e_l + 0.6 \cdot e_r) \tag{7}$$

Where: e_l is the unit carbon emissions from bamboo landfill, and e_r is the unit carbon emissions from bamboo recycling.

Finally, during the service phase of scaffolding, different materials exhibit distinct usage cycles. Define the service life of steel scaffolding as l_1, and that of bamboo scaffolding as l_2, while the actual usage duration at the case site is denoted as P. Since scaffolding components are reusable, their utilization period at the case site constitutes only a portion of their full life cycle. Therefore, for calculating carbon emissions during the production and disposal phases of steel and bamboo components, proportionality coefficients of P/l_1 and P/l_2 should be applied respectively.

The total carbon emissions of BSHS ***CE(X)*** are thus as follows:

$$CE(X) = P/l_1 \cdot (C_{p1} - S_{p1}) + P/l_2 \cdot (C_{p2} - S_{p2} + C_d) + C_t \tag{8}$$

where P is the actual usage duration at the case site, $\boldsymbol{l_1}$ is the service life of steel scaffolding, and $\boldsymbol{l_2}$ is the service life of bamboo scaffolding.

For this project, installation of the tower's exterior scaffolding commenced on September 5, 2018, and its dismantlement was completed on October 20, 2019, resulting in a total service period of 13.5 months. This paper adopts 120 months as the service life for steel fastener-type scaffolding and 30 months for bamboo scaffolding (Gebremariam et al., 2024; Zhang et al., 2010).

3.2.2. Formulation for cost

For the rental cost part, the total rental cost ***RC*** of the two materials is:

$$RC = w_1 \cdot p_1 + w_2 \cdot p_2 \tag{9}$$

where $\boldsymbol{p_1}$ is the unit rental price of steel pipe, $\boldsymbol{p_2}$ is the unit rental price of bamboo pole. According to the estimated market prices for scaffolding rentals. The ratio of p_1 to p_2 is around 2.5, p_1 equals to CNY184/t, thus p_2 equals CNY73.6/t.

For the labor cost part, the joints between components are the primary consideration. The labor cost of the case site ***LC*** is:

$$LC = f(n_1 + n_3) \cdot (1/t_{e1} + 1/t_{d1}) \cdot s_1 + n_2 \cdot (1/t_{e2} + 1/t_{d2}) \cdot s_2 \tag{10}$$

Where: $\boldsymbol{n_1}$ is the number of bamboo-bamboo joints;

- $\boldsymbol{n_2}$ is the number of steel-steel joints;
- $\boldsymbol{n_3}$ is the number of bamboo-steel joints;
- $\boldsymbol{t_{e1}}$ is the average number of bamboo joint erection per worker per day;
- $\boldsymbol{t_{e2}}$ is the average number of steel joint erection per worker per day;
- $\boldsymbol{t_{d1}}$ is the average number of bamboo joint dismantled per worker per day;
- $\boldsymbol{t_{d2}}$ is the average number of steel joint dismantled per worker per day;
- $\boldsymbol{s_1}$ is the average daily salary of metal scaffolders; and
- $\boldsymbol{s_2}$ is the average daily salary of bamboo scaffolders.

According to the statistics from Hong Kong Occupational Safety and Health Council (HKOSHC 2016), bamboo scaffolding demonstrates significantly shorter erection and dismantling times than steel scaffolding due to its lightweight nature and band strapping assembly method. Using average values, a bamboo scaffolder can erect 247 joints per day (t_{e1}), while metal scaffolders can erect 133 joints per day (t_{e2}). And the number of dismantling joints is 702 (t_{d1}) and 213 (t_{d2}) for bamboo and metal scaffolders, respectively. To simplify the calculation process, for the bamboo-steel joints, the erection and dismantling speed is the average of those of bamboo-bamboo joint and steel-steel joint.

Only licensed scaffolders can take the job of erecting and dismantling bamboo scaffolding. According to the report of Hong Kong media (HK01 2025), the daily salary of bamboo scaffolders is around 3000 HKD, while the daily salary of normal metal scaffolders is about 1300 HKD, the ratio is around 2.3:1. Taken this ratio as reference, the average daily salary of metal scaffolders (s_1) in Shenzhen region is 300 CNY. Thus, the daily salary of bamboo scaffolders (s_2) in Shenzhen region can be inferred around 692 CNY. Considering that the BSHS is in the initial stage of promotion, the bamboo scaffolders require extra training to be licensed (SCMP 2025), the daily salary of bamboo scaffolders will be calculated with a training cost coefficient f of 1.2. In the BSHS, both bamboo-bamboo joint and bamboo-steel joint must be executed by licensed scaffolders. Therefore, the total cost is the sum of rental cost and labor cost:

$$TC(X) = RC + LC \tag{11}$$

3.2.3. Constraint

The constraint of this optimization is to fulfill the mandatory structural requirement of Shenzhen's scaffolding regulation. According to the safety and technical standard (HCBSM 2023) issued by the Shenzhen Government, the *Comprehensive Safety Factor* β for normal working scaffolding should meet the condition that $\beta \geq 2.0$, and the newly developed scaffolding should fulfill the requirement that $\beta \geq 2.2$. In this paper, $\beta \geq 2.2$ is taken as the safety constraint. The *Comprehensive Safety Factor* β is defined as:

$$\beta = \gamma_0 \cdot \gamma_u \cdot \gamma_m \cdot \gamma_m' \tag{12}$$

where γ_0 is the coefficient for importance of a structure, γ_u is the weighted average of load factor coefficients, γ_m is the partial safety factor for resistance of material, and γ'_m is the material strength adjustment coefficient.

For the *coefficient for importance of a structure* γ_0, the value of which should be determined by the safety level. Within the context of the case site, the building height exceeds 40 m, and the type of scaffolding is landing working scaffolding, the safety level thus should be type II, which means γ_0=1.0, on the basis of the standard.

For the *weighted average of load factor coefficients* γ_u, the value of this variable is 1.395 for working scaffolding and 1.318 for shoring scaffolding in the light of the standard, γ_u=1.395 in the context of the case site.

For the *partial safety factor for resistance of material* γ_m, the value should be 1.165 according to relevant provisions of the current national standard *Technical code of cold-formed thin-wall steel structures GB 50018–2002* (MOHURD 2002) for steel-pipe scaffolding. For the bamboo scaffolding, the *Standard for design of engineered bamboo structures T/CECS 1101–2022* (CECS 2022) set the lowest *partial safety factor for resistance of material* of each grade of bamboo to 1.03. For the newly developed scaffolding:

$$\gamma_m = 1.165\mathbf{a} + 1.03(1 - \mathbf{a}) \tag{13}$$

Where: $\boldsymbol{a}$ is the ratio of steel-pipe to the BSHS.

For the *material strength adjustment coefficient* γ'_m, the value of this variable for the stability bearing capacity of newly developed working scaffolding should be 1.433.

Therefore, in the context of the case site, the *Comprehensive Safety Factor* should meet the conditions below:

$$C(X) = \beta - 2.2 \geq 0 \Rightarrow \mathbf{a} \geq 0.52 \tag{14}$$

This means that the ratio of steel pipes to the BSHS should be no less than 52 %.

3.3. Optimization algorithm and analysis

This paper applies NSGA-II algorithm (Deb et al., 2002) to solve the BOO problem. Alternatively, there are some other algorithms that can be applied in BOO/MOO problems including Tree-structured Parzen estimator (TPE) (Bergstra et al., 2011), Ant Colony Optimization (ACO) (Dorigo et al., 1996), and Strength Pareto Evolutionary Algorithm 2 (SPEA-2) (Zitzler et al., 2001). NSGA-II is an algorithm with more balanced performance in all aspects among the above algorithms.

Fig. 5 illustrates characteristic points typically observed in BOO

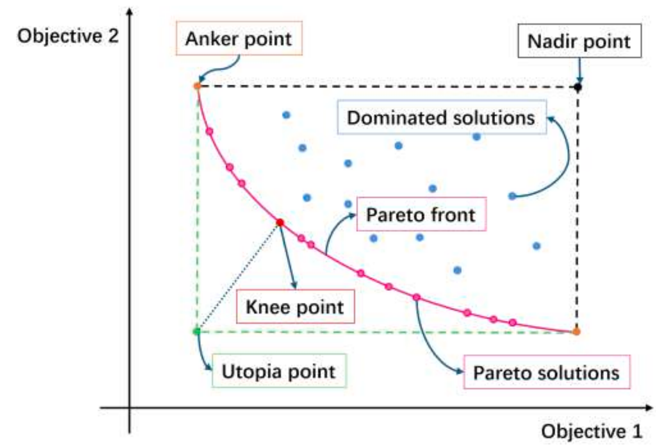

Fig. 5. Characteristic points in the result of solving typical BOO problems.

solutions. The two *Anker points* in orange represent the solutions where the minimum values of the two objectives are achieved. These two minima collectively define the '*Utopia point*', which represents the ideal but unattainable solution for this BOO problem (Zhou and Xue, 2023). The *Nadir point*, by contrast, represents the least desirable solution. The *Pareto solutions* in pink indicate solutions for which no other alternative is superior in both objectives simultaneously. Collectively, all Pareto solutions form the *pareto frontier*. Solutions excluded from the Pareto set are *dominated solutions*, as they are inferior on one or both objectives compared to Pareto solutions. The *Knee point* is the point on the pareto frontier closest to the Utopia point, and it can theoretically be taken as the final solution.

However, in real construction projects, the decision-maker can select the final solution that best matches the site conditions from the Pareto Frontier based on different weights of the two optimization objectives. Furthermore, across different deployment stages, cities, and site conditions, the coefficients in the formulations can be changed, to deliver scenario-based design and analyses.

4. Experimental result and analysis

4.1. Experimental settings

The experiments were performed on a desktop computer equipped with a 13th-generation Intel® Core™ i7–13,700 K (3.40 GHz) processor and 128 GB of memory. The optimization process employed the NSGA-II algorithm (Hamdy et al., 2016) through the Wallacei X plugin (ver. 2.7) (Makki, 2025) on the Grasshopper platform (ver. 1.0), which is a graphical algorithm editor tightly integrated with Rhino (ver. 7)'s 3D modeling tools (McNeel, 2025). The NSGA-II parameters were set to default values after preliminary testing: crossover probability = 0.9, mutation distribution index = 20, and crossover distribution index = 20. Remainders of NSGA-II parameters followed established guidelines in the literature (Yusoff et al., 2011; Verma et al., 2021). Each generation included 100 individuals, and 100 generations were executed, resulting in 10,000 evaluated solutions.

4.2. Experimental results of the BOO problem

4.2.1. Experimental results

The total computation time was 92 min and 11 s to solve the BOO problem using NSGA-II using Wallacei X on Grasshopper. A total of 537 Pareto-optimal solutions were obtained from 100 generations. Fig. 6 presents three example scaffolding modules derived from the Pareto solutions.

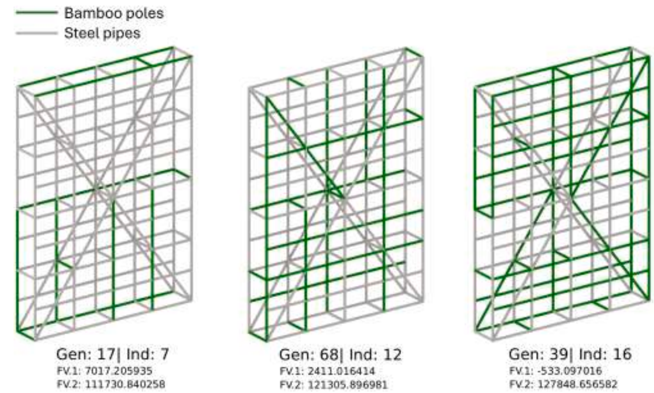

Fig. 6. Examples of Pareto solutions for the scaffolding module.

4.2.2. Pareto frontier and the knee point

Each pink or blue point in Fig. 7 represents a BOO solution, where the x- and y-coordinates correspond to the two objective function values. Pink points denote Pareto-optimal solutions. The results indicate a curved pareto frontier, demonstrating a negative correlation between the two objectives.

The knee point on the pareto frontier was selected as follows. First, we normalized the two objectives based on the maximum and minimum values in

Fig. 7; Then, the point (113,323, 32) closest to the Utopia point was identified as the knee point. The reference steelwork baseline at the point of (108,245, 9957) is also marked in the figure, which represents the total cost and carbon emissions of the steelwork scaffolding, respectively. Compared to the steelwork baseline, the knee point achieved a 99.6 % reduction in life cycle carbon emissions with only a 4.7 % increase in total cost. Fig. 8 shows the schematic rendering of the knee point. Green pipes represent bamboo elements, while silver pipes indicate steel components.

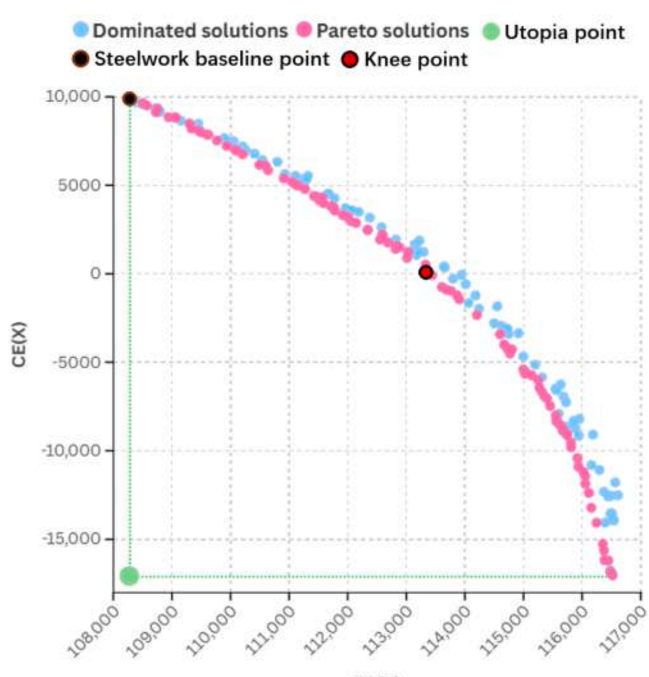

Fig. 7. Pareto frontier and solution analysis.

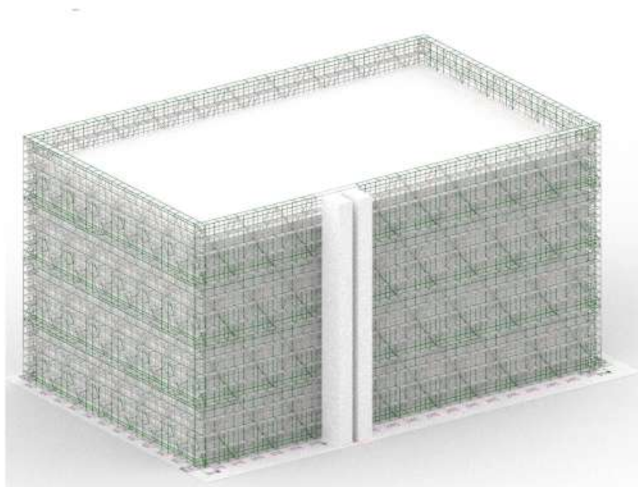

Fig. 8. Schematic rendering of the solution located at (113,323, 32).

4.3. Scenarios-based analysis

4.3.1. Structural reduction factor analysis

The final solution may vary depending on the applied partial safety factor. In the early stage of BSHS adoption, data on material strength are limited, and practical experience remains inadequate. To reflect such constraints in the formulation, we moderate the structural reduction factor to γ_m (*the partial safety factor for resistance of material*) of BSHS. For example, when the reduction factors were 0.9 and 0.8, the corresponding constraints became $\boldsymbol{a} \geq 0.72$ and $\boldsymbol{a} \geq 0.81$, respectively. The results are shown in Table 1 and Fig. 9. The results indicate that varying the reduction factor primarily affects the overall steel proportion in the BSHS, ranging from 52 % to 81 %. Nevertheless, all selected optima denotes that a modest increase in total cost results in a substantial reduction in life cycle carbon emissions.

In practice, the final BSHS solution could be altered from the knee point by decision-makers. For example, factors such as the national Emissions Trading System (ETS), technological and workforce readiness, and government incentives must be considered. Depending on the specific situations, the weights of the two objectives should be adjusted, and the most suitable solution on the pareto frontier will be selected as the final solution.

4.3.2. Comparison to the carbon trading price

The carbon trading price in China has been trending upward in recent years (Wang et al., 2024). The current average secondary market price in China is CNY 95.96 per t/CO2e (ICAP 2024). The selected optimal solution to the BOO problem is (113,323, 32), indicating a carbon reduction cost of CNY 511.63 per tCO2e compared with the original all-steel solution (108,245, 9957). As mentioned in Section 3.2.2, at the very initial stage of promoting the BSHS, the training cost for the bamboo scaffolders should be considered in the total labor cost. In the above experiment, the training cost coefficient f in Eq. (10) was set to 1.2 to reflect this concern. However, the training cost coefficient will gradually decrease as the BSHS becomes more widespread in real projects, eventually returning to $f = 1$. This paper also conducted BOO experiments for f values of 1.0, 1.05, 1.1, and 1.15 to simulate the

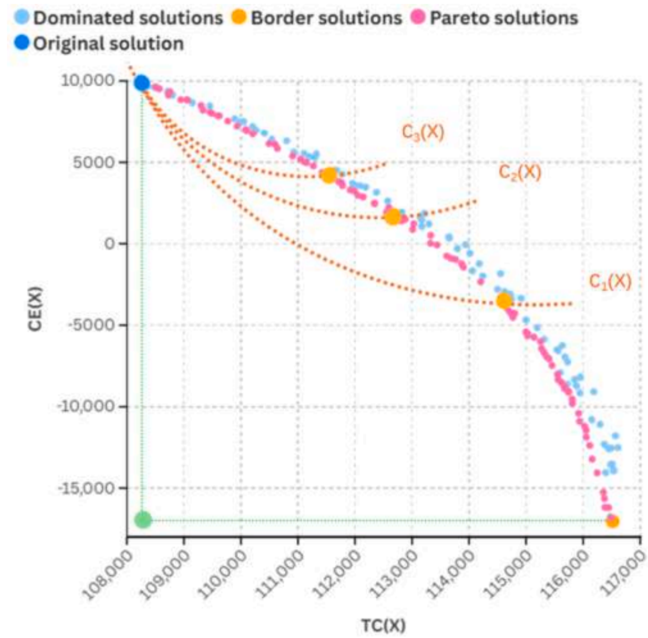

Fig. 9. Pareto solutions under different constraint requirements.

regression process, with the results shown in Fig. 10 and Table 2.

When f value decreases, the relationship between the two optimization objectives BOO simulation output gradually changes from negative correlation to positive correlation. The light blue area in Fig. 10 represents the range of feasible solutions under the constraint. When $f =$ 1.15 and 1.1, certain regions of the solution distribution (light pink area) exhibit a near-linear positive correlation trend. However, many feasible solutions still show a near-linear negative correlation, and no solution can completely dominate the original solution. The carbon reduction costs of the optimal solutions selected at these points are 246.6 % and 327.6 % of the current carbon trading price, respectively.

When $f = 1.05$, solutions in the pink area show a trend of near-linear positive correlation. In addition, most solutions in this area dominate the original solution. However, due to the existence of constraints, there is still no solution within the feasible range that can completely dominate the original solution. At this point, the carbon reduction cost of the optimal solution within the feasible range is only 33.7 % of the current carbon trading price. This also means the promotion and application of bamboo-steel hybrid scaffolding begin to yield practical benefits at this point.

When $f = 1$, that is the ideal situation, the distribution of all solutions approaches a near-linear positive correlation, meaning the minimum values that simultaneously satisfy both the carbon emissions and total cost optimization objectives can be achieved. Within the feasible range, solutions that can completely dominate the original solution have emerged. Compared to the all-steel solution, the BSHS can reduce both the life cycle carbon footprint and total cost simultaneously at this point.

Overall, the training cost coefficient f will gradually decrease as the BSHS becomes more widespread in real projects. Although a high f value in the early stages of promoting BSHS will cause the carbon reduction cost to be much higher than the average carbon trading price, once f falls back to a reasonable range (around 1.05), the carbon reduction cost of

Table 1
Pareto solution analysis of three reduction factor values.

Reduction factor	Constraint	min CE(X)	min TC(X)	Selected solution	Improvement in CE(X)	Improvement in TC(X)
1	$a \geq 0.52$	−3420	108,245	(113,323, 32)	99.6 %	−4.7 %
0.9	$a \geq 0.72$	1770	108,245	(112,550, 1929)	80.6 %	−4.0 %
0.8	$a \geq 0.81$	4300	108,245	(111,425, 4389)	55.9 %	−2.9 %

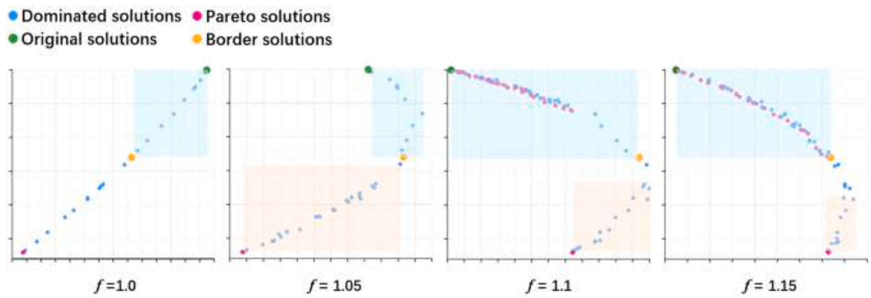

Fig. 10. Solutions for different f values.

Table 2
Carbon reduction cost for different f values.

f value	Final solution	Carbon reduction cost per t/CO2e	Percentage to current carbon trading price
1.20	(113,323, 32)	511.63	533.1 %
1.15	(111,023, 1121)	314.39	327.6 %
1.10	(109,675, 3916)	236.71	246.6 %
1.05	(108,664, −2981)	32.38	33.7 %
1.00	(105,639, −2981)	−201.42	−209.8 %

BSHS projects will be lower than the market carbon trading price. In the ideal case where $f = 1$, it is even possible to achieve a win-win situation of both cost savings and carbon emission reduction.

5. Discussion

5.1. Practical considerations and underlying mechanisms

To promote BSHS, the licensed bamboo scaffolder is a decisive factor. Thus, the certification programs are required. Currently, limited engineering experience with the hybrid scaffolding and the need to license bamboo scaffolders from scratch increase short-term adjustment costs, making BSHS slightly more expensive in terms of carbon reduction than the current average carbon trading price. However, as the new scaffolding is scaled up and widely adopted, the cost premium will gradually decline. An optimized BSHS can achieve significant reductions in carbon footprint with only a minimal cost increase—or potentially no increase at all. The main contributor to the carbon reduction is bamboo's carbon sequestration capability. Another considerable contributor is the reuse and recycling of disposed bamboo poles.

The optimized BSHS integrates two building materials with distinct mechanical properties. To mitigate potential safety risks brought by this integration, this paper suggests two approaches. One is localizing the structural reduction factor in Eq. (13). Decision-makers can adjust this reduction factor for strength redundancy with reference to the analysis in Section 4.3.1. The other is rigorous on-site protocols in practice. Licensed scaffolders and multi-stage on-site safety inspections are the two key levers in practical construction safety.

5.2. Policy implications

Government and regulators always play a key role in the local econo-technological evaluation and adoption of BSHS. Standardization regarding local materials and building standards is the first thing should be established in parallel with a few exemplar pilot projects. Strict criteria for scaffolding bamboo processing are crucial to ensure uniform structural integrity. Key features about bamboo poles, such as the harvesting age, diameter variations, moisture, and chemical treatments, should be taken into the grading criteria.

Secondly, government and regulators can leverage carbon market-assisted mechanisms to promote BSHS. Carbon sequestration benefit achieved by substituting steel with bamboo can be traded in commercial programs such as Emission Trading Schemes (ETS). The initial cost premium of BSHS can thus be offset.

Last but not least, government and regulators should include hybrid configurations into the temporary structure code. Moreover, a certification category for "hybrid scaffolders" should also be established to ensure workforce competency in assembly of mixed materials.

5.3. Limitations and future works

Nevertheless, this study has three major limitations. First, the analysis focuses only on the two dominant material choices in current scaffolding markets. With ongoing advances in material science, emerging sustainable materials, such as recycled plastic composites (Acuña-Pizano et al., 2022), bio-based polymers (Skoczinski et al., 2024), recycled aluminum (Thalmaier et al., 2025), and 3D-Printed biodegradable materials (Alkhalidi and Hatuqay, 2020) are gradually introduced to the market. Second, the discussion addresses only sustainability and cost issues during the initial stage. Additional aspects could be incorporated as further optimization objectives. Third, in defining the formulations, various standards and documents related to bamboo materials are involved. However, calculations may contain deviations since that some references are outdated, and regulations differ between Hong Kong and mainland China.

Therefore, future work is suggested in four aspects. First is about material selection. Future studies will examine different hybrid materials, including newly developed ones. And for optimization objectives, practical considerations such as construction time, overall weight, wind resistance, fire resistance, moisture, and corrosion performance will be included. Thus, the BOO model can be extended into a more comprehensive MOO framework (Jin et al., 2020). Moreover, alternative algorithms of BOO problems can be tested to identify the most efficient ones in the context of BSHS. Lastly, emerging technologies such as Generative Artificial Intelligence (GenAI) and information entropy-enhancement for NSGA-II (Zhou and Xue, 2025) can be adopted into the MOO/BOO framework.

6. Conclusion

Scaffolding is a primary type of temporary structure, which accounts for 10–25 % of total construction costs and 18–30 % of on-site labor requirements. It is urgently needed for sustainable transformation to fulfill the requirements of SDGs. Bamboo is an ideal scaffolding material due to its sustainability, strength, flexibility, and long history of use.

This paper proposes a BOO approach for BSHS, with carbon emission and total cost defined as two optimization objectives. A case site in Shenzhen, China, was introduced to evaluate the BOO-BSHS framework. After the selection among 91 Pareto-optimal solutions, the final design achieved a 99.6 % reduction in life cycle carbon emissions with only a

4.7 % increase in total cost compared to the steelwork. Further analysis suggests that BSHS is potential to achieve simultaneous reductions in both carbon emissions and cost when it is widely adopted and worker training costs decline. This represents a possible win-win scenario for the scaffolding industry.

The contributions of this study are two-fold. First, the BOO formulation of BSHS quantifies sustainability and cost goals of bi-material scaffolding. Second, the BOO results confirmed that BSHS considerably reduces life cycle carbon footprint and maintains cost efficiency and safety compliance. The field of temporary construction structures is always overlooked by mainstream sustainable building research. This paper expands the application of BOO into the field of scaffolding, establishing a methodological framework. The framework captures the trade-offs between the two scaffolding materials regarding environmental impacts and economic costs.

The BOO framework can be applied beyond the pilot case in Shenzhen. It can be adopted to other urbanizing regions adjacent to bamboo-producing area such as South and East Asia and Africa. What's more, the optimization framework serves as an adaptive template that can be customized for any hybrid-material scaffolding, not only bamboo and steel. Nevertheless, this study is limited by its focus on common scaffolding materials, incomplete project objectives, and the reliance on outdated regional bamboo codes.

Future research will thus test more materials, integrate additional objectives into an MOO framework, explore more efficient algorithms for BOO problems, and apply emerging technologies such as GenAI and Vision-Language Models (VLMs) to enhance site analysis and hybrid scaffolding design. These advancements are expected to accelerate the scaffolding industry's transition toward sustainable development.

CRediT authorship contribution statement

Xi Wei: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Fan Xue:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Jiajia Wang:** Software, Methodology, Formal analysis, Data curation. **Dong Liang:** Resources, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Fan, XUE reports financial support was provided by University Grants Committee Research Grants Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The work presented in this paper was supported by the Hong Kong Research Grants Council (C7080-22GF).

Data availability

The data used in this work will be available upon reasonable request.

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