Multi-objective optimization for parametric bamboo-metal mixed scaffolding design in Hong Kong

Xi Wei[1]*, Fan Xue[2]

Abstract: Bamboo, as an outstanding decarbonization construction material, has historically been the primary choice for scaffolding in Hong Kong. In contrast, globally adopted modern metal scaffolding ensures top-tier safety and stability at construction sites, and this type of scaffolding is utilized at some large-scale construction sites in Hong Kong. Apart from these two well-established scaffolding methods, this paper proposes a parametric bamboo-metal mixed scaffolding system to cater to the requirements of sites. The mixed system is parametrically generated by the multi-objective optimization, taking into account multiple site-specific objectives such as time efficiency, load-bearing capacity, and cost-effectiveness. The proposed designs leverage the strengths of both bamboo and metal scaffolding. In summary, the unique attributes of this innovative scaffolding system are well-suited to the demands of small-scale construction sites and contribute to the global decarbonization efforts within the construction industry.

Keywords: Bamboo-metal mixed scaffolding; multi-objective optimization; site-specific scaffolding system; sustainable construction.

1 Introduction

Bamboo scaffolding is a type of scaffolding commonly found in Hong Kong and is also used in southern China and various Southeast Asian cities (Fang et al. 2004). In Hong Kong, the use of bamboo scaffolding is not only driven by considerations of cost and time, but also serves as a means of inheriting traditional scaffolding techniques. Its existence is close to a thousand years (Huang 2021), and bamboo scaffolding-like structure is depicted in the renowned "*Along the River During*

[1]Xi Wei
Department of Real Estate and Construction, The University of Hong Kong, Hong Kong SAR, China
* Corresponding author, weixi77@hku.hk

[2]Fan Xue
Department of Real Estate and Construction, The University of Hong Kong, Hong Kong SAR, China
E-mail: xuef@hku.hk

the Qingming Festival" painted by Zhang Zeduan from the Northern Song Dynasty (Figure.1a) (SCMP 2022). The craftmanship of constructing temporary bamboo structures is not only used for scaffolding projects on construction sites but also finds application in temporary gatherings or stage spaces during some important festivals in the Great Bay area (Figure.1b). The distinctive feature of bamboo scaffolding lies in its utilization of natural bamboo as the primary material, combined with bamboo or nylon strips for tying purposes.

Figure 1 Traditional bamboo temporary structure. (a) Bamboo scaffolding-like structure in "Along the River During the Qingming Festival" (b) Temporary bamboo opera theatre

In Hong Kong, the primary sources of bamboo scaffolding materials are the Zhaoqing region in Guangdong Province and certain areas of Guangxi Province. Among the more than 1,200 species of bamboo worldwide, moso bamboo (*Mao Jue*) and penny bamboo (*Kao Jue*) are the principal types used at construction sites.

Bamboo scaffolding significantly contributes to the global decarbonization of the construction phase. Carbon emissions from the construction industry are one of the major causes of global warming, and how to make the construction industry carry out sustainable development has always been a concern for all walks of life. Scaffolding, as an important part of the building construction project, has a budget of about 15% of the total project cost (Hou et al. 2017), and the implementation of environmentally friendly scaffolding systems can notably decrease the overall carbon footprint of a project. Therefore, the promotion and application of sustainable scaffolding types, such as bamboo scaffolding, should be encouraged. (Laleicke et al. 2015).

In Hong Kong, bamboo scaffolding offers five key advantages over metal scaffolding as below:

1. Lower cost: The region surrounding Hong Kong is rich in bamboo resources, making it a more cost-effective option. High-quality bamboo is approximately 5% of the price of metal tubing (MBMSS 2009), presenting an attractive choice for various construction sites.

2. Lightweight: Bamboo has nearly half the weight of standard metal tubing of the same length, making it a crucial option for specific building projects that require truss-out structures.

3. Faster assembly and disassembly: Due to the lightweight nature of bamboo and the extensive professional training of workers, bamboo scaffolding can be erected up to six times faster and dismantled up to 12 times faster than steel scaffolding.

4. Flexibility: Bamboo's flexibility allows for the size of members to be adjusted according to site conditions, which is particularly advantageous in a high-density city like Hong Kong.

5. Lower carbon footprint: Bamboo's natural material properties result in a significantly reduced carbon footprint compared to metal scaffolding, promoting the sustainable development of the construction industry.

Overall, these benefits make bamboo scaffolding an appealing choice for construction projects in Hong Kong and other regions with similar conditions.

During the 1990s, nearly all construction projects in Hong Kong utilized bamboo scaffolding, with only 5% of projects employing metal scaffolding (Chang & Yu 2002). Construction projects under the supervision of the Building Department even achieved a 100% bamboo scaffolding usage rate, including many large-scale projects such as the Convention and Exhibition Center. However, this trend is gradually shifting, as metal scaffolding now accounts for 30% to 40% of construction projects in Hong Kong, particularly in prominent public projects like the M+ Museum, where metal scaffolding has been used exclusively. Common metal scaffolding can be further categorized into steel scaffolding and aluminum alloy scaffolding.

Bamboo scaffolding is gradually being supplanted due to several factors. The primary concern is safety. According to Bambhava (2013), the most important factors that employers consider when choosing the type of scaffolding are "safety" (32%) > "availability" (30%) > "cost" (25%) > "erection and dismantling time (12%)". Safety is the primary consideration. However, bamboo's characteristics, including uneven strength, susceptibility to moisture and damage, and inadequate wind resistance, have resulted in safety incidents related to bamboo scaffolding. Another significant factor contributing to the decline of bamboo scaffolding is the high demands it places on construction workers. As per the Code of Practice for Bamboo Scaffolding Safety in Hong Kong (HKLD 2001), qualified workers must undergo an extensive training period of up to three years and secure a certificate of authorization before being permitted to erect and dismantle bamboo scaffolding. As society accelerates, fewer young people are willing to invest several years to acquire this skill. Table.1 and Figure.2 show the comparison of scaffolding made of bamboo, steel and aluminum materials.

Table 1. Comparison of Bamboo, Steel and Aluminum alloy Scaffoldings

Material	***Bamboo***	***Steel***	***Aluminum alloy***
Cost	Lower	Higher (In Labor)	Higher (In Material)
Safety (Strength)	Lower	Higher (In Weight Bearing)	Higher
Safety (Durability)	Lower (susceptible to moisture, rot, and insect attacks)	Higher	Higher (In Corrosion)
Availability	Lower (Specific Regions)	Higher (Worldwide Spread)	Higher (Worldwide Spread)
Erection and Dismantling Time Consumption	Lower	Higher	Higher
Flexibility	Higher	Lower	Higher
Weight	Lower	Higher	Lower
Sustainability	Higher (Natural Material)	Lower	Lower
Maintenance	Higher	Lower	Lower

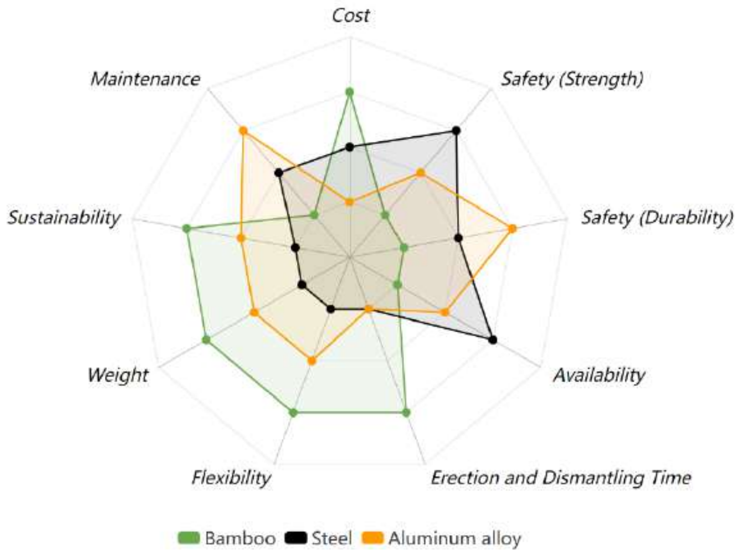

Figure 2 Comparison of Bamboo, Steel and Aluminum alloy Scaffoldings

Bamboo scaffolding and metal scaffolding have different suitable applications in construction sites. For instance, small truss-out renovation projects greatly benefit from the lightweight and quick-to-assemble bamboo scaffolding. In contrast, large-scale projects that prioritize safety and have longer construction timelines are more suitable for metal scaffoldings. However, in high-density cities like Hong Kong, construction projects of varying scales and requirements must often choose between bamboo and metal scaffolding, leading to certain compromises on safety or cost. This situation not only reduces project efficiency but also results in a waste of resources. A more tailored approach to scaffolding selection, considering the specific needs and constraints of each project, could help mitigate these issues and optimize overall construction efficiency and resource utilization.

Therefore, this paper aims to propose a hybrid bamboo-metal mixed scaffolding system that quantifies a project's scaffolding requirements in terms of strength, weight, cost, and time consumption based on the actual circumstances of the project. This approach involves a multi-objective optimization of material combinations for scaffolding components, generating a site-specific scaffolding combination scheme that leverages the respective advantages of both materials. In this paper, a building façade renovation project in the Sham Shui Po area of Hong Kong was selected as a case study to demonstrate the effectiveness of a bamboo-metal mixed scaffolding solution.

2 Literature Review

2.1 Hybrid material scaffolding

In current literature, many of the researchers are conducting experiments and exploring alternative materials for scaffolding due to the high carbon footprint of steel scaffolding during production, transportation, and installation, as well as its larger self-weight. Examples of these alternative materials include aluminum alloys (Chang et al. 2021), high-strength plastics, fiberglass resins (Małek et al. 2022). These materials provide new options for construction scaffolding selection and demonstrate superior characteristics compared to steel or bamboo in certain aspects. However, they also introduce new limitations. At present, there is no single scaffolding material that consistently outperforms others across most criteria. This highlights the need for continued research and development in the field of scaffolding materials and the potential benefits of hybrid systems that combine the advantages of multiple materials to optimize performance in various construction settings.

The new material scaffolds mentioned above still adhere to a single-material system, and there is limited research on mixed-material scaffolds in existing literature. So Yu Shing (2009) proposed a Metal-Bamboo Matrix System Scaffold (MBMSS), where the primary load-bearing components of the bamboo scaffolding system were replaced with steel pipes to enhance the overall structural strength and consequently, safety. The remainder of the secondary structural and non-structural components mainly used bamboo material to minimize cost and self-weight. However, this hybrid material system is not site-specific. The ratio of bamboo to steel is fixed at around 6:4, and it simply provides a third option between bamboo scaffolding and steel scaffolding for construction projects in Hong Kong. It does not address the issue of wasted scaffolding resources due to differing objectives at various types of construction sites. This paper aims to address this gap by proposing a site-specific hybrid bamboo-metal mixed scaffolding system.

2.1 Optimization on scaffoldings

As a crucial component of the building construction process, scaffolding is produced, transported, installed, used, maintained, and dismantled in a manner that considers all relevant aspects. Therefore, the decision-making process for scaffolding use involves balancing multiple needs, some of which may even conflict with each other. Consequently, scaffolding optimization is of immense importance.

Jin (2023) developed an automated decision-making model to optimize scaffolding, selecting three factors for consideration: accessibility, worker protection, and health risks in scaffolding construction. These factors were chosen to optimize the scaffolding planning method, reduce construction costs, and enhance the safety of the scaffolding system.

Similarly, Hou et al. (2017) formulated a multi-objective discrete firefly algorithm to optimize the time and cost of the scaffolding construction process, generating a case-specific scaffolding scheduling plan. Hou et al. (2014) developed a mathematical optimization algorithm framework to digitize the scaffolding erection and dismantling process in virtual simulation scenarios, aiming to reduce risk during the construction process.

Kim et al. (2016) developed an optimization engine based on Building Information Modeling (BIM) to generate multiple alternative scaffolding plans. These plans were then simulated by a safety simulation engine based on real-life construction site conditions to identify safety hazards.

These models and algorithms all underscore the complex interplay of factors involved in scaffolding use and the need for robust optimization strategies. However, the main object to optimize in these models is only the plan and frame of the scaffolding systems rather than including the material of the scaffoldings.

3 Research Method

This paper presents a multi-objective optimization method for bamboo-metal mixed scaffolding system based on site-specific situation and demand analysis, which is divided into four parts as shown in the Figure.3. Analysis of the site situation to quantify the site-specific demands; 2. Define the objective optimization functions according to the site demands; 3. Solving the MOO formulation by the Wallacei X plugin on Grasshopper platform; 4. Pareto frontier and final solution. This systematic approach allows for a comprehensive analysis of site-specific needs and the optimization of the scaffolding system to meet these needs, balancing multiple objectives and integrating the advantages of both bamboo and metal materials.

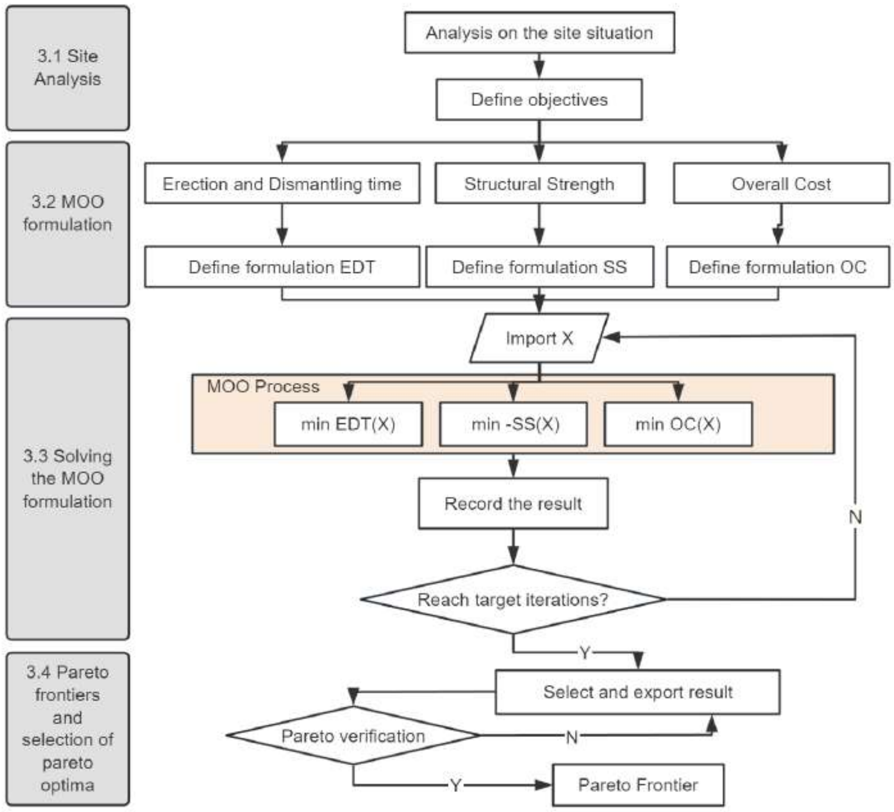

Figure 3 Research method

3.1 Site analysis

This paper selected a local renovation project in Hong Kong as the case study. The project involves the lower part of Building No. 39 on Un Chau Street in the Sham Shui Po area. The façade of the building measures approximately 7.8 meters in width and 6.9 meters in height. The site is located on the side of the street and houses commercial stores with doors facing the street. This case study provides a practical example for the application of the proposed bamboo-metal mixed scaffolding system.

To minimize the impact on the normal activities of the stores at the site, one of the main optimization objectives is to minimize the time consumption for the erection and dismantling of the scaffolding system. Additionally, ensuring the safety of the system is another optimization objective due to the site's location in an area with higher pedestrian traffic density compared to regular residential areas. Finally, cost, as a fundamental optimization objective, is also considered. For this site, the traditional bamboo scaffolding framework is shown in Figure 4. Define set $\mathbb{X}$ =

$\{x_1, x_2, \ldots, x_n\}$, n = | 𝕏 |, and x_i is one of the bamboo elements within the scaffolding framework.

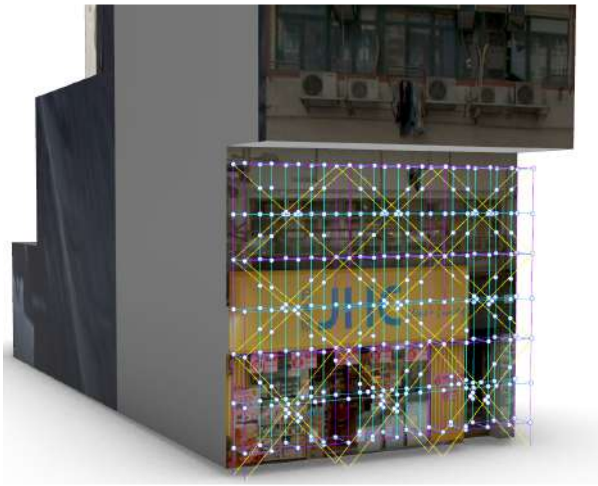

Figure 4 A bamboo scaffolding frame with the group of different parts

3.2 MOO formulation

The MOO formulation for bamboo-metal mixed scaffolding system consists of three objectives, as shown in Eq. (1).

$$\textbf{optimized } F(X) = \textbf{min } EDT(X), -SS(X), OC(X)$$

$$\textbf{subject to } X = \{x_1, x_2, \ldots, x_y\}, x_i \in \mathbb{X}, \text{and } 1 \leq i \leq y \leq n, \quad (1)$$

where X ⊆ 𝕏 is a collective metal element set; x ∈ 𝕏 represents a metal tube that replace the bamboo element; EDT(*X*), SS(*X*), and OC(*X*) are the main objective functions regarding time consumption, safety, and material cost, respectively; and y = | X | is the quantity of metal tubes that been used as the replacement of bamboo elements.

For the erection and dismantling time, this paper took a simplified way to quantify and compare the time consumption of each scaffolding element during the process of erection and dismantling. Because of the characteristic of being modular, the time consumption can be calculated by the unit time and the number of the element joints. The ratio of the erection and dismantling time between bamboo and metal is around 1:6 and 1:12 respectively (SCMP 2022). Define the time consumption of a bamboo-bamboo joint as a, and the number of bamboo-bamboo joint as b_1, define the time consumption of a metal-metal joint as c, and the number of metal-metal joint as b_2. To simplified the calculation, we set $c = 9a$, which is the average ratio of erection and dismantling time consumption. For the bamboo-metal joint, the time consumption can be calculated by the average of bamboo-bamboo and metal-metal scaffolding, which is $5a$, and the number of bamboo-metal joint is b_3. Thus, the first objective of time consumption can be defined as below:

$$\boldsymbol{EDT(X)} = a * b_1 + 9a * b_2 + 5a * b_3 \quad \textbf{(2)}$$

Regarding the safety issue of the scaffolding system, it is necessary to optimize the structural strength of the overall system. The design strength of metal scaffolding is around 4 kPa and 1.45 kPa for bamboo scaffolding (MBMSS 2009), thus the strength ratio of the two material can be inferred correspondingly. By simplifying the strength ratio of bamboo material and metal material in the optimal state, set the structural strength of bamboo under the same function as k, and then the structural strength of metal as $2.75k$.

As shown in Figure.4, in the scaffolding framework, the bamboo elements in different positions have different functional attributes and structural contribution degrees. The purple part is the main support structure, the number of bamboo elements is t_1, the number of metal elements is l_1, and the weight of the component attached to this part is 2; the cyan part is the regular support structure, the number of bamboo elements is t_2, the number of metal elements is l_2, the weight of this part is set to 1; the yellow part is brace, the number of bamboo elements is t_3, the number of metal elements is l_3, the weight of this part is set to 1.5 since the scale of the structure of the wind resistance requirements are smaller; The rest of the components are auxiliary connecting components, the number of bamboo elements is t_4, the number of metal elements is l_4, and the weight of this part is set to 0.5; the node part is not given weight in this paper due to the similarity of the strapping technique and the metal coupler in terms of structural strength. In the context of the selected site, $\sum(t+l)=n$. Therefore, the second objective relating to the structural strength is defined as below:

$$\boldsymbol{SS}(\boldsymbol{X}) = k * [2(t_1 + 3l_1) + (t_2 + 3l_2) + 1.5(t_3 + 3l_3) + 0.5(t_4 + 3l_4)] \qquad (3)$$

For the cost aspect, the way to quantify the material cost is similar to the method of quantifying the structural strength. Define the unit cost of each bamboo element in average as e, then the cost of metal element in average is $2e$. Therefore, the third objective regarding system overall cost is defined as below:

$$\boldsymbol{OC}(\boldsymbol{X}) = e * \sum t + 2\mathrm{e} * \sum l \qquad (4)$$

In order to unify the optimization direction of the three objective functions, in this paper, the second objective function SS(X) is inverted in the calculation to facilitate the simulation of multi-objective optimization in the later stage.

3.3 Solving the MOO formulation

This paper employs the *Wallacei X* plugin (ver.2.7) on *Grasshopper* to calculate and solve the MOO formulation Eq.(1) using the NSGA-II algorithm. For each group of structural elements, there are two parameters to control the number and position of which bamboo element is replaced by metal element. By inputting the parameters into *Wallacei X* as gene pools, the three objective functions defined in the previous section can be calculated using the built-in functions of Grasshopper. The amount of the generation was set to 200, and the population size of each generation was set to 100, thus 20,000 population size in total.

3.4 Pareto frontier and the final solution

After a calculation of 11 minutes and 22 seconds, the MOO formulation was solved within the *Wallacei X* plugin. The number of unrepeated Pareto optimal solutions from the last generation of simulations was 20, which forming the Pareto frontier of this MOO problem.

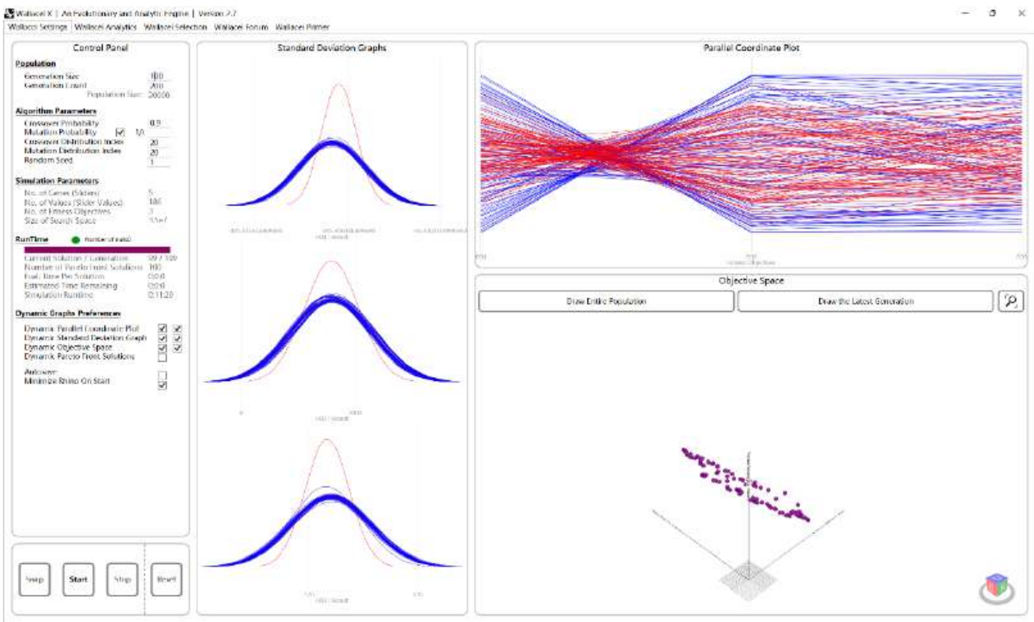

Figure 5 MOO problem solving interface

Figure 5 shows the Wallacei X interface solving the problem. The parallel coordinate plot depicts the relationships among the three objectives. The first objective and the second objective show a strong negative correlation, which means the functions EDT(X) and SS(X) show a positive correlation, the more time spent on the erection and dismantling stage, the more structural strength is within the system. Meanwhile, the second objective SS(X) and the third objective OC(X) show a positive correlation, which means the more structural strength of a system, the more cost it will take for the construction site.

After obtaining the Pareto Frontier, the determination of the final solution can be made by the site decision-makers. A comprehensive analysis of the demands can be conducted to finalize the choice, considering the weighted relationships among the various objectives. In the case of the selected site discussed in this paper, a detailed demands analysis has not been performed. Therefore, the final solution was chosen based on the average rankings of the three objectives collectively. Figure 6 illustrates the final material placements for the scaffolding framework, with the red components representing metal pipes and the green lines indicating bamboo tubes.

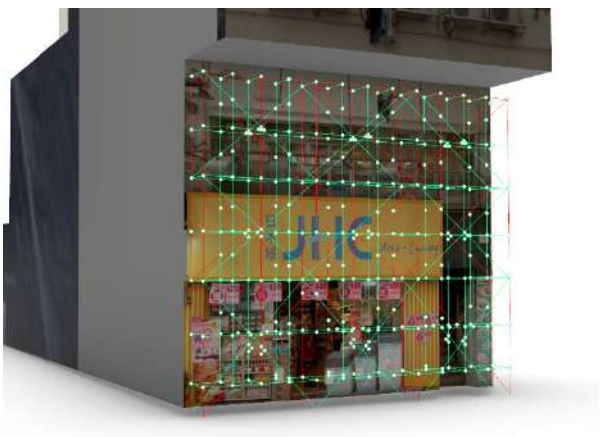

Figure 6 3D visualization of the final solution of the proposed bamboo-steel scaffolding system.

4 Discussion

4.1 Pros and cons

This paper presents a novel scaffolding system that employs multi-objective optimization to facilitate the mixed use of bamboo and metal materials, tailored to various construction scenarios. In a context where most scaffolding systems exclusively offer a binary choice between bamboo and metal frameworks, this innovative design delivers customized bamboo-metal hybrid scaffolding solutions for different construction sites, effectively addressing the diverse requirements of distinct projects.

The primary contributions of this paper can be divided into two folds. First, by incorporating a mixture of bamboo and metal materials, the significant drawbacks of both types of scaffolding can be mitigated, enhancing the safety of pure bamboo scaffolding and avoiding the high cost and low efficiency associated with pure metal scaffolding. Second, the ratio of different materials in the new scaffolding system is determined through multi-objective optimization, which is tailored to each specific construction site. This approach fully capitalizes on the advantages of both materials, catering to the diverse demands of various construction projects in terms of time, cost, safety, and durability. Consequently, this minimizes waste and reduces the carbon footprint of construction projects.

This paper presents certain limitations as well. First, it solely considers bamboo and steel scaffolding materials, overlooking the emergence of various other types of scaffolding materials in the market, such as aluminum alloys, high-strength plastics, and fiberglass. Each of these materials possesses unique properties that cater to diverse needs. Moreover, the chosen scaffolding structure is based on the traditional bamboo scaffold framework, which is relatively denser due to the disparities between bamboo and metal materials. However, after substituting some components with metal materials, the overall scaffold frame still adheres to the bamboo style, potentially resulting in excessive structural redundancy. Lastly, the calculation of the strength and deformation of the bamboo-metal mixed scaffolding system is oversimplified by equating the strengths of the two materials to a fixed ratio and adding them together. In reality, the stress conditions of different materials in various positions may differ, necessitating a more comprehensive mechanical simulation analysis for the evaluation of structural deformation.

4.2 Future work

To address the three primary limitations previously mentioned, the future work of this paper can be segmented into the following three areas. First, a comprehensive review of existing scaffolding materials, particularly newer ones, can be undertaken. This analysis would assess the feasibility of integrating these materials further into the proposed bamboo-metal mixed scaffolding and incorporating additional materials as design variables in future multi-objective optimization.

Second, future work should consider incorporating the number of components and the spacing between them as part of the variables in the multi-objective optimization process. Additionally, future research will involve evaluating and compiling the entire life cycle of the scaffolding system, extending beyond the on-site phase to encompass the production and transportation of raw materials, as well as storage and disposal after dismantling.

Lastly, during the formulation stage of defining structural deformation, mechanical simulation plugins for Grasshopper platforms, such as Kangaroo and Karamba3D, can be employed to perform mechanical simulations on mixed scaffolding systems with varying materials. This approach would yield accurate component deformation variables, serving as the foundation for multi-objective optimization. Multiple advanced technologies can be applied in the field of scaffolding design and management such as Machine Learning (Liang & Xue 2023), Blockchain (Zhao et al. 2023), CIM (Li et al. 2024), 4D Point Cloud (Liang et al. 2024), etc.

5 Conclusion

Bamboo scaffolding is a type of scaffolding with exceptional sustainability features and is considered intangible cultural heritage in Hong Kong. It offers several unique advantages compared to metal scaffolding. However, due to increasing safety requirements for construction projects and the demand for standardization and durability in large-scale construction projects, the prevalence of traditional bamboo scaffolding in the Hong Kong construction market is diminishing. On the other hand, metal scaffolding also has notable limitations, with high costs and low assembly and disassembly efficiency being its primary drawbacks. In most cases, construction projects are forced to choose between bamboo scaffolding and metal scaffolding, leading to compromises and concessions. This results in a waste of time and cost in many construction projects, as well as a higher carbon footprint during the production, transportation, and assembly processes.

This paper proposes a bamboo-metal mixed scaffolding system, which analyzes the specific requirements of construction projects concerning various scaffolding characteristics, such as safety, cost, erection and dismantling time, durability, flexibility, self-weight, and other factors. A multi-objective optimization method is employed to optimize and select the materials of components at different positions. On the one hand, it combines the advantages of both material types while also preventing waste of time and costs. This paper selected a section of the facade of No. 39 Un Chau Street, Sham Shui Po, Hong Kong, as a case study, analyzed the requirements, formulated corresponding optimization objectives, and performed simulations. In future research, the review and application of new materials, as well as the comprehensive mechanical simulation analysis of the mixed scaffolding system, will be conducted to enhance the rigor and comprehensiveness of the study.

The design of a mixed scaffolding system allows for customization of metal and bamboo components based on the specific requirements of a construction project. The computational results of the pilot project demonstrated that this approach is technologically feasible and holds great significance for optimizing scaffoldings, balancing engineering efficiency, structural strength, and project costs – at least for small-scale projects. Broader adoption of this mixed scaffolding system in cities near bamboo habitats can contribute to the global decarbonization efforts within the construction industry.

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