Reinterpreting Traditional Windows Lattices Patterns in Contemporary Design through Parametric Design and Digital Fabrication

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Windows' lattice patterns are essential parts of traditional Chinese garden architecture in Suzhou, as they boast unique artistic charm and profound cultural connotations. Furthermore, classical lattices have been widely applied in contemporary design. Existing research mainly focuses on the design principles of lattices themselves, such as ice-ray lattice patterners. However, the selection of lattice patterns is often based on subjective perceptions of designers without specific criteria. Therefore, this paper intends to take the daylighting performance of windows' lattices as a reference criterion for designers to choose their types. Parametric design has been demonstrated to perform well in timber design and sustainability analysis, while robotic fabrication excels in accurately assembling complex standard timber designs. This research introduces a file-to-fabrication workflow to assist the designer in selecting suitable lattices in contemporary design and accurately assembling their design. A landscape wall composed of a selected lattice pattern is used to identify the feasibility of the workflow.

Keywords: *Lattice patterns, Robotic fabrication, Digital design, Daylighting analyses.*

INTRODUCTION

The windows of Chinese traditional architecture (Figure 1) are not only practical components but also an important part of architectural aesthetics. Window lattices are not merely decorative elements but multifunctional components, serving functions such as sunlight penetration, aesthetic expression, and cultural symbolism. The designs of window lattices in Chinese-style architecture often incorporate art forms like calligraphy and painting, demonstrating the profound heritage of traditional Chinese culture. The window-lattice designs in Chinese gardens and buildings frequently embody the artistic conception of landscape paintings. Through methods such as borrowing scenery and framing views, they seamlessly integrate natural and humanistic spaces, reflecting the philosophical ideal of "harmony between man and nature." Therefore, in contemporary Chinese-style

Figure 1
A classical lattice pattern window.

architecture, the window-lattice design remains widely applied.

The traditional Chinese window lattice pattern has been extensively employed in architectural practices, with numerous scholars exploring its cultural significance, generative principles, and sustainability implications. As illustrated in Figure 2a, a China-style pavilion designed by the Shanghai Jiangnan Architectural Design Institute (上海江南建筑设计院) in 2021 exemplifies the application of this pattern, drawing inspiration from classical window designs. In this project, the lattice serves dual functional purposes: facilitating sunlight penetration and regulating wind flow. Jianguo Liang(梁建国), a renowned architect specialising in Chinese-style design, is particularly adept at incorporating lattice patterns as decorative elements and functional sunlight-modulating components in his works, as depicted in Figure 2b. Furthermore, lattice patterns inspired by traditional designs are prevalent in various settings across China, including gardens, pavilions, parks, and tourist attractions.

In academic fields, scholars focus on cultural significance and design principles. Regarding cultural values, the lattice pattern design is always inspired by plants, flowers, animals and classical Chinese words (Gu, 2007; Shi, 2005). The pattern designs all embody wishes for happiness and auspiciousness. For instance, the commonly seen characters such as "囍 (Happiness)", " 福 (Good Fortune)", and "寿 (Longevity)" are elements with the theme of auspicious implications in traditional architecture(Wang, 2021). At the same time, the details of the patterns are also related to people's social status(Gu, 2007; Shi, 2005; Wang, 2021; Yi, 2018). The patterns on the windows of wealthy families are usually more exquisite and intricate. In addition, the patterns are integrated with the local architectural style and aesthetic concepts. In contemporary Chinese-style building design, cultural value remains a primary criterion for the selection of lattice patterns. Another relevant criterion lies in the radiation ability of lattice patterns, particularly when applied in contemporary design. As a decorative element for windows, lattice patterns can significantly influence daylight penetration, a factor that warrants further investigation (Hosseini et al., 2018). However, only a limited number of studies have conducted relevant research in this area.

In the realm of design principles, Dye (1974) investigated the underlying logic of traditional Chinese lattice patterns through mathematical methodologies. Xu (2012) further extended this approach by conducting a mathematical analysis of flower lattice patterns. Subsequently, researchers began to explore the digital generation of these lattice designs. Lee and Tiong (2013) examined the algorithmic generation of lattice patterns based on their mathematical foundations. He and Schnabel (2018) focused on the Chinese flower windows of the Lingering Garden in Suzhou, employing parametric design methods to uncover the logic behind their intricate patterns and to achieve their digital

Figure 2
a, A classical lattice pattern used in contemporary pavilion; b, a classical lattice pattern used in interior design.

generation. Their study demonstrates the viability of parametric generation in the context of traditional Chinese flower windows, offering methods that can be broadly applied in the integration of cultural heritage with digital technologies. Additionally, Rian (2024) investigated the potential application of ice-ray lattice patterns in the design of shell structures.

According to the existing research, traditional windows' lattice patterns are essential parts of traditional Chinese garden architecture in China, as they boast unique artistic charm and profound cultural connotations (Zhang et al., 2021). Furthermore, classical lattices have been widely applied in contemporary design (Majewski & Wang, 2009). Existing research mainly focuses on the design principles of lattices themselves, such as ice-ray lattice patterners (Rian, 2024). However, the selection of lattice patterns is primarily based on subjective perceptions of designers and cultural values without specific criteria. Therefore, this paper intends to take the daylighting performance of windows' lattices as a reference criterion for designers to choose their types. Parametric design performs well in timber design and sustainability analysis, while robotic fabrication excels in accurately assembling complex standard timber designs. This research introduces a file-to-fabrication workflow to assist the designer in selecting suitable lattices in contemporary design and accurately assembling their design. The paper addresses the following questions:

1. How can we develop a database based on the daylighting ability of classical lattice patterns?
2. How can we reinterpret the lattice pattern in contemporary design?

Figure 3
The file-to-fabrication framework.

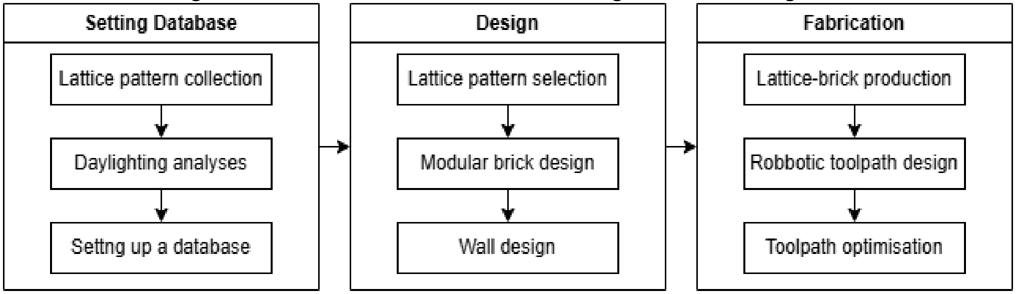


Figure 4
A traditional tall window in Suzhou City.

METHODOLOGY

To answer these questions, the paper introduced a file-to-fabrication framework (Figure 3) that integrates daylighting analysis, voxelization, robotic fabrication and machine learning. The Suzhou Ming-Qing lattice pattern has been selected as a case study for the analysis. First, the type of windows' lattices are collected based on existing research, and then Ladybug (Roudsari & Pak, n.d.), a Grasshopper plugin, is introduced to analyse daylighting ability under specific settings. The data will be used to set the database as the reference in the design process. Second, a landscape timber wall, where a standard lattice unit is selected as a brick element. Given that the design is situated in Suzhou, a lattice unit with relatively lower daylighting performance is deliberately selected to maximise shade generation, aiming to relieve the summer heat for occupants. Finally, the timber wall is manufactured using a CNC router and assembled with the assistance of a UR10 robot. The tolerance is analysed by using LunchboxML (LunchBox Grounp, n.d.), a machine-learning plugin of Grasshopper, to predict the robot's pathway.

Data collection and daylighting analyses

The initial phase of this research involves the systematic collection of data pertaining to the types and dimensions of window lattice patterns in Suzhou. Two seminal rule books serve as critical resources in this data collection process, as they meticulously document the dimensions, types, and construction methods of lattice patterns. The first is the *Yuanye* (园冶), authored by Ji Cheng and published in 1634. This work is recognised as the world's first monograph on garden design and provides invaluable insights into the historical and technical aspects of lattice patterns. The second key text is *Yinzhao Fayuan* (营造法原), originally compiled by Yao Chengzu, with

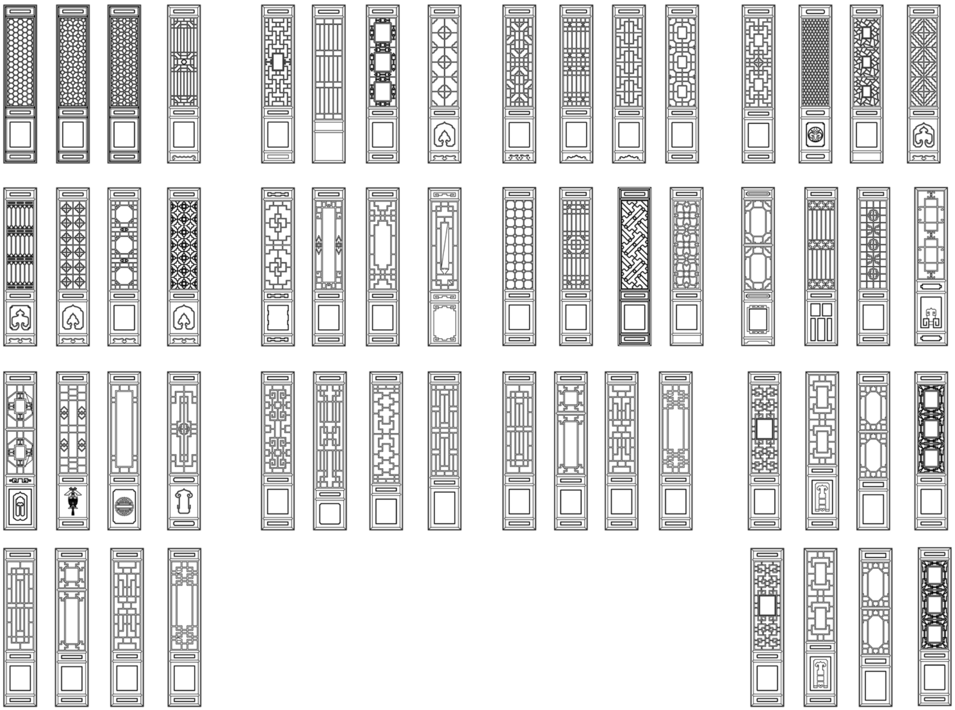


Figure 5
Forty-eight traditional Chinese tall windows in Suzhou.

Figure 6
Five selected tall windows.

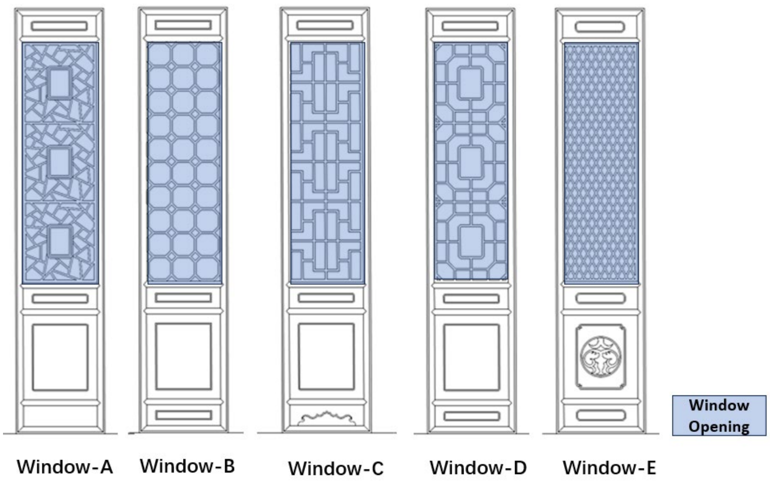
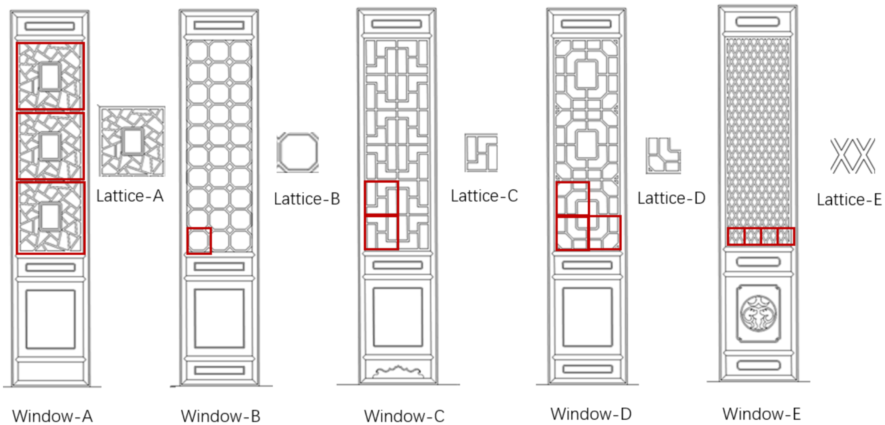


Figure 7
Lattice patterns of five selected tall windows.



supplementary editing by Zhang Yongsheng and scholarly review by Liu Dunzhen. First published in 1959 (and republished in 1986), this book offers a comprehensive account of the construction methods of ancient architecture in the regions south of the Yangtze River of China. It is an essential reference for understanding the form, structure, and evolutionary development of architectures in the region, making it indispensable for this study.

After revising these books, based on the shape of windows, there are primarily seven types: Chinese tall windows, moon-gate windows, fan-shaped windows, square windows, hexagonal windows, scroll-shaped windows, and gourd-shaped windows. In this study, we selected the Chinese tall window as the research focus due to its widespread application in Chinese-style architecture as a primary enclosure structure, as illustrated in Figure 4. A total of forty-eight lattice patterns for tall windows are documented in two reference books (Figure 5). To assess the feasibility of the proposed workflow, five out of forty-eight lattice patterns are selected (Figure 6).

After analysing these lattice patterns, the research finds that they operate as modular units. As shown in Figure 7, a lattice pattern for a tall window can be created by moving and rotating a basic lattice unit. By using this basic unit as a modular component in contemporary design, diverse outcomes can be achieved. The placement of the lattice within a given geometry can be controlled through grid planes.

Additionally, the study analyses the daylighting performance of five selected lattice patterns to establish a database. This database serves as a reference for selecting lattice patterns in contemporary design. Ladybug is used to evaluate the daylighting performance of these patterns when applied to tall windows. A box-shaped house model, measuring 3 meters in height, 3 meters in width, and 4 meters in length, is employed for the simulation.

Five tall windows, each featuring one of the five lattice patterns, are analysed to compare their daylighting performance. The lattice windows are oriented to face south to ensure optimal natural lighting. Weather data for Shanghai are input into Ladybug for the analyses, as the climatic conditions in Suzhou are similar to those in Shanghai. The window opening area is 0.6m^2 without any lattice pattern covering it. In this research, the lattice patterns are defined as shading elements to assess their daylighting performance. The window-A, B, C, D and E is covered by lattice patterns A, B, C, D, and E, with corresponding window opening areas of 0.425m^2, 0.491m^2, 0.362m^2, 0.484m^2, and 0.480m^2, respectively.

Table 1
Average daylight autonomy of five selected lattice windows

Type of Lattice pattern	Average Daylight Autonomy (DA)	Area of window opening (m^2)
Lattice-A	34.22%	0.425
Lattice-B	48.83%	0.491
Lattice-C	44.35%	0.480
Lattice-D	45.25%	0.484
Lattice-E	16.18%	0.362

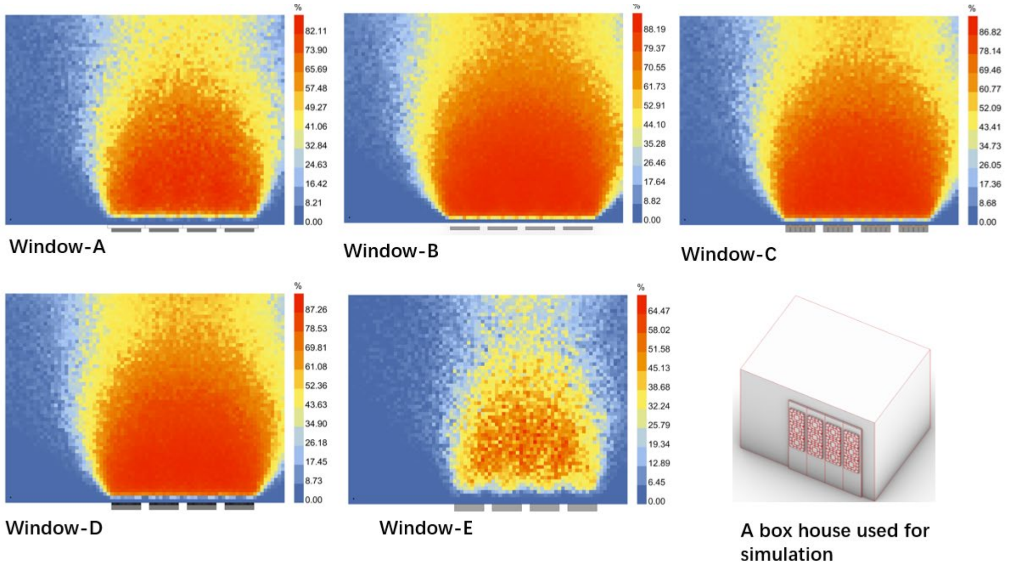


Figure 8
The daylighting performance analyses of five lattice patterns in tall windows.

In this study, average daylight autonomy (DA) is employed to evaluate the radiation performance of the lattice pattern, with lower

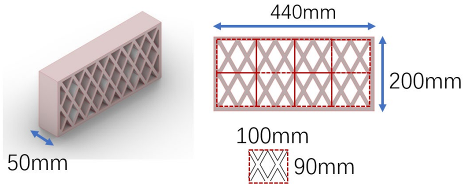


Figure 9
A brick unit consisting of eight standard Lattice-E patterns.

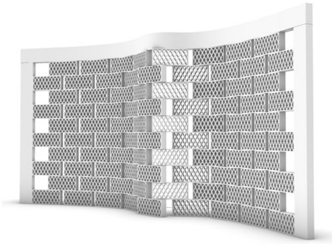


Figure 10
A landscape wall consisted of timber lattice-brick units.

values indicating poor performance. The results, as depicted in Figure 8 and Table 1, suggest that Lattice-B outperforms the other patterns in terms of daylighting performance (48.83%), while Lattice-E exhibits the lowest daylighting efficiency (16.18%) among the tested patterns. The higher density of shading components per square meter in Lattice window-E compared to other windows could be the reason for its poorer daylighting performance.

Design and Fabrication

In the design process, a landscape wall incorporating a selected lattice pattern is designed and fabricated to evaluate the feasibility of the proposed file-to-fabrication workflow. Given the climatic conditions in Suzhou, where summers typically span five months, lattice patterns with lower daylighting capability are prioritised to mitigate the effects of solar radiation. Based on the analytical results from the initial phase, Lattice-E has been selected for this purpose. A modular brick unit is designed by using Lattice-E following traditional generation principles. The brick unit consists of eight standard Lattice-E (Figure 9). The dimensions of one lattice pattern are 100mm in width and 90mm in height, which is its original size.

A grid system is applied to the given surface during the design process to generate the wall structure. A cuboid measuring 44 cm in length, 5 cm in width, and 22 cm in height serves as the control unit to determine the placement of Lattice-E within the wall. These cuboids are arranged in alignment with the planes defined by the grid points. The resulting timber-wall (Figure 10), measuring 4.4 meters in length, 2.2 meters in height, and 0.05 meters in width, is designed. Subsequently, the lattice and common brick walls are analysed to evaluate their radiation performance (Figure 11). The analysis revealed that the lattice-brick wall exhibits lower radiation levels compared to the common brick wall.

Finally, the wall, 4.4m in length, 2.2m in height and 0.08m in width, is fabricated through human-robot collaboration. A UR10 robot equipped with

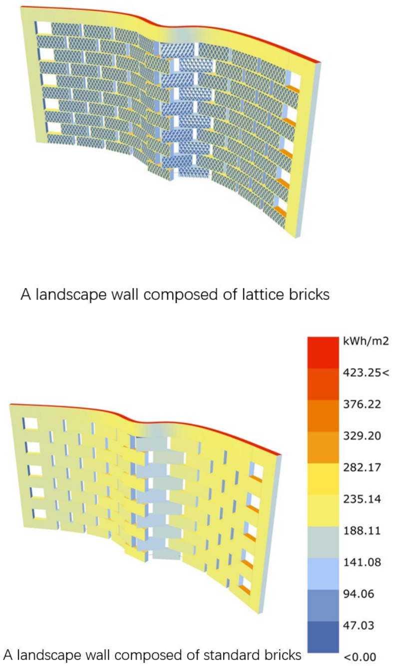


Figure 11
The radiation capability of two timber landscape walls composed of lattice-bricks and common bricks.

a Robotiq140 gripper assemble the lattice patterns, which is produced using a CNC router. This process aims to demonstrate the practicality and efficiency of integrating traditional lattice patterns into modern fabrication workflows. As the limitation of our robotic arm, the wall will be divided into four parts be assembled in strict adherence to a standard assembly workflow.

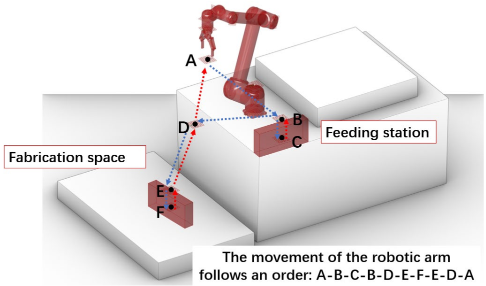


Figure 12
The standard toolpath for the robotic assembly.

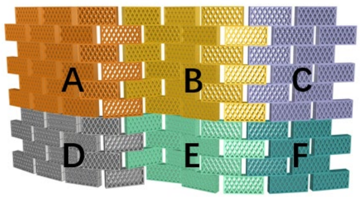


Figure 13
The wall is divided into six parts.

The standard toolpath of the robotic arm is designed considering the laboratory environment to preclude potential collisions (Figure 12). The robotic arm begins and ends the fabrication process at point A, while point D serves as a precautionary measure to avert any potential collisions between the arm and the assembly target. To mitigate the risk of collisions, after retrieving a component at point C, the robotic arm first returns to point B before proceeding to point D, rather than moving directly from point C to point F, where it might encounter other components. The elevations of points B and E are suitably adjusted in accordance with the height of the components being assembled, ensuring a safe clearance to prevent collisions between the robot and the components. Points B and E function as holding points to decelerate the robotic arm's rapid movement, which can lead to the deflection of timber components due to inertia. Such deflection can result in increased tolerances during the fabrication process. Consequently, a reduced speed is established for the movements between points E and F, as well as between points B and C. Furthermore, a higher speed is designated for the robotic arm's transition from point B to point D, relative to the previous segments, to enhance the efficiency of the robotic fabrication process. Due to the robot’s limited working radius of 1.3 meters, the wall is partitioned into six sections (Figure 13), which are first preassembled robotically. These sections are subsequently manually integrated and bonded with wood glue. To verify the reliability of the proposed file-to-fabrication workflow, two additional timber walls are assembled, as illustrated in Figure 14.

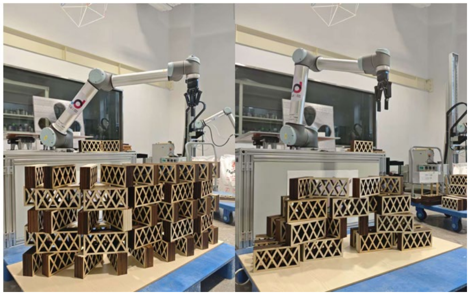


Figure 14
Two timber walls are assembled to test the feasibility of the proposed workflow in this paper.

The primary source of tolerance in robotic fabrication of traditional Chinese architectural elements stems from discrepancies between the virtual and physical environments. In this study, the coordinates of virtual and physical lattice-brick units will be collected and analysed to establish their relationship using machine learning techniques, specifically non-linear algorithms. The trained machine learning model can be utilised to calculate the physical coordinates of lattice-brick units based on its virtual coordinates, thereby reducing adjustment time in future assembling process. This analytical process will be detailed in our forthcoming paper.

CONCLUSION

The paper introduces a database centred on the daylighting performance of lattice patterns. This research also contributes to the collection and digitalization of forty-eight traditional Ming-Qing style lattice-patterns from tall windows in Suzhou. This collection lays an initial foundation for establishing a reference database to assist designers in selecting appropriate lattice patterns during the design process. The selection criteria are based on the daylighting performance of the lattice patterns. Normally, the selection of lattice considers the culture means, such as To prove the feasibility of the database, five lattice patterns were selected for analysis. A box-shaped house model, measuring 3 meters in height, 3 meters in width, and 4 meters in length, is used for the simulation. The results indicate that the daylighting capability of Lattice-E is the lowest, while the performance of Lattice-B is the best. This outcome could be attributed to the fact that the covering area of Lattice-E in the window opening is higher than that of the other patterns. It indicates that the timber lattice pattern can serve as be a type of shading element. The designers can apply lattice patterns in modern architecture and consult the database to select a pattern that matches the building's daylighting requirements. Some structures may require low-level daylighting to avoid direct sunlight, while others may need sufficient daylighting to enhance illumination.

This paper innovatively introduces a file-to-fabrication workflow that reinterprets traditional lattice patterns in contemporary design. In the design phase, the paper applies the modular properties of lattice patterns to generate brick units using Lattice-E. These brick units are then employed in the design of a landscape wall, where their positioning within the wall is governed by grid planes. The radiation analysis results of the lattice-brick wall, when compared to a conventional wall, indicate that the former can reduce wall temperatures during summer due to its lower daylighting performance (Figure 11). Consequently, this wall design can create a shaded space in Suzhou during summer, providing superior thermal comfort compared to a standard wall.

The workflow is designed to introduce a paperless approach in the fabrication step, where designers create their designs in a virtual environment and subsequently complete the fabrication through human-robot collaboration. This entire process eliminates the need for complex paperwork to assist labourers in understanding the construction process.

The research also has a few limitations. The ventilation performance of the selected lattice patterns for a tall window in Suzhou was not analysed, and only five of them were simulated. Therefore, to strengthen our database, all forty-eight patterns will be analysed in the future. Additionally, other types of windows will be collected and analysed. The machine learning model used to optimise the fabrication toolpath will be developed in future work. The fabrication process will also be completed in the future.

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