PROJECT

Printing Architecture: How Additive Manufacturing Methodologies are Posited to Transform Building Construction?

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The Lotus House in the 2018 Solar Decathlon Competition not only demonstrated the ability of 3D printing technology to produce an innovative, attractive, and sustainably-designed structure but, more importantly, contributes to the knowledge for implementing customized architecture in the prefabricated housing industry. Led by a trans-disciplinary group of faculty members in the disciplines of Architecture, Construction Management, Computer Science, and Engineering, the Lotus House project was developed with oversight by and in partnership with companies at the forefront of the construction market and composite materials industries in both the U.S. and China.

In the 1920s, Le Corbusier first posited his theory of a dynamic parallel between the current modern automobile and the Parthenon in Versune architecture. He stated that a house was a "machine for living in." The automotive industry thus began playing a crucial role in thinking around modern architecture. However, although there were many experimental design attempts to take advantage of mass production and prefabrication, such as the Villa Stein by Le Corbusier, the Dymaxion aluminum house by Buckminster Fuller, and the Package House by Walter Gropius, none of them were accepted by the general public and soon were abandoned. In the latter part of the 20th century, the rapid development of digital design tools engendered architectural design customization attempts in

Figure 1. Lotus House.

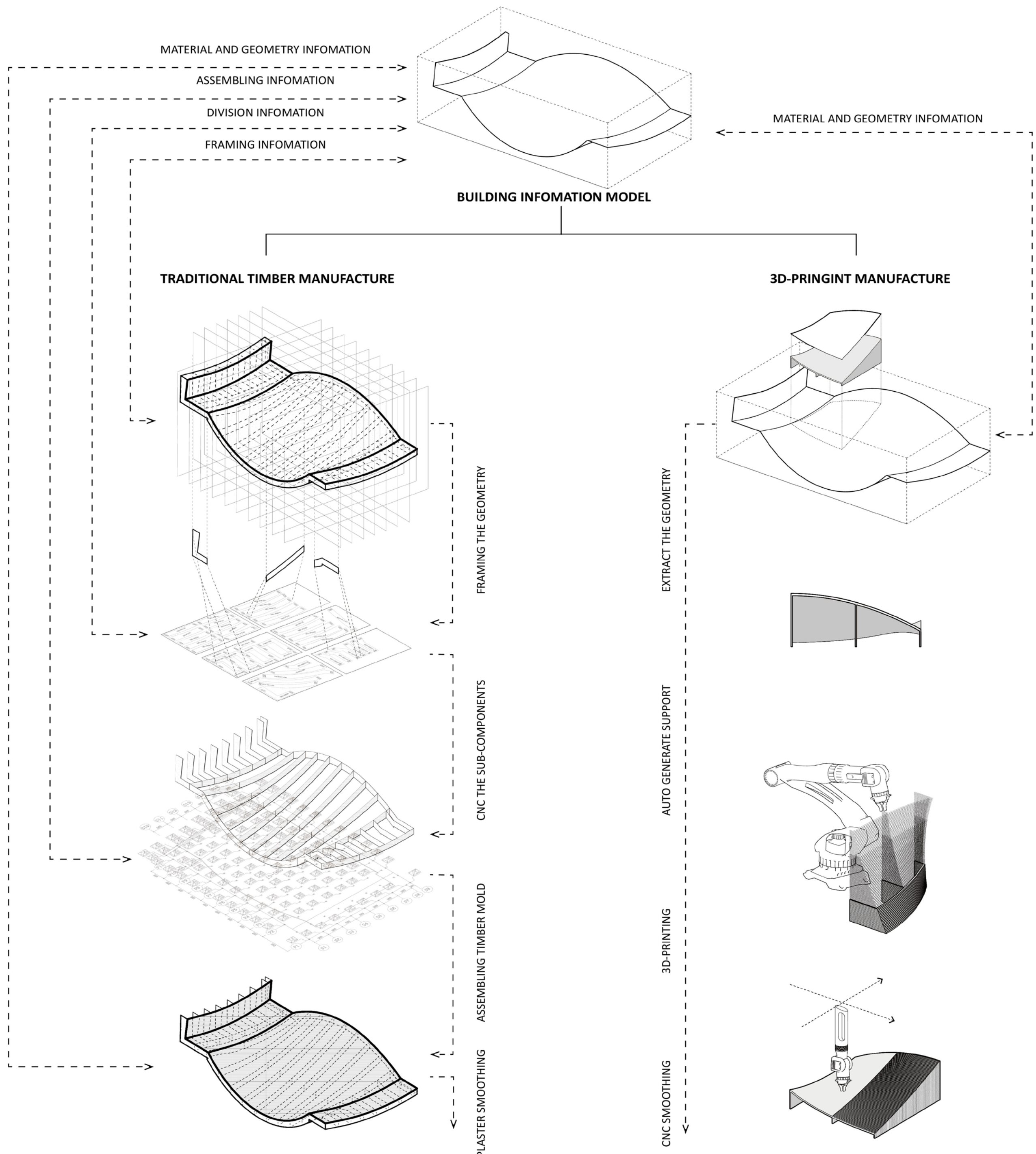


Figure 2.Information flow comparation.

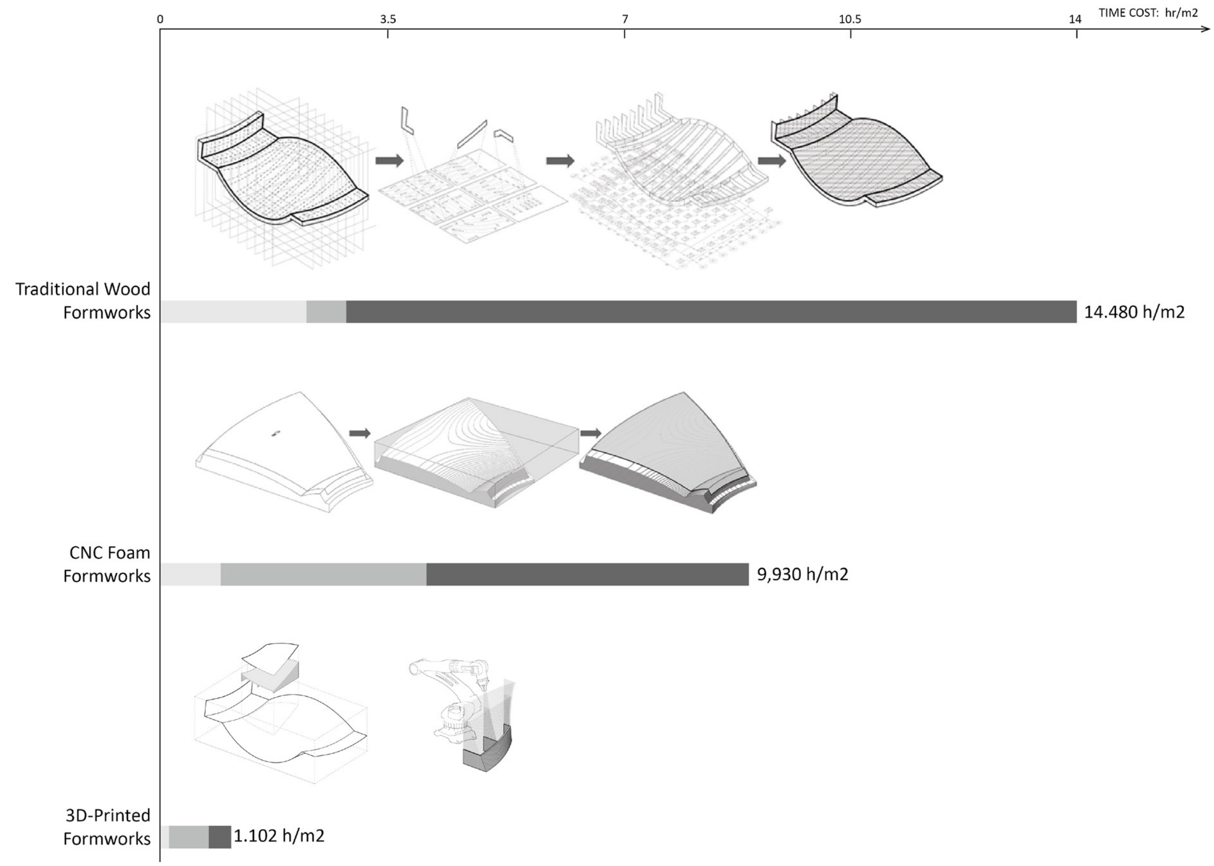


Figure 3. Time cost comparation

mass production. In 1964, Goldberg used a customized steel mold to produce irregular shapes of concrete in Marina City. In 2003, Stephen Kieran and James Timberlake stated in their book, Refabricating Architecture, that regulating the lines of an information management system were the new Modular, which coordinates all manufacturers. However, the ideal building information model (BIM) still only exists theoretically since the traditional customized manufacturing process requires a great deal of redundant information, which lowers the efficiency of coordination within the design process and erodes the advantages of mass customization. Additive manufacturing can eliminate additional production parameters to the coordination of the subcomponents, such as the size of raw materials. More importantly, 3D-printing provides a potentially standardized production process for specialized building segments and makes it is possible to coordinate different component manufacturers through a BIM in a more effective way.

The Lotus House is a 650 sq. ft., single-story home we designed for the Solar Decathlon Competition in 2018. We used a new design-build process utilizing 3D-printing technology and new materials as a part of our additive manufacture research initiative. It was our goal, by integrating this additive manufacture method to a BIM central model, prefabrication, off-site preassembly, and innovative materials, to deliver a higher quality, sustainable future architectural prototype at a lower cost and less design-construction time. For example, the traditional on-site assembly process of a single dwelling, such as the Farnsworth House, required on-site assembly of more than 1,267 building segments by construction workers. On the other hand, the Lotus House required on-site construction labor for only 50 components, which included 35 prefabricated panels with the steel skeleton embedded, 10 customized window panels, and several doors and skylights. The proof of the success of this new design-build process is that the Lotus House was completely constructed on the site within an impressive 20-day schedule with unskilled labor.

Compared to the typical current standard prefabricated building design, contemporary architecture requires more customized components to achieve its culture, context, and sustainable concerns. For example, the organic shape of the Lotus House was based on the look of a traditional courtyard in northern China and it utilizes a passive design strategy focused on the globe warming and energy crisis. A slight shift between 12 pieces of 3D-printed double-curve parabolic wall in the Lotus House provides plenty of sunlight and soft diffuse reflection to light up the interior living space while resisting extra sun radiation to lower the energy consumption. Also, a GFRC (glass fiber reinforced concrete)-Steel-GFRG (glass fiber reinforced

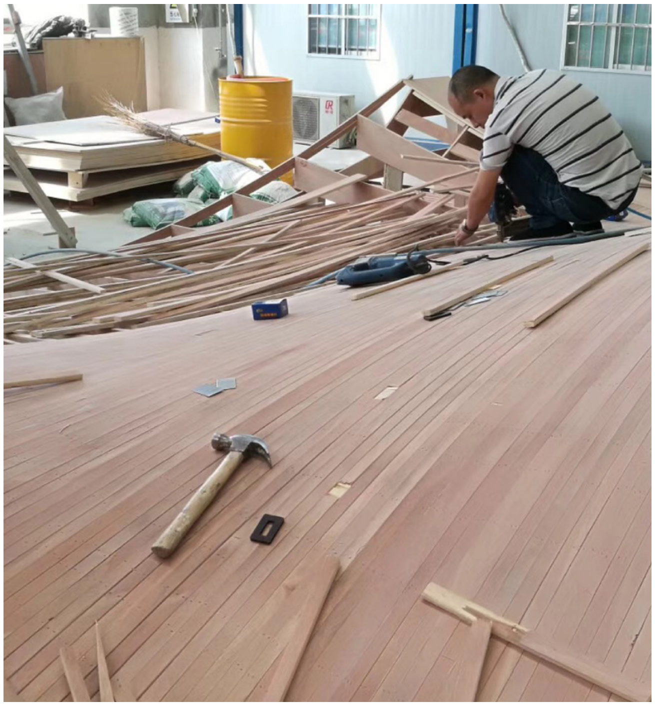


Figure 4. Traditional wood form works.

Figure 5. CNC foam form works.

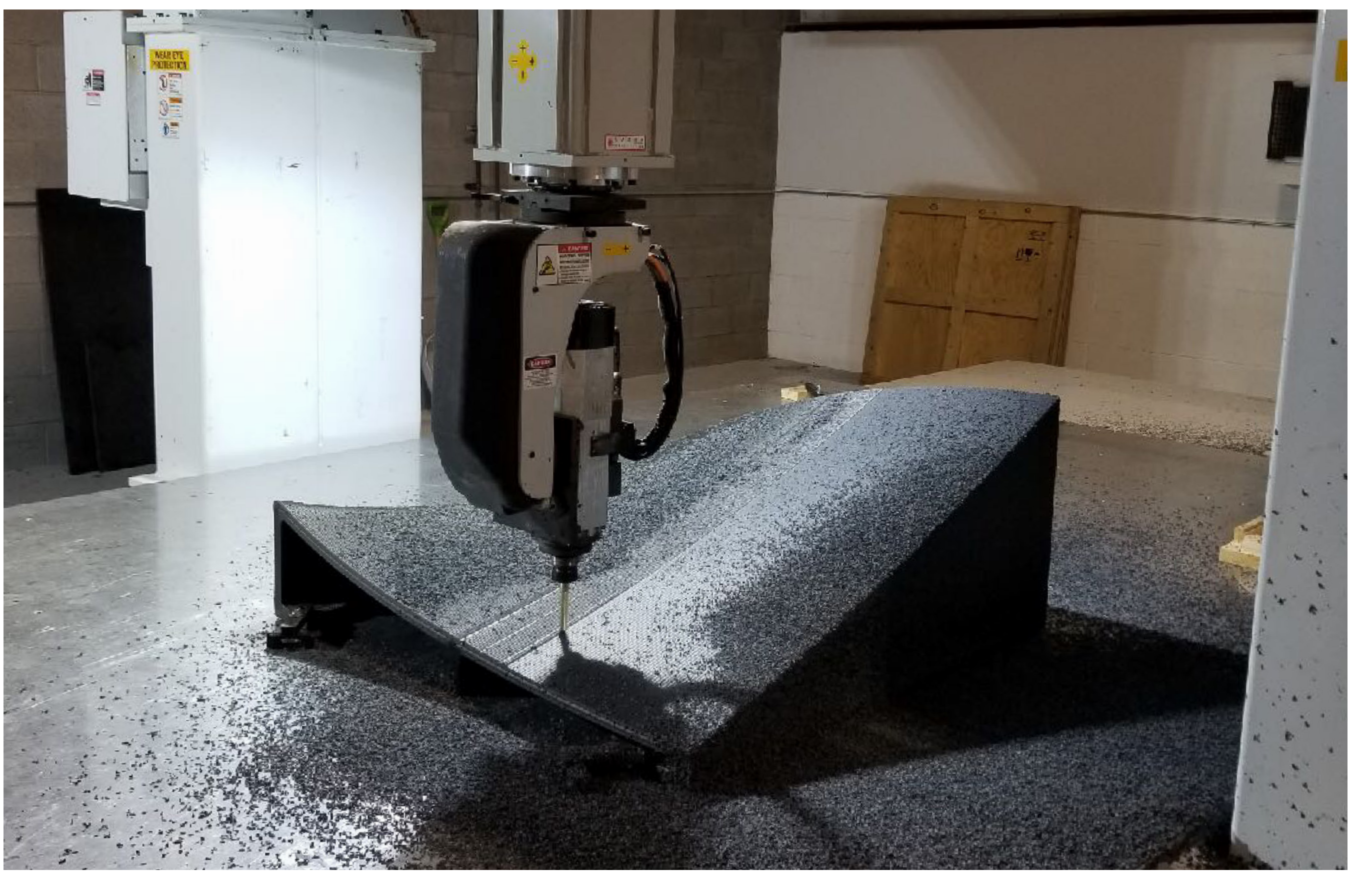
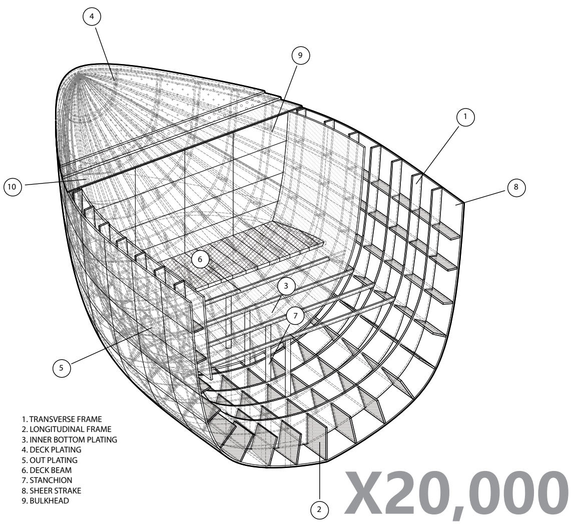
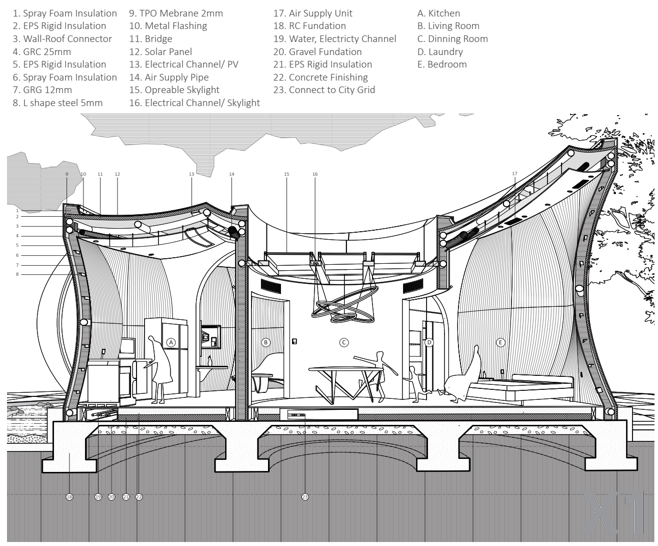
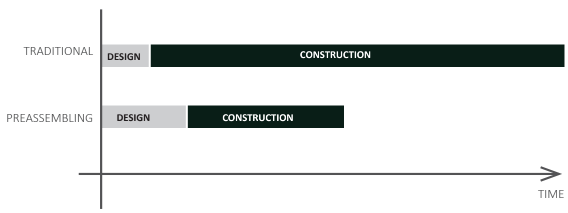


Figure 6. 3D-Printing form works.







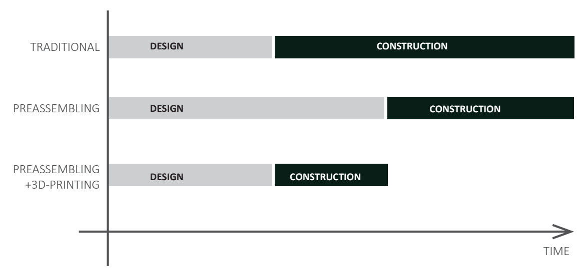


Figure 7. Time cost comparation between building and other Automated manufacturing。

gypsum) structure was substituted for traditional concrete construction wherever possible to lighten the overall weight of the structure, add sustainability, and increase assembly opportunities. Compared to the Crete House, which was another prefabricated single dwelling we constructed in 2017, by making substitutions for conventional material with new, contemporary materials, the overall weight of the structure was reduced by 50.7% percent, which led to a significant CO2 emission reduction during the transmission and construction.

The Lotus House project was designed and coordinated by students from Washington University in St. Louis base on a central information model while most of the building segments were produced by different manufacturers all over the world. To develop a quantitative comparative study of the effectiveness and economic differences of various form-making approaches, three GFRC prefabrication processes were utilized: 1) traditional wood form works, 2) CNC foam form works, and 3) 3D-printed form works composed of 20% carbon fiber reinforced ABS thermal plastic polymer. All three approaches were based on one central information model and we not only fully documented the quality of the final product by using digital models and 3D laser scanning, but we also calculated the differences between the cost and time expended for designers to coordinate their information and for manufacturers to produce the components, as well as other difference among sustainable factors such as the reuse rate and carbon assumption. As our results show, our additive manufacturing method could tremendously reduce the redundant information among different manufacturers and thereby lower their cost while accelerating the design process and make one fully-coordinated BIM not only theoretically possible, but a reality.

Our study demonstrated that 3D printing technology can both improve productivity and decrease construction cost harmoniously in the most difficult construction type of mass customization of an organic structure. In the future, this study will be the foundation for conducting a cost analysis of utilizing 3D printing for other customized building types and situations.

ENDNOTES

1. Le Corbusier, *Toward a New Architecture* (London: J. Rodker, 1931), 7.
2. Hongxi Yin, Baoyue Wang, and Jian Zhu, "Design-Build: A Real-World Experimental Pedagogy for Architectural Education," in *Annual Meeting Proceedings* (Washington, DC: ACSA Press, 2019), .
3. Stephen Kieran and James Timberlake, *Refabricating Architecture* (:McGraw-Hill Companies, 2004) 6, 171.
4. Richard J. Kirby, *Fiberglass Forms — A Progress Report* (:Aberdeen Group, 1962), 3.
5. Dongchen Han et al., "Technical Analysis and Comparisions of Formwork-Making Methods for Customized Prefabricated Buildings: 3D Printing and Conventional Methods," *Journal of Architectural Engineering* 26, no. 2
6. Ryan E. Smith, Peter L. Gluck, Mimi Hoang, Chris Sharples, and James Garrison, "New York Modular," *Journal of Architectural Education* 71, no. 1 (2017): 110–11, https://doi.org/10.1080/10464883.2017.1260934.

Figure 9. 3D-Scaning commpare to the digital model.

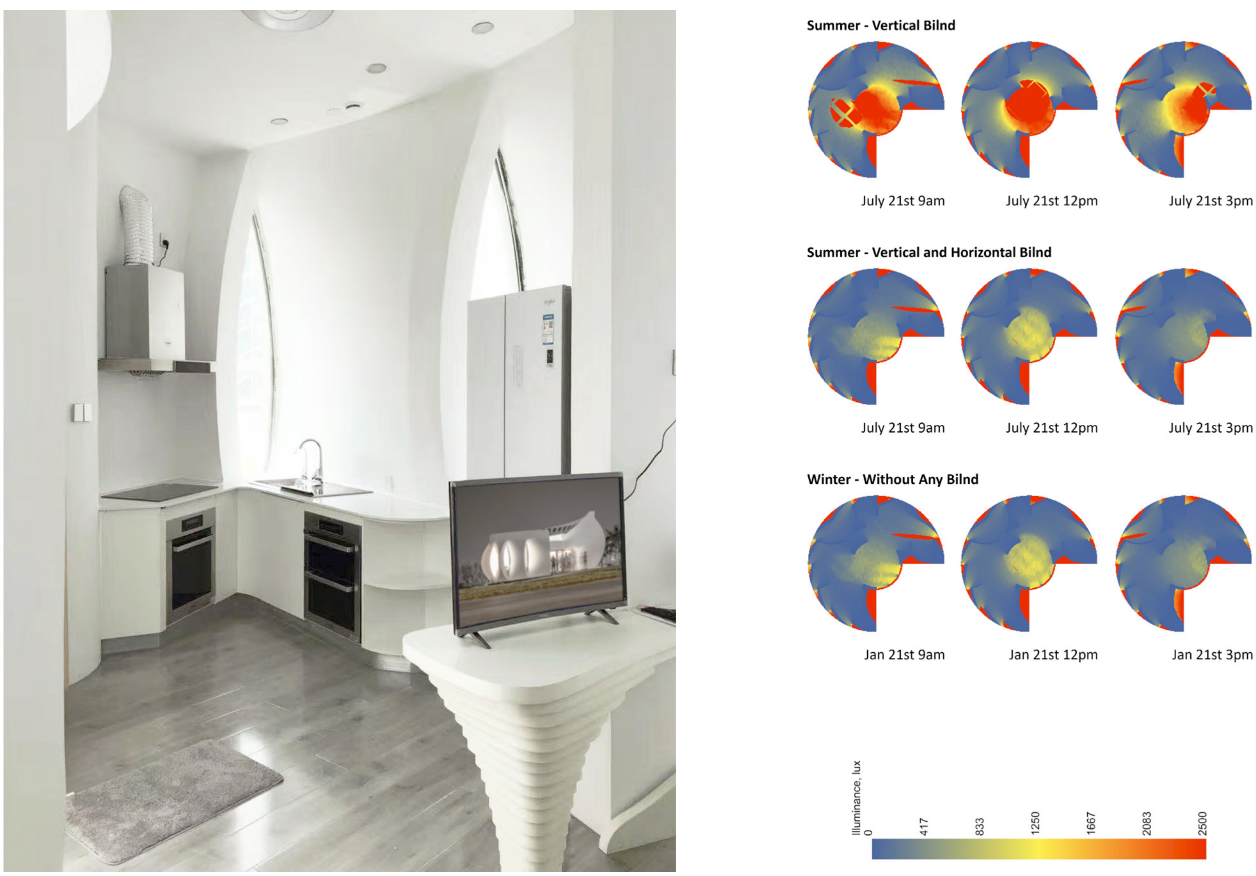


Figure 10. Lotus House interior lighting environment.