Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Material Saving Analysis of Shell Structure——Taking the Structure of Solar Ark 3.0 in Solar Decathlon China 2022 as an example

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Abstract

Shell structures, known for their high-performance characteristics, are widely utilized in architectural design for their material-saving advantages. Despite the recognized material-saving benefits of shell structures compared to equivalent-sized frame structures, their material consumption across different lifecycle stages has not received adequate attention. Consequently, a holistic understanding of the environmental impact of material savings in shell structures throughout their lifecycle remains elusive. In this study, Solar Ark 3.0, a shell structure designed by our team, serves as the research subject. The material consumption during shell fabrication, transportation, and on-site construction is analyzed. By employing Material Flow Analysis (MFA), the quantitative analysis of material consumption and its flow direction is conducted. Comparative analysis is then applied to contrast the material consumption of Solar Ark 3.0's shell structure with equivalent-sized frame structures at various stages. The study also examines the variations in material consumption across different lifecycle stages of Solar Ark 3.0 and compares them with equivalent-sized frame structures to elucidate the differences in environmental impact weights. The findings reveal that shell structures exhibit significant material savings in terms of building materials compared to equivalent-sized frame structures. However, the extent of process material savings varies across different stages. Additionally, the distribution of material consumption across lifecycle stages differs between shell and frame structures, manifesting distinct environmental impacts during component production, transportation, and on-site construction phases.

Keywords: Shell structure, Material saving, Material flow analysis, Life-cycle assessment,

1. Introduction

Research indicates that the structural impact across the lifecycle of buildings varies significantly among different building types [1-2]. Shell structures, as an efficient architectural form, exhibit compressive force characteristics that align with the load-bearing properties of concrete materials. Consequently, concrete shell structures tend to require less concrete material compared to equivalently sized frame structures. However, current studies on the material-saving characteristics of concrete lack comprehensive support from engineering practice records, particularly in terms of statistical data regarding material usage during component fabrication, transportation, and on-site construction phases. This gap hampers a comprehensive comparison of material-saving advantages between shell and frame structures, particularly throughout the construction phase.

The study of material-saving has significant implications for analyzing the environmental impact of structures. However, current research primarily focuses on the design methods and direct economic benefits of material-saving, without adequately demonstrating its direct environmental significance [3-4]. Presently, environmental impact assessments primarily include life cycle carbon emission assessment (LCC), life cycle cost assessment (LCCE), and life cycle energy assessment (LCE) [1-2, 5-6]. However, these assessment indicators are often used to evaluate the overall performance of buildings. When it comes to evaluating relatively small-scale structures, there is a relative lack of sufficient data support and accuracy assurance. In contrast, Material Flow Analysis (MFA) is an analytical method for assessing the quantity and flow of materials within specific systems, enabling a more detailed analysis and management of resources [7], thus compensating for the deficiencies of the assessment methods mentioned above, this study proposes the adoption of Material Flow Analysis to assess the direct environmental impact of material-saving in shell structures.

2. Methodology

Material Flow Analysis enables a systematic and quantitative representation of the spatial and temporal flow characteristics of relevant elements throughout the entire lifecycle of buildings [7]. With the ongoing interdisciplinary research, in recent years, Material Flow Analysis has also begun to integrate with fields such as urban planning and architectural design [8-9]. Its characteristics of comprehensive process and quantification align well with the current demand for precise analysis of material-saving in structures at different stages of the lifecycle.

The scope of Material Flow Analysis has gradually expanded from the narrow focus on material element flow analysis in environmental ecology to include the flow of materials, products, people, information, and other elements [7, 10]. Environmental impact assessments conducted using Material Flow Analysis exhibit a significant openness and diversity in the selection of analysis objects. By selecting different analysis objects and analyzing their flow paths and quantities, researchers can identify direct connections between the analyzed material objects and the environment.

Therefore, this study directly tracks the consumption and flow of materials associated with shell structures at different stages of the lifecycle to reflect their environmental impact. Drawing upon extensive on-site engineering records from an actual project, Solar Ark 3.0, and leveraging Building Information Modeling (BIM) models for construction simulation and project management, the study calculates the material requirements for shell structures at various lifecycle stages. This approach aims to accurately depict the material consumption patterns of shell structures throughout their lifecycle.

The material consumption required for architectural production activities encompasses not only the building materials needed to form components but also a significant amount of process materials. The production, transportation, and on-site construction of components constitute the three most concentrated stages of material consumption throughout the building lifecycle. Taking concrete components as an example, apart from concrete material, the production stage requires the assistance of formwork to shape the concrete components. During transportation, temporary padding materials are necessary to prevent damage to the components during transit. In the on-site construction process, it may also be necessary to erect formwork for concrete pouring to connect components. Based on these circumstances, the study selects the component production, component transportation, and on-site construction stages as the lifecycle scope for investigating the material-saving aspects of the Solar Ark 3.0 shell structure (Figure 1).

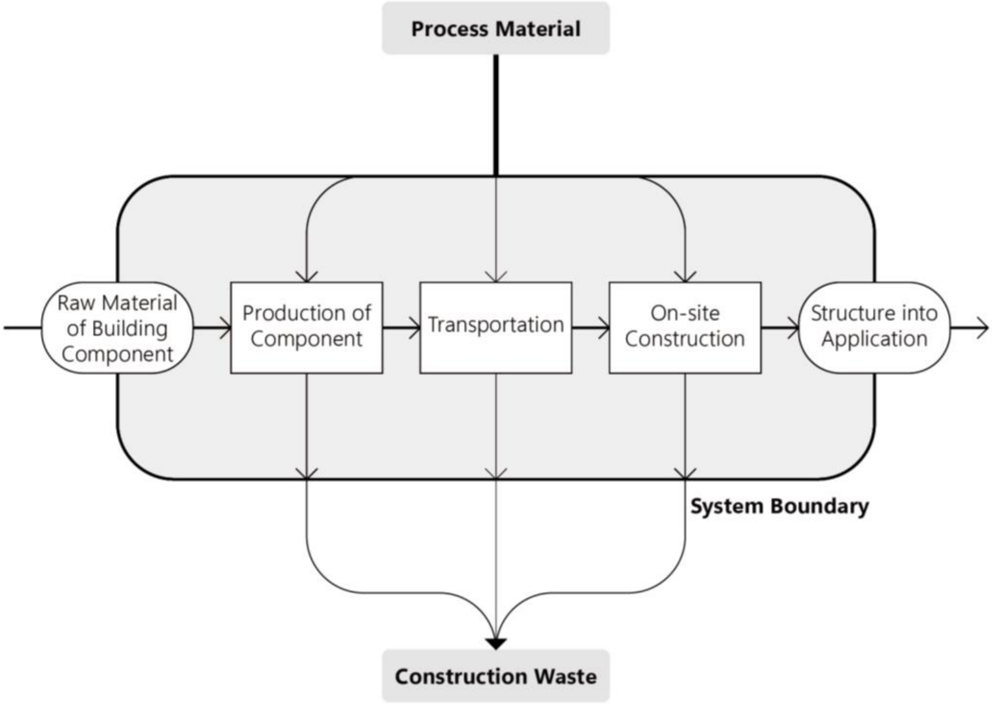

Figure 1: Model of Material Flow Analysis for Structure Material

In order to provide a clearer demonstration of the material-saving characteristics of shell structures, the study conducts a comparative analysis of material consumption by selecting equivalent-sized concrete structures. The study chooses a prefabricated UHPC shell with dimensions of 16.8m*16.8m and compares it with an equivalent-sized prefabricated concrete frame structure (Figure 2). The frame structure adopts the common method of prefabricated beam bottom reinforcement anchoring connection. The study estimates the building materials and process materials required during the component production, transportation, and assembly stages.

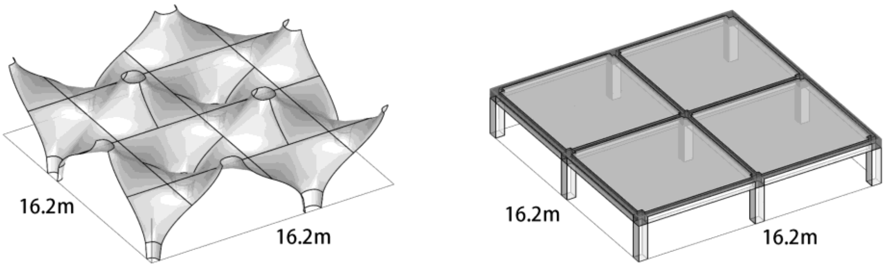

Figure 2: Analytic Target of Material Consumption Calculation

3. Case study of Solar Ark 3.0

3.1.Project background

Solar Ark 3.0, a collaborative project by Southeast University, ETH Zurich, and Sanming College, participated in the 2022 Solar Decathlon China. It is a prefabricated ultra-high-performance concrete (UHPC) shell building. (Figure 3) The building consists of 20 prefabricated standardized UHPC shell units. Compared to traditional reinforced concrete frame structures, Solar Ark 3.0 maximizes the utilization of UHPC's excellent compressive performance in terms of structural efficiency. This section will utilize a wealth of on-site engineering records and visual data to present the material consumption during the component production and transportation stages of Solar Ark 3.0's shell structure, along with an analysis of material flow to showcase its environmental impact. Additionally, the study explores the differences in material-saving characteristics at different stages between Solar Ark 3.0 and traditional prefabricated concrete frame structures.

Figure 3: Photograph of Solar Ark 3.0

3.2.Project documentation

3.1.1. Production of Component

The production of the shell components of Solar Ark 3.0 involves three main stages typical of prefabricated building components: formwork fabrication, component prefabrication, and demolding (Figures 4-7). Among these stages, formwork fabrication is the pivotal process in shell production. The formwork for Solar Ark 3.0's shell undergoes two main phases: wooden formwork fabrication and fiberglass-reinforced plastic (FRP) demolding, each involving intricate procedures. During the design phase, the utilization of ruled double-curved surfaces alleviates the difficulty of formwork shaping for the shell. Furthermore, the standardized shell structure allows for the completion of the entire shell production using only two sets of formwork for the 20 shell units.

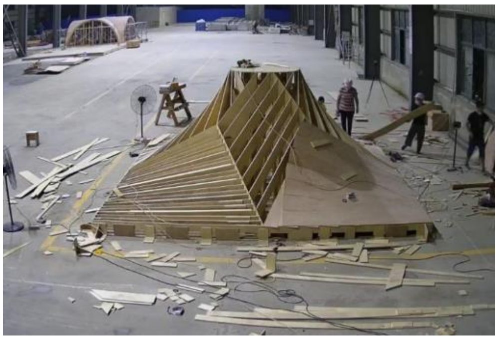

Figure 4: Timber Formwork

Figure 5: Fiberglass Formwork

Figure 6: Component Fabrication

Figure 7: Demolding

From the current situation, although formwork serves as a crucial foundation for component production, its environmental hazards are quite evident. Because a large amount of concrete formwork used in construction projects is no longer utilized after the project's completion, a significant portion of formwork material becomes the most prominent solid waste in the construction phase. According to engineering records, the discarded formwork materials generated in factories, coated with waterproof and fireproof materials, cannot be incinerated for disposal. As a result, they are often irresponsibly discarded, posing environmental hazards to soil and water bodies.

Undeniably, Solar Ark 3.0 has considered the environmental impact of formwork from the design stage onwards. However, starting from the structural form of the shell, it is inevitable that compared to traditional prefabricated concrete frames, more formwork is required to assist in component formation. Without undergoing the process of mass production and productization of shell components, the formwork for the shell would quickly become discarded, becoming an unavoidable presence of solid waste.

3.1.2. Transportation

Ensuring that components produced in factories arrive intact at the construction site is a prerequisite for the smooth completion of construction. Any bumps or damage to concrete structural components during transportation can pose significant safety and aesthetic hazards to the building. This necessitates the use of more padding and reinforcement materials during the transportation of concrete components. Individual shell components, lacking inherent stability due to the influence of gravity, often require additional reinforcement measures to be considered during loading. Furthermore, due to the complexity of their structural form, a limited number of shell components can typically be loaded onto a single vehicle, placing higher demands on the dimensions, shapes, and standardization of building shells.

The standardized design and structural component methods of Solar Ark 3.0's shell structure have improved the efficiency of shell component transportation. Field installations have demonstrated that a 17-meter truck can transport 8 UHPC shell units (Figures 8-9). However, due to the need for concrete shell structures to resist shear forces, the connections of the shells need to be curved, which results in the contact surface between the shell and the truck not being completely flush. Therefore, more padding and reinforcement materials need to be placed on the contact surface to ensure structural stability. When necessary, some complex curved structures may also require temporary steel connectors to ensure smooth transportation. In practical engineering, wood and foam materials are commonly used as padding, which become construction waste upon arrival at the site and cannot be reused.

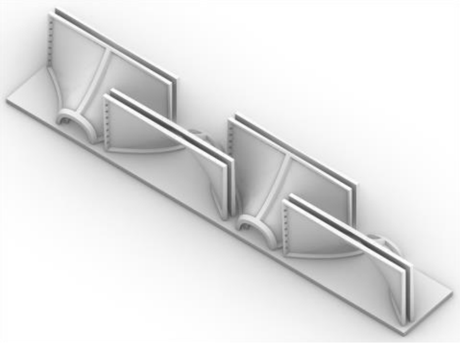

Figure 8: Simulation of Loading

Figure 9: Documentation of Loading

In contrast, concrete frame components of buildings do not have high transportation requirements. Due to the inherent stability of beam and column components, they can often be stacked and placed more easily during transportation. Therefore, a large amount of padding and fixing materials are not necessary to ensure the stability of the building structure during transportation.

3.1.3. On-site Construction

During the design phase, Solar Ark 3.0's shell was already planned to be bolted together (Figures 10-11), eliminating the need for any additional concrete pouring at the construction site. The steel frame used to support the UHPC shell connections can also serve as installation frames for enclosure components after UHPC installation, without the need for dismantling or disposal. Therefore, no additional process materials were generated during on-site construction.

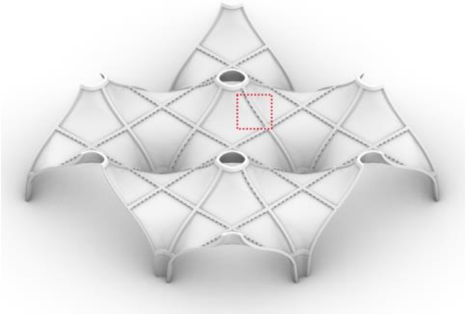

Figure 10: Simulation of assembly

Figure 11: Documentation of bolts

However, common prefabricated concrete frame structures often require secondary concrete connections, necessitating on-site formwork pouring during construction. After pouring, concrete formwork is often unable to be retained and is discarded as temporary materials after use. Additionally, extensive wet operations often result in the generation of wastewater on-site. In complex construction sites, formwork and wastewater can easily become construction waste and are often irresponsibly disposed of, posing environmental hazards.

4. Results and discussion

Table 1: Calculation of Material Consumption

Period	Prefabricated Shell Structure of Solar Ark 3.0		Prefabricated Concrete Frame Structure	
	Genre	Mass	Genre	Mass
Production of Component	Building Material	47t	Building Material	119t
	Process Material	0.34t timber 0.57t fiberglass	Process Material	0.18t timber
Transportation	Process Material	0.08t timber	Process Material	0.02t timber
On-site Construction	Building Material	0	Building Material	13.7t
	Process Material	0	Process Material	0.32t timber

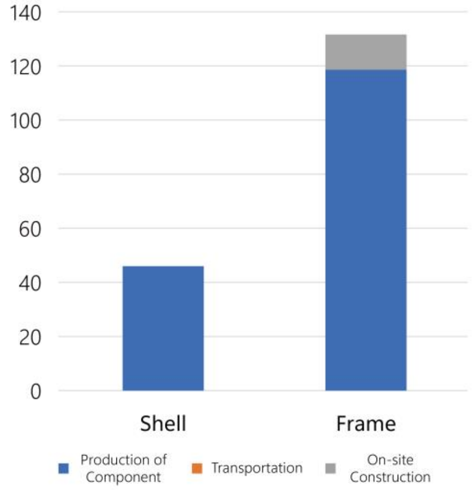

Figure 11: Comparison of Building Material

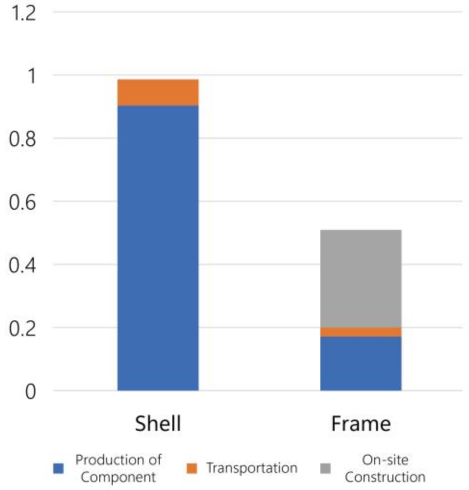

Figure 12: Comparison of Process Material

The study contrasts the material consumption of equivalent-sized UHPC prefabricated shells and concrete prefabricated frame structures, illustrating different distribution patterns of building materials and process materials during the production, transportation, and construction stages (Figures 11-12). Through data calculations, it can be concluded that the UHPC prefabricated shell used in Solar Ark 3.0 effectively reduces the building materials required in the construction production process, requiring only 35% of the equivalent-scale frame structure, and does not require formwork for secondary connections during on-site construction. The reduced building materials and bolted connection method offer clear advantages for environmental health.

In terms of process materials, Solar Ark 3.0's shell production, transportation, and assembly stages have been designed to minimize the use of process materials as much as possible. However, due to the complex formwork processes and relatively higher transportation difficulty of shell structures, more process materials are generated during the production and construction stages compared to prefabricated frame structures. Therefore, careful management of process materials is necessary for shell structures to minimize their environmental impact during production, transportation, and construction phases.

The study demonstrates that the analysis of material-saving cannot merely rely on a coarse analysis of building raw materials but needs to be refined to different stages of construction. Despite this, shell structures still exhibit a significant advantage in material-saving overall. However, further expansion and validation of this conclusion are required through additional data calculations from more actual engineering projects in the future.

Acknowledgements

Solar Ark 3.0 would not have been possible without the support of students, teaching staff, researchers, and administrative staff from the School of Architecture of Southeast University China. Furthermore, Dr. Cong Meng from Southeast University Architectural Design and Research Institute Co., Ltd., Mr. Yang Zhiqian from Sobute New Materials Co., Ltd., and Mr. Hu Yong from Tongyu (Jiangsu) Construction Technology Co., Ltd. made a significant contribution to the materials and the prefabrication.

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