BUILDING INFORMATION MODELLING BASED TRANSPARENT ENVELOPE OPTIMIZATION CONSIDERING ENVIRONMENTAL QUALITY, ENERGY AND COST

DIAN ZHUANG[1] and XING SHI[2]
[1]*School of Architecture, Southeast University, China.*
[2]*College of Architecture and Urban Planning, Tongji University, China.*
[1]*zhuangdian@seu.edu.cn, 0000-0003-0747-2775*

Abstract. The balance of energy consumption, indoor environmental satisfaction and cost is a continuing challenge in the field of building energy efficiency research. Building transparent envelope play a key role in building energy-saving design. While in existing BIM system, the separation of component family and local supply chain hinders the integrated performance evaluation and design. This paper proposes a general sustainable performance optimization model for transparent envelope design from the product perspective. A performance data integrated BIM technique framework, linking BIM with multi-dimension performance data stored in external database, is introduced as the foundation of local supply chain based optimization process. A multi-objective optimization model for window components is constructed for the early design stage. Three comprehensive design targets in the engineering practice, energy consumption, life cycle cost and IEQ are evaluated and optimized, representing the concern from government, developer and occupant, respectively. Autodesk Revit as the technique platform, its internal material library and adaptive component system are directly integrated for model control and feedback. An optimization tool is developed as an individual plug-in for user interaction and performance visualization. As a case study, the multi-objective optimization process is applied to design a school building in China.

Keywords. BIM; Multi-objective Optimization; Transparent Envelope; Sustainable Performance; SDG 3; SDG 7; SDG 11; SDG 12.

1. Introduction

Energy shortages and the climate problem caused by it have been the focus of global attention in recent years. In 2018, building construction and operations accounted for the largest share of global final energy use (36%) and energy-related carbon emissions (39%) (UN Environment and the International Energy Agency, 2019). In response to these problems in the Architecture, Engineering and Construction (AEC) industry, various concepts of sustainable building have been proposed. The optimization of

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sustainable performance in the building design stage is also playing a key role in practice. Figure 1 is the modified MacLeamy Curve (Piroozfar et al., 2019) representing the influence of building design decisions on life-cycle environmental impacts. It shows the importance of performance optimization in the early stage. The impacts of performance optimization will gradually decrease with the development of the engineering stage, and the required cost will gradually increase. On the other hand, building transparent envelopes have a huge impact on the sustainable performance of the building, and its use is maintained high popularity in public buildings (Zhao and Du, 2020). Compared with the site construction of nontransparent envelopes, transparent envelopes such as windows are usually procured directly from local suppliers and installed in reserved window openings during the project. However, the performance optimization in the early design stage always deviates from the local supply chain, resulting in the gap between the actual performance and the expected performance. This paper proposes a performance integrated BIM (P-BIM) framework oriented by sustainable performance-driven design. A real-time updated external component product library with essential performance information is integrated in Building Information Modelling (BIM) for data management and further usages. A multi-objective optimization model considering three comprehensive performance indicators for transparent envelope design is constructed based on P-BIM.

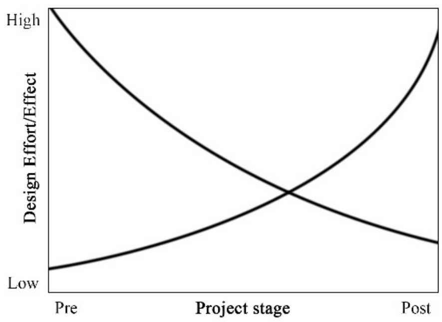


Figure 1. Modified MacLeamy Curve

1.1. BUILDING SUSTAINABLE PERFORMANCE

At present, there are many types of sustainable building evaluation systems with different classifications of sustainable performance. From the perspective of AEC industry, the stakeholders of a construction project can be divided into three categories: the occupant, the government, and the developer. Occupants needs include comfort, functional convenience, etc.; government needs include energy consumption, carbon emissions, etc.; developer needs include cost control, land use, etc. These stakeholders also represent three basic types of performance that are always contradictory and need to be balanced regardless of the stage in the sustainable design of buildings: applicability, environmental protection and economy. The ISO: 14040-14044 standard also divides the generalized life cycle performance evaluation into three categories: Environmental, Social, Economic (ISO, 2006), and the international organization Calcas also emphasized this classification method in the D20 full life cycle analysis blue book (Action et al., 2009). Hashempour divided the performance of green building design into three basic types: environment, economy and society in the review article (Hashempour et al., 2020). Thus, this study attempts to realize the evaluation and optimization of these three comprehensive performance in the early design stage. They are further specified as energy consumption, Indoor Environmental Quality (IEQ) and Life Cycle Cost (LCC).

1.2. SUSTAINABLE PERFORMANCE IN BIM

Recently, the research on the integration of BIM and sustainable performance mainly focus on two performance types. The first is the overall performance of BIM-based building projects, including building energy consumption, carbon emissions, costs and environmental comfort indicators. This research has made great progress in the past ten years, mainly concentrating on the performance evaluation based on the standard BIM interactive format (Ying and Lee, 2019; Kim et al., 2016) and the integration of the external simulation engine with BIM platform (Jin et al., 2019; Cemesova et al., 2015). However, existing studies indicate shortages of the ability to evaluate multi-dimensions performances and interact with BIM data. The second is the performance defined by basic elements like building components or materials, including the heat transfer performance, sound insulation performance and light transmission performance. This research are still in the exploratory stage. The integrated data is mostly building monitoring data and IoT data (Tang et al., 2019; Riaz et al., 2014), lacking of the basic performance data in the design stage. The P-BIM framework established in this paper aims to realize the interaction and management of building basic performance data, and construct a series of comprehensive performance evaluation technologies to support the performance-driven design process in the early design stage.

1.3. TRANSPARENT ENVELOPE

Transparent envelope plays a decisive role in the sustainable performance. For energy consumption, its heat transfer coefficient is much greater than that of the nontransparent envelope, which leads to great heat loss (Sun et al., 2018). The heat loss caused by the air tightness of doors and windows accounts for a large amount of energy consumption (Grynning et al., 2014). The natural light from the windows has a complex effect on energy consumption. Studies have shown that transparent envelopes are associated with 60% of building energy consumption (Lee et al., 2013). From the perspective of occupant comfort, transparent envelope brings natural light into the room, which increases the illuminance and brings glare at the same time (Alam and Islam, 2017). Solar radiation also causes thermal comfort changes such as overheating (Lai et al., 2017). Transparent envelope has the lowest surface density thus has a great impact on acoustic comfort. In our previous study, it has been confirmed that the transparent envelope has too much influence on the IEQ so as to hinder the simultaneous decision-making of the nontransparent envelope (Dian et al., 2021). The optimization model in this paper is carried out for the transparent envelope independently.

2. Methods

P-BIM framework is proposed as the basis of the optimization model. Based on the framework, a multi-objective optimization model of window size and configuration considering energy consumption, IEQ and LCC is established.

2.1. P-BIM FRAMEWORK

Performance integrated BIM (P-BIM) technical framework is proposed to support the digital energy efficient design of building under the BIM system. The technology introduces external databases to store various external related data information, establishing a dynamic relationship between external data and BIM model data. The specific technology platform and data interaction logic in P-BIM are shown in Figure 2. Autodesk Revit platform is used as the basic model data back-end, and the MySQL database is introduced as the external data back-end; Rhino.Inside digital design platform is selected as the data center to realize the interaction and management of data stored in the data back-end. Visual programming is the basic method to develop the performance evaluation and optimization procedures using Rhino.Inside. Finally, GHPlayer platform are selected to complete user interaction and model feedback for specified functions. The multi-objective optimization model constructed in the following article is a specific performance-driven design application under the framework of P-BIM.

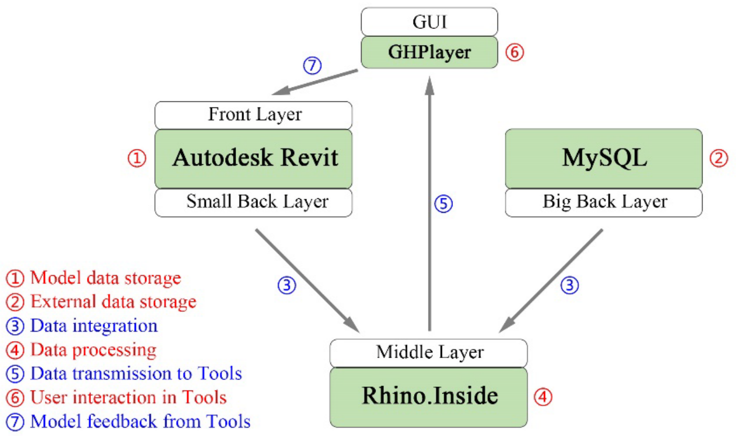
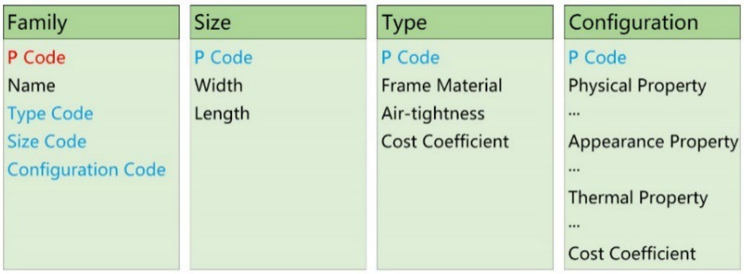


Figure 2. P-BIM components and workflow

2.2. INTEGRATION OF LOCAL SUPPLY CHAIN

Building transparent envelope size and configuration are selected as the optimization variable. The variables emphasize the design characteristics of the P-BIM of the local building product industry, referring to the product lists of various Chinese window manufacturers (SHANGHAI LEAD GLASS CO.,LTD, 2021; Jin Jing Group, 2021). The performance data of the transparent envelope is stored in multiple independent table in MySQL platform. The basic construction logic of the form is shown in Figure 3. The top-level table is a specific window product family, which includes three main contents: size, window frame type and glass configuration. These items are stored in three bottom-level independent tables. The data query from bottom to the top is realized by unique codes as a primary key.

Figure 3. Window performance data tables



2.3. OPTIMIZATION MODEL

The parametric control of design variables, the multi-dimensional performance evaluation and the optimization algorithm are three main parts of the optimization model. Model control and performance evaluation are based on the parametric building energy model translated from BIM model. Building form, envelope construction and operating parameters are translated from Revit to Rhino.Inside platform. On this basis, a dynamic link between the MySQL and the Rhino.Inside based on SQL scripts is built to complete the real-time update of optimized design variables and related performance data.

In terms of performance evaluation, LadybugTools is selected as the simulation platform for energy consumption and IEQ. For the IEQ index, this paper introduces the evaluation method of the indoor environment from Tiberiu et al. in 2012 (Catalina and Iordache, 2012). The energy consumption and thermal comfort are simulated by the EnergyPlus engine; the visual comfort is simulated by Radiance and DAYSIM engines; the acoustic comfort is directly calculated by the indoor sound pressure level calculation formula; and the indoor air quality is calculated by the indoor ventilation volume per person. The whole building envelope LCC evaluation is implemented using the Global Cost calculation formula in the EN 15459 standard (GB-BSI, 2007). The energy cost in the operation stage is further added to the formula to increase accuracy.

Genetic algorithm (GA) is selected as the core optimization algorithm in this study. GAs' performance has been tested in a myriad of reviews and comparative studies, and the literature overwhelmingly suggests that GAs have been the most popular and robust heuristic approach to Multi-objective Optimization problems in the field of building optimisation (Ines et al., 2020; Ciadiello et al., 2007). This study uses the Octopus tool in Rhino.Inside as a genetic optimization engine. Focusing on the Strength Pareto Evolutionary Algorithm (SPEA-2) and the Hypervolume Estimation algorithm (HypE), Octopus yields the best trade-offs to choose among different searched objectives, and is widely used in architectural multi-objective optimization (Li et al., 2020).

2.4. PROJECT INFORMATION

A school building located in the city of Nanjing, Jiangsu Province, China, is selected to validate the proposed optimization model. The school building has three floors with a total construction area of 2311.6 m2, including 15 standard classrooms shown in Figure 4. The windows in these classrooms are optimized of their size and configuration.

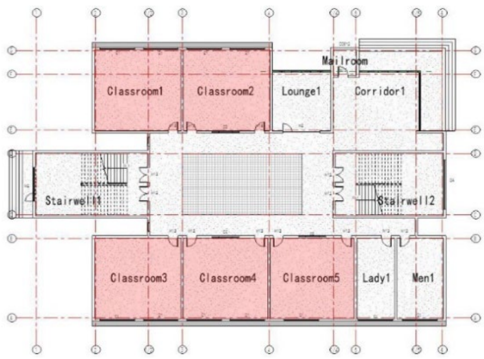


Figure 4. Target rooms in the case building

3. Results

The optimization process tends to be stable in the 15th iteration. In the 31th iteration, 73 Pareto front solutions are generated. The Pareto front is defined as the set of non-dominated solutions, where each objective is considered as equally good (Ranajeet et al., 2020). The performance distribution of Pareto front solutions in the steady state tends to be separated into two groups as shown in Figure 5 and Figure 6. Solutions in group 1 have better performance in cost (30.08-30.80*105¥), with relatively poor IEQ points (64.82-72.89 points) and energy consumption (227.54-229.60 kwh/m2); solutions in group 2 have better performance in energy (225.86-227.37 kwh/m2) and environment quality (67.07-73.88 points), with relatively higher price (31.37-32.28*105¥).

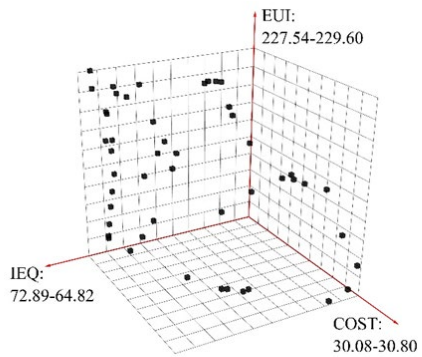


Figure 5. Pareto front solutions group 1

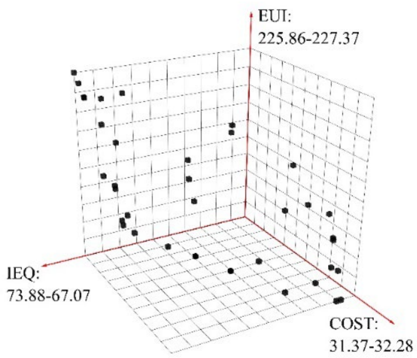


Figure 6. Pareto front solutions group 2

The formation of the two Pareto front solution groups is caused by the difference of window configurations. Group 1 represents various types of single-layer glass, including ordinary glass of different thicknesses and coated glass configurations while group 2 represents multi-layer low-e glass configurations. The distributions of the two groups are basically the same, forming a fusiform shape in the 3D solution space, which represents the mutual restraint relationship between the three performances. Among them, the cost and the other two performances show an obvious non-linear negative correlation, while the relationship between energy and IEQ is relatively fuzzy but still showing a negative correlation. The distribution is consistent with the actual situation, which indicates the reliability and necessity of the optimization process.

For final decision, two Pareto front solutions in the two groups are selected after calculating the Euclidean distance between Pareto front points and origin. We selected the point with the smallest distance to the origin point as the optimized solution. The optimized window configurations and window size information in the two Pareto front solution groups are shown in Table 1. Solution 1 represents the choice of achieving better energy saving and occupant comfort with little cost. Solution 2 represents the choice of achieving the best performance with sufficient funds.

Table 1. Decision-making solutions.

	Solution 1	Solution 2
Frame type	Aluminium alloy	Aluminium alloy
Glass configuration	Single glass 6	Double low-e 6 + Air 12 + Glass 6
Width	South: 2.3 North: 2.2	South: 2.2North: 2.4
Length	South: 0.8 North: 1.2	South: 0.9 North: 0.9
Sill height	South: 1.5 North: 1.5	South: 1.5 North: 1.3
EUI	228.47	226.40
LCC	30.48	31.97
IEQ	70.07	72.54

4. Discussion

In this study, the optimization process of window components in the local supply chain is conducted by introducing P-BIM framework. Compared with the traditional optimization process in window construction and size, the proposed optimization process indicates the following advantages.

The proposed optimization process enables the industrialized products to play a part in advance in the preliminary design stage. The current construction engineering industry has gradually completed the industrialization transformation, and various building components have gradually completed marketization reforms. On the other hand, the architect responsibility system is being implemented rapidly, and architects' attention should shift from the design stage to the complete project life cycle. Based on the above requirements, the traditional operation mode of separating the design phase from the procurement phase is no longer adequate for the current industry status. The technology proposed in this paper can take industrialized products to the initial stage and integrate them into the design process, which responds to the above needs.

The proposed optimization process adapts to the needs of regional differences. The supply chain of building component products will change following the project location and project undertaker. The proposed optimization model is automatically linked with the structured database by the index query. The constructed database provides a standardized data storage method, ensuring the stability with the change of component data, which guarantee the adaptability and flexibility of the optimization process.

The proposed optimization process bridges the gap between expected performance and actual performance. In the traditional building sustainable performance optimization design, the window size and layer thickness are optimized directly in the form of continuous variables. The design results obtained often cannot correspond to specific component products, so the component products with similar parameters to the optimal solution are selected for further use. However, the performances and parameters often do not follow a simple linear relationship, and neither do parameters amongst themselves. Huge performance gap may be caused from the seemingly similar building components. The optimization model constructed in this study directly screens the building component products as variables, and directly evaluates the performance changes caused by the actual components to guide decision-making. This eliminates an important factor leading to the performance gap from the root.

5. Conclusions

In response to the emergency needs of digital energy efficiency design based on BIM, a performance integrated BIM framework and a multi-objective optimization model constructed on it are introduced. The study integrates external supply chain products and multiple performance driven design functions in BIM system. The optimization model is constructed to optimize the size and configuration of the windows, which plays a key role in building sustainability. With the aid of P-BIM technique, three comprehensive performance are evaluated and optimized dynamically in a digital building energy model in BIM. The optimization results demonstrate that there is a contradictory relationship between the three comprehensive objectives, and the window glass configurations lead to the separation of solution groups obviously. Best solutions in each group are finally picked up with different performance preference trends.

Energy consumption, life cycle cost, and occupant comfort represent the core demands of construction projects from the perspective of the government, developers, and users respectively. Among them, energy consumption responds to the needs of energy efficiency in SDG 7. The optimization of indoor environmental quality responds to the concerns for mental health, well-being and communicable diseases in SDG 3. For the purpose of economizing on raw materials and reducing consumption, LCC optimization responds to the needs of sustainable consumption and production in SDG 12. The three performance are highly comprehensive and always contradict with each other. The holistic optimization of the economic, social and environmental performance enhance sustainable built environment in SDG 11. This study establishes the evaluation and optimization tools of the three performance under BIM system through the introduction of the P-BIM framework. The tools can be widely applied to different types of projects and industrial supply chains, and has strong practical significance.

On the other hand, the optimization model established in this paper puts forward the perspective of building products in the initial stage of design. The integration of local supply chain has the following three aspects of significance for construction engineering. First, it conforms to the current trend of industrialization and marketization of building components. Second, it conforms to the local characteristics of the project and the industry. Third, it reduces the gap between expected performance and actual performance.

In summary, the local supply chain based comprehensive sustainable performance optimization is taken into the early design stage with the help of P-BIM framework. The gap between the expected performance and the actual performance is reduced, and the architect's control of the project life cycle is promoted.

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