AN INFORMED METHOD - VISUALIZATION FOR MULTI-OBJECTIVE OPTIMIZATION IN CONCEPTUAL DESIGN PHASE

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Abstract. The relationship of different performance objects may be very complicated that designers can’t guarantee the improvement of one object don’t affect the others. Multi-objective optimization algorithms provide Pareto optimal design solutions, but because of the nonlinearity introduced by the objective functions, the relationships in the objective space do not extend to the decision variable space and vice versa. Based on the design of building blocks and west facade in a practical project, the paper put forward a visualized method for optimization process of building performance, and combine the multi-objective optimization algorithm with the visualization of fitness landscape, so that architects can easily obtain the knowledge of complex relationships between building performance and building parameters. It is more conducive to obtain a design scheme which can balance the requirements of appearance and performance at the same time, and achieve the ultimate goal of improving the efficiency of design.

Keywords. Visualization; Multi-objective optimization; Fitness landscape.

1. Introduction

Building energy consumption has always accounted for a larger proportion of the world’s continuously increasing energy consumption. At present building energy consumption even exceeds 33% of the total in China, simultaneously office buildings account for a large proportion. Therefore, the energy demand has become an important consideration during the whole design phase, but the inconvenience of using professional energy simulation tools has hindered the architects’ intuitive consideration of building energy consumption in the early design stage of their project, which also has affected the optimization of building energy consumption.

In recent years, various plug-ins have been developed based on the Grasshopper platform in Rhinoceros, supporting architects to easily integrate building designs with various professional performance simulation software such as EnergyPlus, Radiance, Openfoam, etc. A variety of optimization plug-ins such as Galapagos, Octopus, Opossum make it possible for architects
to optimize building performance in the early design stages. Scholars such as Christoph Waibel, Kristoffer Negendahl, Kavan Javanroodi and others have used Grasshopper in their related studies for buildings’ performance optimization.

In most cases during conceptual design stage, a complex building performance optimization can be decomposed into several sub-tasks in which the number of performance target is small and there are only 2D or 3D variables. This low-dimensional data can directly be visualized by the use of 3D surface diagram or 3D point cloud diagram, at the same time, this visualization method can maximize the readability of the relationship between the data. We apply this method in the design process of a practical project and want to show a new design approach for architects.

2. Background

Table 1. The specific indicators of the office building.

<table>
<thead>
<tr>
<th></th>
<th>HEIGHT</th>
<th>TOTAL AREA</th>
<th>UPPER FLOORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFFICE AND CONFERENCE</td>
<td>24m&lt;h&lt;45m</td>
<td>58000</td>
<td>4-6</td>
</tr>
</tbody>
</table>

The project is the headquarter building of an big company, located in Shandong province, which belongs to the cold region of China. In urban design phase, the basic shape of building in the site has been specified. The building has four strip-type blocks arranged in parallel from east to west, which are connected by a north-south block to form a large office complex. The first and second floors include public service functions, and the upper floors are all for office and conference functions, the specific parameters are shown in Table 1. We attempt to make an optimization of the initial investment and later operational energy consumption of the building early from the concept design process. This complex optimization problem can be broken into several secondary optimization issues, including building volume settings and glass curtain wall optimization. At the same time, we need to notice that the main goal of the design practice is not to find out the ultimate performance optimization in every level, but to enable the architects using the tool which can help them intuitively understand the impact of current morphological operations on building performance, in addition, they can optimize the performance indicators of building as much as possible while guaranteeing its facade’s artistic qualities.

3. Framework

3.1. SAMPLING

Based on grasshopper platform, a parameter space sampling is made. Compared with random sampling or grid sampling, Latin hyper-cube sampling (LHS) can ensure that the structure of the samples is similar to the overall structure. We use sampler tool of design-space-exploration tool set for sampling operation, in order to give full use of the CPU performance, IDF files are generated in batch
mode using Honeybee linking with EnergyPlus. Then the files are fed into Honeybee’s batch energy calculation tool for parallel calculation, obtaining the target performance of each parameter combination.

3.2. GRASSHOPPER TO MATLAB

With the help of GH_CPython, a data exchange interface is built. Sample data is sent to MATLAB through MATLAB API, meanwhile other input parameters can be set to determine which metamodel algorithm will be used for the fitting operations of subsequent data.

3.3. METAMODEL GENERATION AND VISUALIZATION

According to the parameters of the interface program, architects can decide which algorithm is used for generating the metamodel, so that they can choose ANN, RBF, Random Forest, Kriging, MARS and SVM modules. Besides, an automated framework is designed to filter out best metamodel with high R² value. Taking ANN as an example, the candidate network structure is a single hidden layer neural network with 6-20 neurons or a double hidden layer neural network with 2-4 second hidden layers. First, different network structures are trained, then through the evaluation of new test data, a neural network that meets the maximum R² value can be chosen as the best metamodel to predict a certain performance index. (Figure 1)

A metamodel is used to perform grid sampling on decision variable space to obtain a function surface or three-dimensional point cloud that visualize the relationships of design parameters and building performance. The Z-axis value or the color of the sampling point represents the performance index (depends on whether the number of parameters is two or three). Multiple performance indicators are juxtaposed, and the viewing angles are synchronized, so that architects can accurately grasp the changing trend of each performance with different design parameters. (Figure 2)
3.4. DATA FEEDBACK INTERFACE

Also, through customized GH_CPython components, designers can input new design parameters to feed to the metamodel in MATLAB, and quickly get the predicted performance indicators in real time. How the interface is used depends on whether the designer can directly select test points based on the visualization results of the previous step. If the designer hopes to select only a more satisfactory value range based on the previous step and intends to perform multi-objective optimization on this basis, he can directly link this interface to an optimizer such as Octopus. The method successfully avoids the slower sampling process of the first step and can help quickly obtain approximate results of performance values. The approximate results are sufficient to meet the accuracy requirements of the conceptual design.

The framework shown in Figure 3 summarizes the whole process.
4. Case studies

4.1. VISUALIZATION OF ARCHITECTURAL FORM AND PERFORMANCE

From the perspective of the concept design, it’s worth detailed study how the height and depth of the four east-west blocks influence the changes in the overall performance of the building. According to the national regulation, in order to reduce heating energy consumption as much as possible, buildings in northern cold regions should reduce the shape coefficient. How can this established regulation be reflected in specific building mass design? From the perspective of architects, intuitively, the depth of the building should be increased and the height of the building should be reduced to minimize the external surface area of the building, but it’s not clear how much the changes of different parameter can impact the energy consumption. Considering that the northern buildings need more direct sunlight in winter, there should be enough distance between them. Meanwhile, it’s also not certain whether the demand is contradictory to energy consumption or not. All these questions should be answered from building simulation analysis during the project design process.

4.1.1. Design Task - One

The total area of each east-west block is set to 7,500 square meters, and there are three variables- the number of floors, building depth and building height. On this basis, the more the number of floors, the smaller the area of each floor, and the length of the building will be shortened with the same depth. Secondly, when all other things being equal, the higher the floor’s height is, the more energy correspondingly increased. However, if considering the entire building mass, a higher height will also increase the total area of shadows between the building masses, potentially affecting the lighting effect. (Figure 4)

![Figure 4](image.png)

Figure 4. (a) 26m, 5 floors, 5.1 m/floor. (b) 21m, 4 floors, 3.9 m/floor. (The first and second floors are not included in the analysis diagram.)

4.1.2. Results Visualization

One hundred sampling points of the three parameters are simulated, the visualization results in MATLAB is shown below in Figure 5.
From the visualization, it can be intuitively seen that the cooling energy consumption gradually increases with the increase of the building height and the decrease of the building depth, but has a weak correlation with the number of building layers. The relationship between heating energy consumption and other parameters is more complex. It is the largest when the height of the building is 4.8m or 4.2m, with the number of floors is 6, however the correlation with the building depth is weak; the trend of total energy consumption is the superimposed effect of the two; sunshine duration is negatively correlated with all the design variables.

The model construction and calculation have taken two hours in total. The performance visualization is simple, but instructive for the design process. After combining the above performance analysis results and building modeling requirements, our team finally choose a layer height of 4.5m, 6 floors and a depth of 18m to be the control parameters for further design.

4.2. PARAMETER OPTIMIZATION OF CURTAIN WALL ON WEST FACADE

4.2.1. Design Task - Two

During the design phase, part of the focus is the design of the west facade as the main facade. The final design is shown in the following Figure 6. It is hoped that the simple and repetitive facade elements can be used to create a whole building image. From the perspective of sun-shade, the west facade of the building is generally designed as a solid wall. Since the west facade of the project is directly facing the urban main road and represents the images of the headquarters, therefore, a zigzag glass curtain wall system is set up. The light getting in can meet the requirements of the internal office function while the office spaces are being protected from too strong sunlight by self-shielding. The inclination angle and extension distance of the zigzag glass curtain wall also affect the building skin investment cost, indoor lighting effect, cooling and heating energy consumption. However, architects do not have an intuitive impression of how each performance changes under different parameter combinations.

In consideration of limitations of the simulation time, the window units between the two column spans were selected for parameterization. Thereby the size and rotation angle of the window units were variables. The visualization performances are the material investment cost, $UDI_{100, 2000, 60}$ value, cooling and heating energy consumption.
4.2.2. Visualization Results

The rotation Angle ranges from -90 to 90 degrees, 100 combination samplings have been made, the batch simulation has taken 2 hours, and 4 juxtaposed visualization results are obtained. The results are shown as follows:

- **Material Cost:**
  
  The general trend is that as the rotation angle approaches zero and the window length decreases, the cost gradually decreases. A curved surface with a V-shaped depression in the middle is formed, axial symmetry, and the lowest value may achieve when the window length is zero.

- **UDI100–2000/60 Value:**
  
  To consider multiple analysis points, $UDI_{100–2000/60}$ is defined as the percentage of floor area (represented by the percent of analysis points) that receives the “useful” illuminances (i.e.100-2000 Lux) for at least a specified percentage of occupied hours. Nabil and Mardajevic proposed that the effective illuminance value range should be determined between 100-2000Lux. The percentage of occupied hours is initially set to 60% in this case.

  The result shows that $UDI_{100–2000/60}$ value decreases with the increase of the overhang distance, and a larger rotation angle implies more chance getting higher value; The fitness landscape forms a conical depression around point(0, 2.1), this is because the approximately flat wall and the wider window let excessive amount of beam light in; when the window size turns below 0.4m, the $UDI_{100–2000/60}$ value sharply decreases as the inner space gets insufficient daylight.

- **Energy Consumption:**

  It includes cooling and heating energy consumption; the cooling energy consumption decreases monotonically with the decrease of the window size and the rotate angle’s deviation value from around 10 degree, forming a convex surface; the fitness landscape of heating energy consumption turns to be complex, the value goes very high around the upper left corner, and in the mid-right place
around point(30,0.6) the landscape forms a shallow depression area.

Considering the optimization of the four target parameters, the less energy consumption, material cost and the more UDI is preferred. From the visualization, architects can get an overall understanding of the changing tendency with the change of parameters. One can easily get a knowledge that the window length should be short; The rotation value should better be around 30 degrees to obtain a better heating energy consumption while not affect the $UDI_{100-2000/60}$ value and material cost so much. Based on the above analysis, combined with the corresponding appearance of the zigzag curtain wall, an angle of 30 degrees and the width of 0.7m are chosen as the final design parameters. Figure 7 below shows the final results for the four objectives.

![Figure 7. Visualization for the four objectives. (a: plan view, b: 3D view).](image)

4.3. COMPARATIVE ANALYSIS

4.3.1. Comparison with multi-objective optimization algorithm

![Figure 8. The sampling of a multi-objective optimization algorithm.](image)

Constructing a multi-objective optimization algorithm for the second issue, and result of sampling which is visualized on the fitness landscape in Figure 8. Finally, the parameter combinations corresponding to the pareto front is close to the above
chosen area. But to achieve these points, many physical simulations must be done, which will take a long time. The crucial limitation is that the optimization method can’t help architects to gain a holistic understanding of the design space. Since in the last generation and on the pareto front, most of the samples are in a small range compared with the whole design space.

4.3.2. Comparison with parallel plot

In normal conditions, with use of Design Explorer, through the Parallel plot designers can intuitively filter out better instances from a big number of samples. The performance of the scheme can be visualized and screened effectively even if the parameter space exceeds three (Figure 9-a). However, this method is a sparse sampling of the parameter space, which requires a very dense sampling data, otherwise, the potential optimal parameter combination is ignored. Also, the selection of parameter intervals is a tentative behavior, and it is not easy to know in which range there are matching parameters and whether a new unsampled parameter combination are more suitable or not.

In comparison, our research supplements the display of the parallel plot by including both the parameter range and the changing trend. The three-dimensional surface plot expresses the four different performances of the same combination of parameters, allowing designers to capture multiple performance trends at the same time (Figure 9-b). The juxtaposed display of the 3D surface plot can enable the designer to directly observe the undulating shape of the performance surface in the parameter space, and directly select the optimal parameter area based on this. Moreover, the range presented by the 3D surface plot is continuous and complete, and the changing trend of extreme values is expressed by the appearance of slopes and valleys, and there will be no omission of optimal values.
5. Conclusion

As part of the task to explore the correlation between architectural form and performance, the paper presented a methodology and a visualization platform to obtain and evaluate the impact of different design parameters and performance indicators on building form, focusing on the initial phase of architectural design.

Due to the new possibilities offered by Ladybug Honeybee and other simulation tools, various design performance of the building can be systematically evaluated, including daylight, energy demand and cost estimates, etc. However, the need for multi-target performance optimization in architectural design requires researchers to explore easier ways to achieve visual translation of performance parameters and better integrate into architectural design processes. This paper realizes the visualization of several building performance indicators by building a metamodel, so as to get the best solution quickly and effectively under multi-objective conditions. This method is then applied to two design tasks, one is to optimize the overall size of the building, the other is to optimize the shape of the zigzag curtain wall unit of the west facade. Further confirming the ease of use of this method, it is helpful for the architect to quickly capture the complex relationships between design parameters and multiple performance.

At present, the platform does not focus on obtaining accurate performance values, but rather provides architects with a powerful visualization tool to make them more confident in considering the key factors of building performance, and gain full control over what is beneficial to the operation of the building after completion. As the green building evaluation rules become more stringent, it is becoming more important to consider the key factors affecting building performance from the very beginning. Through the use of this new method, it is more convenient to design energy-saving and environmentally friendly buildings.

References