A Study on Automatic Form Optimization Procedures of Building Performance Design Based on "Ladybug+Honeybee"

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Abstract. This paper discusses a method for integrating parametric design with building form automatic optimization for energy-saving, specifically presenting Ladybug+Honeybee, as a representative parametric building performance analysis tool, and the design methodology that are suitable for the early stage of the building scheme phase. In this study, an ideal procedure for integration of parametric modeling and building performance analysis was developed. The procedure includes four steps: 1) parametric form definition; 2) adaptability relationship analysis; 3) automatic form optimization; 4) simulation measurement and post evaluation. Taking a coastal hotel building in hot-summer-warm-winter area as an example to explore the automatic form optimization for energy-saving.

1. Introduction

Building scheme stage is the foundation and key part of building performance design, which has great potential in energy-saving. However, the conventional scheme stage in building performance design relies too much on the architect's personal experience, which lacks of clear, precise and quantitative energy-saving goals. In recent years, parametric design tools have made breakthroughs in integrated simulation technology, among which Ladybug+Honeybee (hereinafter referred to as L+H) is the most prominent one. L+H can not only integrate several developed software cores in building performance simulations, therefor calculate the coupling of energy consumption, solar radiant, wind, sunlight, temperature, humidity and thermal comfort in the same model; but also realize the automatic form optimization for a specific performance objective by means of the genetic algorithm module in Grasshopper. The high performance of L+H not only makes up for the technical defects of the conventional design methods, but also provides designers a clear direction of energy-saving optimization in the early stage of building schemes. In addition, L+H can set parameter intervals according to the requirements of specifications, and provide precise and quantitative results of form optimization.

Table 1. Comparison of L+H and other similar products

| Name   | Function                        | Application                                | Core         | Type   |
|--------|---------------------------------|--------------------------------------------|--------------|--------|
| Heliotrope | Solar Information and Geometric Information | Generating Sunlight Vector and Calculating Shadow Profile | Python       | GH Plug-in |
| Gerilla | Energy consumption simulation | Heating Energy Consumption and Cooling Energy Consumption | EnergyPlus   | GH Plug-in |
This paper focuses on L+H-driven building performance design strategy. Starting from the stage of building scheme, taking the energy-saving design of a coastal hotel in hot-summer-warm-winter area as an example, which explores how to use L+H tool to compile parametric design flow that can be applied to building form optimization, so as to realize the automatic optimization of building form aiming at energy-saving. At the same time, according to the domestic building energy-saving design standards and norms, post-evaluate the energy consumption related indicators.

2. Relevant Software and Principle

2.1. L+H Parametric Performance Simulation Tool
L+H is a free, open source environmental and building performance analysis plug-in developed in the United States in 2014. Mostapha Sadeghipour Roudsari, one of the developers of L+H, proposed in 2013 that the advantage of Ladybug software is to support full-scale environmental analysis on a single platform. By importing standard EnergyPlus file (.epw meteorological data), interactive 2D and 3D graphical meteorological data visualization such as solar path, wind roses, radiation roses, comfort level, visual field analysis and shadow analysis are provided at the beginning of the design, which directly relates to the design and environment, and accurate results of solar radiation and sunshine hours are obtained to support the design process. Honeybee software, as an extension of Ladybug software, can be further studied. Honeybee can call EnergyPlus, Radiance, Daysim and Openstudio in Grasshopper to simulate thermal comfort, sunlight, and energy consumption. In terms of results, L+H has excellent simulation accuracy and the most diverse forms of information expression.
2.2. **EPW Meteorological Data**

The Meteorological Document Format developed by the U.S. Department of Energy and EnergyPlus is based on 20 different data sources around the world. This includes the typical meteorological year data of CSWD (Chinese Standard Weather Data) developed by Dr. Jiang Yi of Tsinghua University from China. Typical meteorological year is a "hypothetical" meteorological year consisting of 12 typical months with the closest statistical significance to the historical average. The selection of typical months takes into account the weight of each meteorological factor in thermal environment analysis, and selects the month closest to the multi-year average. The main meteorological elements analyzed are outdoor temperature, dew point temperature, horizontal solar radiation, wind direction and wind speed.

2.3. **Galapagos Genetic Algorithm Module**

Grasshopper (hereinafter referred to as GH) is a plug-in running in Rhino environment using program algorithm to generate model. The greatest feature of GH is that it can send more advanced and complex logic modeling instructions to the computer, so that the computer can automatically generate model results according to the proposed algorithm. Galapagos is an operating module based on Genetic Algorithm in GH, which is mainly used to optimize data. Galapagos genetic algorithm module originated from Darwin's theory of natural selection, trying to find the solution to the problem in the way of evolution of nature. Its operation principle can be understood as solving equations, that is, optimizing by specific results or calculating the optimal data at the input end. Once the relationship is set, theoretically the global optimization can be achieved. Galapagos genetic algorithm module has the characteristics of simple operation, fast running speed and intuitive interactive interface.

Galapagos is able to be connected with multiple independent variable parameters at one time, but only one dependent variable parameter can be connected to. Therefore, it is necessary to sort the operations of the objective functions and record the results of the operations when Galapagos deal with multi-objective optimization. The implementation of genetic algorithm generally includes the following five steps: (1)the formation of the initial population; (2)setting the fitness to evaluate the individual, whether the individual is the best; (3)selecting according to the fitness evaluation, appearance of the optimal individual or generating the next generation of new individuals;
(4) generating new individuals by crossover and variation of genes; (5) calculating the fitness of the new individual and repeating the evaluation process of step 2. (Fig. 2)

Figure 2. Diagram of genetic algorithm

3. L+H Driven Form Optimization Method for Energy Conservation Design of Public Buildings

3.1. Optimizing Idea and Process

According to the optimization logic of "parametric form definition-adaptability relationship analysis-automatic form optimization-simulation measurement and post-evaluation". First of all, through theoretical analysis of building functional requirements and related norms, and add the architect's personal judgment to establish the original shape of the building space. Secondly, energy-saving strategies are obtained through L+H simulation analysis of prototype buildings. Thirdly, building form is automatically optimized by constructing the corresponding relationship between the parametric model and the energy-saving strategy. Finally, the energy consumption of all building systems including air conditioning system is simulated to verify its effectiveness.

Figure 3. Work flow of form optimization for building energy saving design
3.2. L+H Simulation and Automatic Form Optimization

3.2.1. Meteorological data analysis. Before the design, it is necessary to analyze climate data, determine reasonable passive energy-saving design strategies, and provide ideas for building form and architectural detail design. The specific operation is as follows. The epw file is imported into Ladybug tool, and the weather data, building energy consumption simulation and human comfort analysis are coupled to calculate. The energy consumption balance chart (fig. 4) and indoor thermal comfort time chart (fig. 5) are generated.

![Figure 4: Partial energy consumption balance chart](image)

**Figure 4.** Partial energy consumption balance chart (taking meteorological data files of Van Nuys Airport, CA, USA, TMY3 as an example)

![Figure 5: Indoor thermal comfort time](image)

**Figure 5.** Indoor thermal comfort time (taking meteorological data files of Van Nuys Airport, CA, USA, TMY3 as an example)

Based on Meteorological data, the energy-saving strategy ranking and the application time range of each strategy suitable for local climate conditions are obtained. For example, as shown in Fig. 4 and Fig. 5, the energy balance sub-map and indoor thermal comfort map of local reference buildings are calculated with meteorological data of Van Nuys Airport, CA, USA and TMY3. By analyzing the information in the diagram, the following energy-saving strategies are generated: first of all, reduce summer solar radiation (corresponding to June-September, the cooling index in Figure 4 increases and the red part concentration time in Figure 5); secondly, increase natural ventilation in spring (corresponding to the increase of mechanical ventilation index in March-May in Figure 4); thirdly, Choosing appropriate enclosure structure (corresponding to the opaque conduct index rising in
October to May of next year in Figure 4). The increase of the index indicates that the reference building cannot meet the specific needs of people in a certain period of time under natural conditions, so it relies on electrical machinery and equipment to make up, while generating energy consumption.

3.2.2. Automatic Building Form Optimization Based on Genetic Algorithm. With the help of L+H tool and Galapagos genetic algorithm module, the parameter logic can be set so that the computer can automatically complete the complex calculation and optimization process, and obtain the optimal results with the goal of energy saving in a relatively short time. Specific operations are as follows: Through GH parameterization platform, the shape optimization strategy is compiled into a parameterized model of controllable shape, which is related to the results of L+H meteorological analysis, so as to establish the quantitative relationship between form and building performance. The Galapagos genetic algorithm module is used to correlate the L+H performance analysis data with the shape control parameters of the form parametric model to form a loop. In Galapagos, the analysis data of L+H is set as Fitness, the shape control parameters of parametric model are set as Genome, the results of shape optimization are controlled by presupposing the specific values of the fitness parameters (or maximum/minimum), and the amount of calculation and optimization are controlled by setting Population (number of examples) and Max. Stagnant (number of iterations), Degree (or number of optimal solutions).

Different arrangements and combinations of shape control parameters will lead to different results satisfying optimal adaptability. Usually, a set of optimal solutions satisfying the adaptability will be generated after calculation, and the larger the amount of calculation, the more the number of optimal solutions will be. On this basis, architects can select suitable building forms, or through setting new adaptive parameters and corresponding shape control parameters, the next round of optimization can be carried out in the existing results.

Taking a building concept volume of 97 meters in length, 48 meters in width and 3.5 meters in height on each floor of 45 floors as an example (Fig. 6), the geometric control parameter settings are: R1 is the base rotation angle, which controls the orientation of the building. The Default building orientation is the North-South orientation. Set the change interval of R1 to be -90°<R1<90°; R2 is the top rotation angle, which controls the direction and degree of building distortion. Set the change range of R2 to be -45°<R2<45°. Relevant settings of R1 and R2 are: R2 is the relative rotation angle of R1. When R2 changes R1 unchanged, the building will be distorted and the overall orientation of the building will remain unchanged. When R1 changes R2 unchanged, the orientation of the building will change and the shape of the building will remain unchanged.

![Figure 6. Conceptual Parametric Model](image-url)
The parametric model is loaded into the solar radiation analysis module of Ladybug and EPW meteorological file is called. Using Galapagos genetic algorithm module, the Total Radiation (total radiation) of Ladybug output is set to Fitness (target parameter), and the parameters of R1 and R2 in shape control module are set to Genome (genome, i.e. independent variable).

After 60 iterations, 50 examples of each generation participated in the calculation of a total of 3100 results. There are two optimal solutions, corresponding to volume change parameters: $R1=42^\circ$, $R2=2^\circ$ and $R1=30^\circ$, $R2=-19^\circ$. The first 20 results with the minimum total radiation for the whole year as the target parameters are shown in Fig. 10.
Figure. 10. Top 20 optimal results with the objective of “reducing the total solar radiation in the entire year”
3.2.3. Simulation Measurement and Post-Evaluation. Because the objective parameters of building energy-saving design are not unique, it can also be combined with other sub-optimization objectives to continue to optimize the building form, approaching the final optimal solution (Fig. 11). After completion, the energy consumption simulation is carried out by combining other design parameters such as air conditioning system, envelope structure and so on, which is verified to form the final scheme.

![Initial Parametric Model](image)

**Figure 11.** Partial optimization approximates the final optimal solution

4. Method Application--Taking a hotel in hot summer and warm winter area as an example

4.1. Project Introduction and Meteorological Data Analysis

The project is located in the middle of the coastline of Haitangwan Bay in Sanya City, east of the junction of Binhai Road and Fengtang Road. It has been built as a high-rise hotel and its supporting facilities. Its land area is 114,000 m². It is proposed to build 48 floors above ground and 1 floor below ground with a total floor area of about 250,000 m². Based on the local meteorological data, the energy consumption balance diagram (Figure 12) and indoor thermal comfort time diagram (Figure 13) are generated by coupling calculation with building energy consumption simulation and human comfort analysis, and the following energy-saving strategies are generated based on the information in the diagram: (1) According to the increase of cooling load index and glazing conductor index in June-September of Figure 12 and the concentrated period of red part in Figure 13, the energy-saving strategy is to reduce solar radiation during April to September; (2) According to the increase of mechanical ventilation index during April to October in Fig.12, natural ventilation during that time should be increased; (3) According to the increase of opaque conductor index from November to March in Fig. 12, the appropriate enclosure structure should be selected.
Figure 12. Sub-item Energy Consumption Balance Chart (Taking the Meteorological Data of Sanya City, Hainan Province as an example)

Figure 13. Indoor thermal comfort time (taking Sanya meteorological data in Hainan Province as an example)
4.2. Parametric Construction and Auto-optimization of Architectural Form

According to the requirements of project construction and energy saving, a parametric model is established (Fig. 14). The form control parameters are set as follows: R is the rotation angle of the building plane with P-P' as the axis (the change range is $-90^\circ < R1 < 90^\circ$), which controls the building orientation (default building orientation is the North-South direction); P-P' axis is the building axis, where point P is the center of the first floor plane of the building, and point P' is the projection of point P on the top floor plane of the building; the building plane is determined by four radius circles of 10 meters and their tangent arcs. The center of the circle moves in the range of 0-20m and 0-40m at both ends of the axis.

According to the method above, the shape optimization is carried out (Fig. 15). The orientation of the building, the change of the plane space of each floor and the height of the tower are optimized in the initial stage; the window-to-wall ratio and the position of the window opening are optimized in the
middle stage; the openable area ratio of the outer window is set in the later stage, hence the final form optimization results are obtained (Fig. 16).

Figure 16. Tower facade of Atlantis Hotel, Sanya, Hainan
4.3. Simulation Measurement and Post-evaluation

Through the hourly energy consumption simulation of 8760 hours in the entire year, the monthly average energy consumption results of the design building and reference building (according to the minimum energy-saving requirements of the national standard), and the annual energy consumption ratio are obtained, as shown in figs. 17 and 18. At the same time, according to the simulation results, further sorting out the energy-saving proportion of each system of the design building (Table 2), and calculating the proportion of energy consumption of the design building to the energy consumption of the reference building is 79.77%, the energy-saving rate of the design building is 60.11%, which is far higher than the requirements of the local standards, and meets the criteria in "Green Building Evaluation Standard" (GB/T 50378-2014), which is “The total energy consumption of building design should be lower than 80% of the specified value of energy saving standard approved or filed by the state”

![Figure 17. Constitutive chart of monthly and annual energy consumption](image1)

![Figure 18. Composition of Monthly and Annual Energy Consumption Ratio for Designed Buildings](image2)
Table 2. Proportion of energy-saving between design building and reference building

| Energy Consumption Type       | Annual energy consumption per unit area (KWh/m²) | Proportion of energy saving |
|------------------------------|-------------------------------------------------|----------------------------|
|                              | Design building | Reference building |                               |
| Lighting                     | 21.11            | 23.46             | 10.02%                       |
| Electrical Equipment         | 38.52            | 38.52             | 0.00%                       |
| Fan                          | 24.18            | 38.60             | 37.36%                      |
| Pump                         | 4.18             | 7.25              | 42.31%                      |
| Cooling                      | 32.27            | 41.63             | 22.49%                      |
| Cooling Tower                | 0.84             | 2.35              | 64.41%                      |
| Total                        | 121.10           | 151.81            | 20.23%                      |

5. conclusion
Starting from the stage of architectural design, this paper studies the process of shape optimization of parametric energy-saving design based on L+H. Taking the Atlantis Hotel in Sanya, Hainan as an example, the validity of the method is verified. It embodies the technical advantages of L+H tool in the aspect of automatic, accurate and integrated shape optimization aiming at building energy saving, and the potential of the whole process design around building performance. This includes the data interaction and visualization in the early stage of design, the automatic optimization of form in the scheme stage, and the optimization of building components in the deepening stage, so as to take care of the building performance with the strength of technology and promote the innovation of the direction, process and method of future architectural design.

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