INVESTIGATION ON THE POTENTIAL OF IMPROVING DAYLIGHT EFFICIENCY OF OFFICE BUILDINGS BY OPTIMIZED CURVED FACADES

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Abstract. With the rapid development of digital design methods, irregular curved shapes have been more and more widely used in buildings, which not only enriches the appearances of buildings, but also provide new possibilities of improving building performance by shape designs. However, existing researches regarding building performance and shapes mostly focus on regular shapes, while curved shapes are rarely explored. This paper aims to employ design optimization method to explore the improvement of building performance that curved shapes could contribute. Specifically, office buildings are chosen as an example and the potential of improving the daylight efficiency of them by optimized curved facades are investigated. Three major cities and two orientations are involved in the investigation. The results prove that curved facades do have significant potential to improve the daylight efficiency of office buildings, and an average improvement of 0.2032 is achieved by the optimized curved facades in the 6 cases conducted in this research in terms of the area-weighted average UDI (useful daylight illuminance) compared with the same building with plane facade.

Keywords. Curved Facade; Daylight; Building Performance; Design Optimization; Office Building.

1. Introduction

1.1. RESEARCH BACKGROUND

With the severe environmental and energy crisis and people’s growing demands of comfortable and healthy living conditions, technical performance of buildings such as energy consumption, daylighting, ventilation and indoor air quality has been an increasingly crucial issue. Shape design, the starting point of architecture design, not only largely determines the spacial effect and aesthetic value of buildings, but also plays an important role in technical performance (Markku 1998, Liu 2017, Krem 2013). For example, Liu (2017) suggests that different orientations, plan proportions and window-to-wall ratios could cause a variation in energy consumption of 17% for office buildings in Tianjin.
Krem (2013) reveals that appropriate plan layouts may lead to a reduction in energy consumption of 6%-32% depending on the climate zone. In order to improve building performance by shape design, various researches have been conducted to explore effective methods, for example, design optimization based on performance, sensitivity analysis that reveals the impacts of shape characteristics on performance, knowledge-aid tools for shape design based on performance, etc.

Meanwhile, with the rapid development of digital design methods, irregular shapes with curved elements have been more and more commonly used in buildings. This not only enriches the appearances of buildings, but also provide new possibilities of improving building performance by shape designs. However, existing researches regarding building performance and shapes, mostly focus on regular shapes, while only few of them cover irregular curvy shapes. Whether curvy shapes do have significant influence on building performance has not been proved quantitatively. Moreover, how to apply the existing design methods to curvy shapes needs to be further explored. As a result of the insufficiency of existing researches, most curvy shapes nowadays are designed only according to the aesthetic aspects, while the potential improvements of performance that curvy shape could contribute are rarely realized. This paper seeks to address this problem by taking typical office buildings as an example and exploring the potential of improving the daylight efficiency of them by curved facades using the design optimization method.

1.2. STATE OF THE ART

Design optimization refers to the technique that employs optimization algorithms to generate new designs based on simulation results and user-defined design objectives (Nguyen 2014). This technique has been intensively explored since this decade and there are 13 publications annually in major journals and conferences after 2010 (Shi 2016). As the achievements of the precedents researches, design optimization has become a mature method for many aspects: 1) the general procedural of design optimization have been formed, which consists of steps including defining design tasks, defining design objectives, performance simulation and optimization (Shi 2016, Nguyen 2014). 2) The major aspects of building performance including energy consumption, thermal comfort, daylighting, ventilation and acoustics have been covered. For example, Ascione (2015), Yi (2009), Jin (2014), Sub (2011), Lartigue (2013) and Xu (2015) employ energy consumption (including heating / cooling load) as the optimization objectives; Lartigue (2013), Caldas (2016), Trubiano (2013) and Zhang (2016) choose daylighting performance as their optimization objectives; while Sakse (2015), Bassuet (2014) and Robinson (2014) optimize building designs for most desirable acoustic quality. 3) different widely-used simulation software packages have been integrated into design optimization so that various building performance can be used as objectives, for instance, EnergyPlus, Transys, Radiance, Fluent, etc. 4) Several optimization algorithms and optimization platforms are available for architects and researches to choose according to their demands. Commonly used optimization algorithms includes genetic algorithm (GA), particle swarm algorithm, simulated annealing, etc., while GenOpt, Matlab, Rhinoceros are
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among popular optimization platforms that have their own advantages each. Despite the advanced aspects above, there is still an obvious shortcoming of the design optimization reported in existing researches, that is most of them can only generate simple and regular shapes such as rectangular shapes, polygonal shapes, L-shapes, U-shapes, etc., and the design variables of optimization are restricted to dimension, proportion, orientation and other basic parameters. Irregular curvy shapes that do not have simple geometrical representations, on the other hand, cannot be generated. In reality, however, possible shapes of buildings are much more various than just regular shapes, especially in recent years when irregular shapes with curved elements have becoming a blooming trend in architecture design. Therefore, this limitation will significantly restrict the applicability of design optimization in design practice, and the demand of designing irregular curvy shapes based on building performance cannot be fulfilled.

There are also few researches that try to overcome this limitation and optimize irregular curvy shapes. For example, Jin (2014) defines a tilted curvy shape with 5 variables (tilt angle, twisted angle, plan length, etc.) and optimizes the shape using heat gain, heat loss and solar heat gain as optimization objectives. Caldas (2016) defines a curvy ceiling with 20 control points and optimizes it for the most desired distribution of daylight factors. Zhang (2016) control a distorted cylinder with 8 control points and optimizes the shape using solar radiation gain and shape coefficient as objectives. Kim (2011) optimize a twisted box for the lowest wind speed in the pedestrian level, where the rotation angles and scale factors of different floors are selected as shape variables. These researches have made crucial contributions to explore the applicability of design optimization in irregular curvy shapes, but may also benefit from improvements: 1) the shape could have more freedom to be optimized, as in the precedent researches the shapes cannot change dramatically, because the irregular shapes are defined by limited geometrical terms such as twisted and tilted (Jin 2014, Kim 2011), or the control points of the shapes can only move within narrow ranges (Caldas 2016, Zhang 2016). 2) The shape could be more realistic with necessary details, as in the precedent researches the shapes are rough and simplified without interior partitions. 3) More general conclusions could be drawn from the optimization results to help architects improve building performance by appropriate design of curvy shapes. For example, to quantitatively prove the potential improvement that an appropriately designed curvy shape could contribute to a certain kind of building performance.

1.3. OBJECTIVE OF THIS RESEARCH

This research aims to employ design optimization method to explore the performance improvements that curved shapes could contribute. Specifically, the daylight efficiency of office buildings are chosen as an example and the potential of improving the daylight efficiency by curved facades are investigated. Lighting takes up a large proportion of the total energy consumption of office buildings and the annual lighting energy consumption can be significantly reduced with natural lighting. Therefore, this research would provide a new method to reduce building energy consumption if curve façades are proven to have the potential of improving
the daylight efficiency.

Two goals are specifically pursued in this research: 1) to implement an optimization process of curve facades of office buildings based on daylight efficiency; 2) to quantitatively investigate the potential improvements of daylight efficiency that curvy facades could contribute for typical office buildings with different orientations and in different cities.

2. Methods

In order to achieve the two goals above, this research employs a methodology consisting of three parts. That is, 1) Parametric modelling of the office building and its curve façade; 2) daylight simulation and objective goal, 3) shape optimization using genetic algorithm.

2.1. PARAMETRIC MODELLING OF THE OFFICE BUILDING AND ITS CURVE FAÇADE

A typical 5-story office building with glazing façades is selected as a reference case in this study (Figure 1). Since only office rooms have strict requirements on lighting, only the office part and its façade (as shaded in Figure 1) is investigated. Based on the reference case, a two-dimensional curved glazing façade can be defined by 36 control points (6 per floor, see Figure 2). The control points can move along the Y axis so that the shape of the façade can be freely adjusted during the optimization process. The length of each room is required to be more than 4 meters to maintain basic function. Moreover, in order to make better comparison, the overall area of the office rooms are kept the same as the reference building (1600 m²). This can realized by moving the entire façade along the Y axis. Material parameters are summarized in Table 1.

Based on the definition above, a parametric model is developed in Rhinoceros with its plugin Grasshopper (As shown in Figure 5b). NURBS surface is employed here to model the curved façade, which allows more flexible geometry representations than using geometrical parameters, and more smooth and precise than mesh representations.

Figure 1. The reference office building.
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Figure 2. The control points of the curved façade to be optimized (marked in pink).

Table 1. Material parameters for the optimization.

<table>
<thead>
<tr>
<th>Material (as the name in DIVA)</th>
<th>Reflectance (%)</th>
<th>Transmittance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside Ground</td>
<td>20</td>
<td>NA</td>
</tr>
<tr>
<td>Ceiling</td>
<td>Generic Ceiling</td>
<td>70</td>
</tr>
<tr>
<td>Floor</td>
<td>Generic Ceiling</td>
<td>20</td>
</tr>
<tr>
<td>Duplex Glass</td>
<td>Glazing Double-Pan Low-E</td>
<td>N.A</td>
</tr>
<tr>
<td>Interior Wall</td>
<td>Generic Interior Wall</td>
<td>50</td>
</tr>
</tbody>
</table>

2.2. DAYLIGHT SIMULATION AND OBJECTIVE GOAL

Daylight simulation in this research is conducted by DIVA, a plugin to Grasshopper that integrates DAYSIM to Rhinoceros and can calculate various daylight metrics including Daylight Factor (DF), Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI). Among these metrics, Useful Daylight Illuminance is used in this research. UDI is defined as the percentage of time that the illuminance at the work plane is within the range from 100 to 2000 lux, and it has the following advantages: 1) it is a dynamic daylight metrics that takes real weather conditions and actual operation hours into account; 2) it defines both the lower limit and the upper limit, so that the issues of daylight oversupply and visual glare are covered; 3) its limits are decided based on the actual preference and tolerance of office workers’ in various experiments; 4) daylight is effective either as the sole source of illumination or in conjunction with artificial lighting.
when the daylight illuminance is within the range of UDI, so UDI is also an useful indicator of the saving of lighting energy consumption.

As per the definition, for cellular offices UDI is achieved only when the illuminances of all the occupants’ work planes are in the range 100-2000 lux. This condition is consistent with occupants’ behavior, since when any one of the occupants experiences discomfort, she or he would turn up the light or deploy shading device. The measuring points are positioned based on a typical layout of office rooms, in order to match the actual seating positions of occupants. Figure 3 shows the arrangement of measuring points in a basic 8-meter long room, where there are 6 measuring points. The number of measuring points will change when room length varies to approximate to the number of occupants in reality (Table 2). All the measuring points are set at a height of 0.75m, and the UDI of all the office rooms is calculated between the hours 9:00-18:00 on workdays. The ambient settings used for the raytracing are (as “Medium” settings in DIVA): ambient bounces (-ab), 4; ambient divisions (-ad), 1024, ambient resolution (-ar), 256; ambient sampling (-as), 256; ambient accuracy (-aa), 0.1.

![Figure 3. The arrangement of measuring points in an 8m long room based on a typical layout.](image)

Table 2. The number of measuring points in rooms with different lengths.

<table>
<thead>
<tr>
<th>Room Length (RL)</th>
<th>Number of measuring points</th>
</tr>
</thead>
<tbody>
<tr>
<td>4m ≤ RL &lt; 6m</td>
<td>2</td>
</tr>
<tr>
<td>6m ≤ RL &lt; 8m</td>
<td>4</td>
</tr>
<tr>
<td>8m ≤ RL &lt; 10m</td>
<td>6</td>
</tr>
<tr>
<td>10m ≤ RL ≤ 12m</td>
<td>8</td>
</tr>
</tbody>
</table>

The objective goal for optimization is defined to maximize the area-weighted average UDI of all the office rooms.

2.3. SHAPE OPTIMIZATION USING GENETIC ALGORITHM

Genetic algorithm is employed here to maximize the objective goals, while the Y coordinates of the 36 control points are the genes for optimization. Galapagos, a genetic algorithm add-in to Grasshopper, is used to perform the optimization. The parameters for optimization are: population size, 100; population of the
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1st generation, 500; reproduction probability, 10%; crossover probability, 75%; maximum generation number, 20. 6 sets of optimizations is conducted, which involves 3 major cities in China with different latitudes and 2 typical orientations of the curve façade (Table 3). The optimizations are conducted on computers with the same configuration (CPU: i7-3720; Memory: 8GB; Graphic: GT650; System: Win7-64ibt).

### Table 3. Settings of the 12 optimizations conducted in this research.

<table>
<thead>
<tr>
<th>Number</th>
<th>City</th>
<th>Latitude / Longitude</th>
<th>Climate/Climate Zone [34]</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Beijing</td>
<td>39.9° N / 116.3° E</td>
<td>Cold Zone</td>
<td>North</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td>South</td>
</tr>
<tr>
<td>3</td>
<td>Shanghai</td>
<td>31.2° N / 121.5° E</td>
<td>Hot/summer-cold/winter Zone</td>
<td>North</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td>South</td>
</tr>
<tr>
<td>5</td>
<td>Shenzhen</td>
<td>22.3° N / 114.1° E</td>
<td>Hot/summer-warm/winter Zone</td>
<td>North</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td>South</td>
</tr>
</tbody>
</table>

### 3. Results

The optimization results are shown in Table 4. It can be seen that for all the 6 scenarios, the optimized curve façades lead to an average increase of 0.2032 of the optimization objective (the area-weighted average UDI) compared with the reference case (plane façade, as shown in Figure 1), which means that averagely in 20.32% more time of the working hours in one year (i.e., 475.5 hours out of 2340 hours), daylight are effective either as the sole source of illumination or in conjunction with artificial lighting. This is undoubtedly beneficial for lighting energy saving and occupants’ visual comfort. The case with the largest improvement of the optimization objective is Case 5 (Shenzhen, north), where the area-weighted average UDI increases by 0.3429 (i.e., 802.37 hours out of 2340 hours). The smallest improvement occurs in Case 1 (Beijing, north), where the area-weighted average UDI increases by 0.0729 (i.e., 170.48 hours out of 2340 hours).

The results above proves that curved facades do have the potential to significantly improve the daylight efficiency of office buildings in different cities and orientations. Architects should take daylight performance into account when designing the shape of facades, while design optimization is a feasible method for them to find a desirable solution. One crucial obstacle for architects to use design optimization is, however, the calculation time, which varies from 7 days 21 hours to 8 days 9 hours in the 6 optimizations conducted in this study. It is impractical for architects to wait such a long time in reality, thus efforts should be made to largely reduce the calculation time in the future.

The results also shows that, curved facades facing the south have larger potential to improve the daylight efficiency than facades facing the north. The 3 optimized facades facing the south lead to an average increase of 0.2227 of the area-weighted average UDI (i.e., 521.04 hours out of 2340 hours), while for the north the average improvement is 0.1831. In terms of locations, it can be seen that curved facades in Shenzhen have larger potential to improve the daylight
efficiency than Beijing and Shanghai. In the 2 cases in Shenzhen, the optimized curved facades lead to an average increase of 0.3272 of the area-weighted average UDI (i.e., 765.65 hours out of 2340 hours), while for Beijing and Shanghai, the average improvements are respectively 0.1476, and 0.1340. This indicates that the potential of curved façade to improve the daylight efficiency of office building are related to latitude: the higher the latitude is, the larger the potential is.

Table 4. The results of the optimizations (the reference case is shown in Figure 1).

<table>
<thead>
<tr>
<th>No.</th>
<th>UDI of reference case</th>
<th>UDI of optimized case</th>
<th>Improvement</th>
<th>Optimal Shape</th>
<th>No.</th>
<th>UDI of reference case</th>
<th>UDI of optimized case</th>
<th>Improvement</th>
<th>Optimal Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.542</td>
<td>0.627</td>
<td>0.0856</td>
<td></td>
<td>4</td>
<td>0.157</td>
<td>0.278</td>
<td>0.121</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(196.34 out of 2340)</td>
<td>(216.66 out of 2340)</td>
<td></td>
<td></td>
<td></td>
<td>(335.54 out of 2340)</td>
<td>(356.94 out of 2340)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.454</td>
<td>0.596</td>
<td>0.142</td>
<td></td>
<td>5</td>
<td>0.258</td>
<td>0.401</td>
<td>0.143</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(197.86 out of 2340)</td>
<td>(246.51 out of 2340)</td>
<td></td>
<td></td>
<td></td>
<td>(335.54 out of 2340)</td>
<td>(384.37 out of 2340)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.488</td>
<td>0.536</td>
<td>0.048</td>
<td></td>
<td>6</td>
<td>0.408</td>
<td>0.590</td>
<td>0.182</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(205.30 out of 2340)</td>
<td>(231.57 out of 2340)</td>
<td></td>
<td></td>
<td></td>
<td>(322.21 out of 2340)</td>
<td>(378.45 out of 2340)</td>
<td></td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>avg</td>
<td>0.536</td>
<td>0.657</td>
<td>0.121</td>
<td></td>
<td></td>
<td>(335.54 out of 2340)</td>
<td>(356.94 out of 2340)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. Conclusion

Herein, the potential of improving daylight efficiency of typical office buildings by curved facades is investigated using design optimization method. Several conclusions can be drawn from this research:

1. Curved facades do have significant potential to improve the daylight efficiency of office buildings. In the 6 cases conducted in this research, the average improvement of the area-weighted average UDI by optimized curve façades is 0.2032 compared with the reference cases with plane façades. Architects should take daylight performance into account when designing the shape of facades.

2. The improvement of daylight efficiency that curved facades could contribute is related to the location of the building and the orientation of the façade. For office buildings in Shenzhen, curved facades have significantly larger potential to improve the daylight efficiency than those in Beijing and Shanghai, while curved facades facing the south have larger potential to improve the daylight efficiency than facades facing the north.

3. Design optimization is a feasible method to optimize the shape of curved facades.
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for best daylight efficiency, and the process can be implemented with software packages that are manageable for architects, including Rhinoceros, DIVA, and Galapagos. One crucial obstacle for design optimization to be used in design practice is the overlong calculation time.

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References