TILTED GLAZING IN BUILDING SIMULATIONS AND ITS EFFECT ON FORM-REFINEMENT OF COMPLEX FACADES

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ABSTRACT

Contemporary high-rise buildings can have complex façade configurations, but existing building simulation programs may not have either the capability or user-friendliness to help architects make better decisions early in the design process that could reduce energy use for these forms. This is especially true with faceted and curvilinear building facades where the glazing is not necessarily vertical. Building codes and software often cannot handle these more unusual curtain wall constructions and dynamic geometries. Consideration of these aspects will become increasingly important as parametric forms become more common.

Advances in technology have been improving the building design process. One of the important competencies of building professionals is controlling the tremendous amount of data and information that is now associated with buildings. Intelligent software programs allow architects to study design parameters in the design phase, and some of the programs can even suggest design solutions. The ability to use the appropriate software programs and integrate them with design intuition has become one of the most important criteria for a technology-savvy architect in the burgeoning filed of computational design.

This paper focuses on tilted glazing and the effect of its angular dependence on direct solar heat gain (DSHG). Spreadsheet calculations were conducted, and the results were linked to an algorithm developed in Grasshopper to demonstrate form refinement of faceted building facades with an emphasis on the angle-dependent DSHG of glazing. This tool can be used at the outset of design or later as one of the components of an energy simulation program where architects can fine tune their initial ideas for the massing of a building. It can help them determine a better tilt angle of glazing for the building and its overall geometry in a specific climate.

INTRODUCTION

With complex geometry in architectural design, it is often difficult to predict the energy performance of the building accurately. This is because most simulation programs are designed for box-shaped buildings. Even building codes or standards, such as ASHRAE, do not take specific requirements for complex geometry issues into account (Ko, 2012). Therefore, sometimes there is no feasible way to consider the code or energy simulation, even if architects and building engineers are willing to do so. Although standardized values for solar heat gain coefficient (SHGC) are determined for normal incidence, this is actually a very rare occurrence during energy simulations, in which the windows experience relatively high incidence angles the vast majority of the time (Arasteh and Kohler, 2009). This procedure addresses the topic of converting normal incidence SHGC to angular dependent data (Arasteh and Kohler, 2009).

Futhermore, there is still a huge gap between building energy performance prediction and sustainable building design. Many contemporary architects would like to apply sustainable design strategies in the early design process, but current energy simulation programs may not have sufficient capability to do so in a meaningful way. Many building simulation programs are not user-friendly, and sometimes the energy calculating process is not flexible enough to apply it directly in the schematic design phase. This makes it more difficult to integrate building performance simulation within the design process even when sustainable design is the goal. In addition, to make better decisions, architects may need the iteration studies of their design, but their energy simulation program may not have features to make this easy to accomplish.

As an initial step towards mitigating this problem for facades with tilted glazing, a spreadsheet was created that followed the ASHRAE Fundamentals Handbook calculation Standards. The results from the spreadsheet can be more accurate than some of the energy

simulation programs as the user can actually input the effective SHGC values from the Window5 program. Simulation programs such as Ecotect and eQuest either do not have the capability to apply accurate effective SHGC values, or even if they do have this capability, they do not automatically input the Window5 value if the user did not select the method (Ko, 2012). Based on the spreadsheet, a potential way to integrate building energy simulations and form-refinement processes of faceted buildings in the schematic design phase was introduced. This algorithm can serve to be one of the functions of future building simulation programs that can be more intuitive and user-friendly, thus affecting the overall building shape design with regard to the efficient use of direct solar heat gain.

INTEGRATION BETWEEN ENERGY CALCULATION AND SCHEMATIC DESIGN PHASE

As briefly mentioned in the previous section, energy simulation programs either do not have any or enough capability to take the complex geometry of tilted glazing of buildings into account, as the DSHG for those buildings is a critical part of the building energy performance prediction (Ko, 2012). Also, the process of the energy calculation in simulation programs is quite different from design tools such as Rhino. One method to integrate DSHG (a main factor in determining cooling loads) and faceted building design (with tilted glazing) was developed. Based on the generative algorithm in Grasshopper, using the raw data from the spreadsheet calculation and conducting real-time iteration studies.

SPREADSHEET CALCULATION OF DIRECT SOLAR HEAT GAIN

1. Direct Solar Heat Gain Calculation

Peak solar gain through a window and its associated cooling load can be a major component in determining the application and evaluation of low-energy systems (Waddell 2010). It is therefore vital to predict the solar gain and the time when peaks occur accurately in order to make decisions about the façade measurements and system selection even at a conceptual design phase (Waddell 2010). SHGC is the one of the main factors for Direct Solar Heat Gain (DSHG) and DSHG is directly related to cooling load estimation which always comes with energy consumption issues. The solar energy flow through a fenestration may be split into two parts, opaque and glazing portions, q_{op} and q_s, respectively, as given in Equation 1 (ASHRAE 2005).

$$Q_{sol} = A_{op}q_{op} + A_s q_s \qquad \text{(Eq. 1)}$$

where, A_{op} refers the area of the opaque part and A_s means the area of the glazing. The glazing portion of the solar energy can be divided into three parts: direct beam radiation (q_b), diffuse sky radiation (q_d), and radiation reflected from the ground (q_r). The equation for incident solar flux to glazing is defined as

$$q_s = q_b + q_d + q_r \qquad \text{(Eq. 2)}$$

Direct normal radiation is one of the main contributors of solar heat gain through fenestration. It can be obtained by multiplying the direct incident solar radiation (E_D) by SHGC. E_D can be calculated by direct normal solar radiation (E_{DN}) and cosine Θ. Θ represents the angle of incidence. Figure 1 shows the effect of incident angle on incident solar radiation. DSHG is obtained from E_{DN}, cos Θ, SHGC (Θ).

$$q_b = E_{DN} * \cos\Theta * SHGC(\Theta) \qquad \text{(Eq. 3)}$$

One should note that the incident angle has an effect on both the cosine and SHGC. The angle-dependence in DSHG is critical and ignoring it can make for a huge difference from reality.
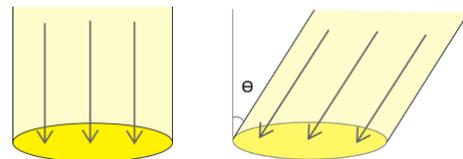

Figure 1 Cosine law and surface incidence

2. Spreadsheet for Direct Solar Heat Gain Calculation

The DSHG calculation is not straightforward in building codes and energy simulation software when the project has glazing that is not necessarily vertical. This can lead to errors in the building performance prediction especially in complex faceted facades. To improve the DSHG calculation, a master spreadsheet that includes incident angle calculation based on the specific location, time, and surface azimuth was developed. The effect of incident angle was reflected in the DSHG calculation based on perpendicular direct incident solar radiation and the effective SHGC to produce the spreadsheet. Using this spreadsheet, one can predict the amount of DSHG from each area of tilted glazing, with time-dependence throughout the year.

The spreadsheet calculation was conducted from 5am to 7pm in January to December on an hourly-basis. It consists of ten different tables and each table refers to AST, the hour angle H, solar altitude, solar azimuth, incident angle, surface solar azimuth, direct solar radiation (E_{DN}), cosine (incident angle, Θ), SHGC, and DSHG in that order. The last table with colored cells

represents the DSHG that the spreadsheet ultimately calculates. Figure 2 is the overall configuration of the spreadsheet.
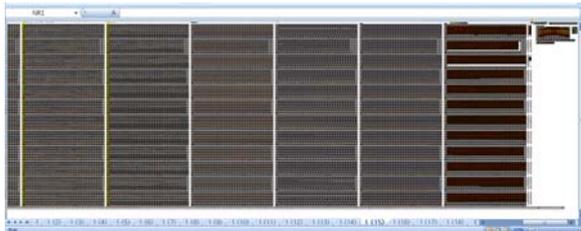

Figure 2 Master spreadsheet

Figure 3 is the DSHG values given as monthly averages, it is intended to clearly show the values of the DSHG for comparison between months the specific time of day. In Figure 3, inputs are in light-green cells: location (altitude, latitude) and orientation (0° south, 90° west, 180° north, and 270° east). Tilt (0° is horizontal, 90° refers to vertical, and over 90° represents tilt towards the outside of the building) and effective SHGC are also input. The outputs represent hourly-base DSHG values, the average for a year, and peak gain. The cells are colored with light yellow to dark brown; lighter colors mean higher values of DSHG and white cells indicate no direct solar heat gain at that time.
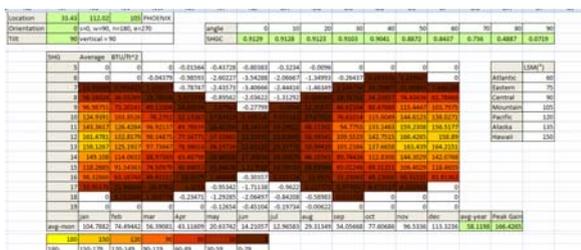

Figure 3 Spreadsheet results, South Façade, Phoenix, Arizona

FORM-REFINEMENT PROCESS IN GRASSHOPPER

This section introduces an algorithm developed in Grasshopper (a plug-in for Rhino 3D), that links to the master spreadsheet. This algorithm can extract the surface azimuth and tilt angle of any surface from a given faceted form of a building in Rhino, and the surface information is input back into the spreadsheet to calculate the DSHG of the surface. Based on this process, one can easily see the total DSHG of a whole building.

In order to show the possible contribution of the form-refinement process, a faceted building design was studied (Figure 4). The use of the parametric tools allows not only for accurate results, but also almost instant variation of direct solar heat gain performance when each of the surfaces has a different angle and orientation. The complexity of this study lies in real-time linkage of the spreadsheet calculation and geometry iteration, which resulted in DSHG data exchange within various forms of the faceted building. The form-refining process was designed by using Rhino as a modeling tool, Grasshopper as a parametric interface, the spreadsheet for DSHG evaluation, and Galapagos for problem solving.

Figure 4 A case project; a faceted building design

1. Genetic Algorithm in Grasshopper

With the introduction of generative and parametric systems for architectural design, the amount of iterations an architect can produce has become limitless (Miller, 2010). However, as architects continue to negotiate complex design problems requiring iterations, variations, and alternatives, it becomes necessary to simultaneously formulate systems for evaluation and validation. Genetic algorithms and evolutionary systems provide a framework by which optimal (locally optimal) solutions can be searched for within an infinite generative field of variation. Using these tools, the parametric system becomes the genome, the field of alternatives becomes the population, and the architect's design goal becomes the fitness criteria.

An examination of the evolutionary system shows that it uses principles of natural selection to automate the search for optimal solutions. One can use evolutionary

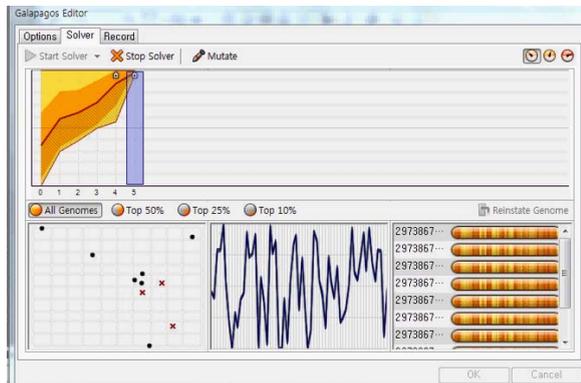systems to look for design solutions that meet specific criteria.

Figure 5 Galapagos, an evolutionary component in Grasshopper

Grasshopper is one of the parametric tools used by the contemporary architectural design industry (Davison, 2009). It is becoming popular with both architecture students and building professionals. The widely-acclaimed Grasshopper is used not only for architectural design, but also for building engineering and research. Designers who are already using Rhino's 3d modeling tools can explore new shapes using generative algorithms with Grasshopper, tightly integrated graphical algorithm editor. Unlike some other parametric tools, one can use Grasshopper without a serious background in computer programming. A component of Grasshopper, called Galapagos, deals with problem-solving evolutionary systems based on the generative algorithm.

For this study, the evolutionary component was designed for form-refinement processes of faceted buildings, with an emphasis on the angle-dependent DSHG of glazing, a key factor for determining cooling and heating load. Without visual programming software such as Grasshopper, this process would have been possible only with time-consuming calculations for the multiple iterations. At the present time, technical innovation allows such studies to be conducted in an easy, quick and accurate way. The intent is to provide a visual tool where architects could fine-tune their initial ideas for the massing of a building and help them determine a better angle of glazing for the building and its overall geometry in a specific climate zone.

2. Linking Grasshopper to the Master Spreadsheet

Figure 6 shows how the form-refinement process is conducted with Grasshopper and the spreadsheet. As a starting point, a faceted building model in Rhino was set up in the interface.
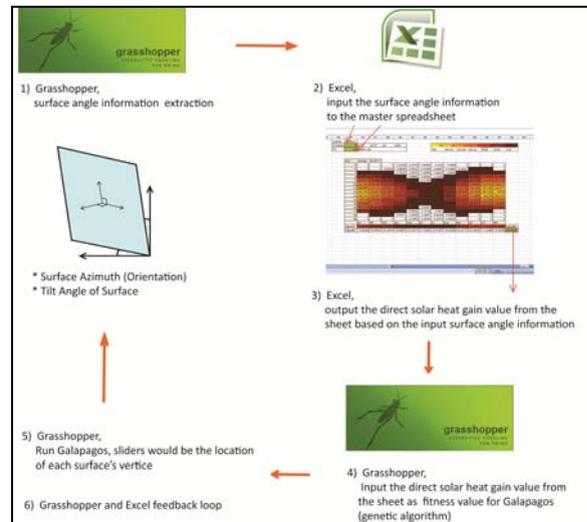

Figure 6 Grasshopper Linked to Spreadsheet

This algorithm can extract the surface azimuth and tilt angle of any surface from a given faceted form of a building in Rhino. The surface information is automatically input back into the spreadsheet to calculate the DSHG of the surface, and then the calculated DSHG value from the spreadsheet is extracted and exported to the Galapagos solver. The solver determines if the value is an optimal solution under the design constraints of Galapagos (such as minimum or maximum value) or not. This algorithm acts as a feed-back loop so architects can have iteration studies without manually inputting options in the simulation programs every single time.

3. Design Tool Documentation

This section documents the proposed design algorithm that can be used to determine an optimized configuration for the faceted building for better DSHG performance. The algorithm is applied to a base case project composed of 70 faceted surfaces. The definition utilizes the master spreadsheet as the calculation engine for DSHG. The definition has been divided into screenshots, each screenshot describes one part of the definition.
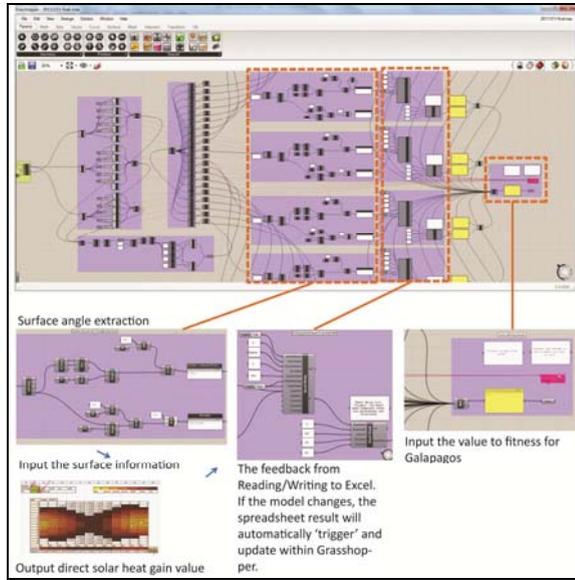
Figure 7 Grasshopper definition structure

Figure 8 shows the geometry construction process. The vertices of the faceted surfaces move along the assigned ellipse. The slider in Grasshopper represents the position of each vertex. If the value in the slider changes, the location of each vertex on the ellipse will consequently move. In addition, the surface that is created based on the three vertices will also change. These changes will be directly applied to the geometry of the faceted building.
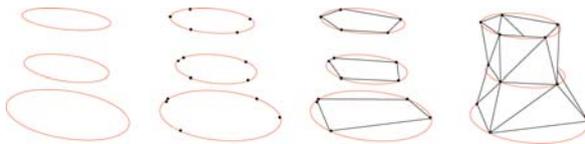

Figure 8 Geometry construction process

Each time that the slider value changes, an iteration will be conducted, and the Galapagos solver will find the best solution which meets the certain constraints that a user inputs. The vertices of the faceted surfaces move along the assigned ellipse. The slider in Grasshopper represents the position of each vertex (Figure 9).
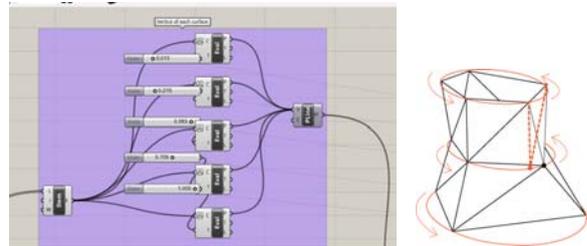

Figure 9 Sliders in Grasshopper and consequence geometry change

3.1 Base Tower Outline

The basis of this design was originated from seven typical floor plans. There were two different ellipses for the boundary for plans; the smaller one represents the minimum boundary and the larger one is the maximum boundary. The first, the third, the fourth, and the seventh typical floor used the big ellipse as their floor boundary and the others were applied to the small ellipse. At first, two boundaries were assigned as "Ellipse" components to one of the definitions shown in Figure 10, and were duplicated using ″Move" components in Grasshopper. Prior to the ellipse duplication, the number of duplications and the offset distance input to a "Series" component (Figure 10). Then, the whole building outline is defined (Figure 11).
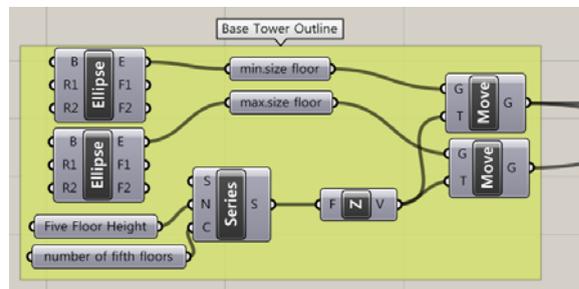

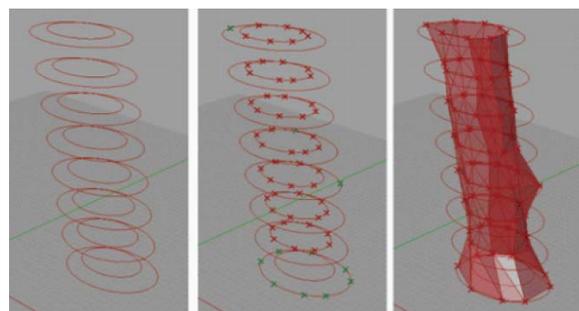*Figure 10 Grasshopper definition: base tower outline*

Figure 11 Base tower outline in Rhino

3.2 Faceted Surfaces Construction

Using a "List Item" component, all of the duplicated ellipses can be retrieved from a list: "0 to 6" for "i" value in the component; each "List Item" component indicates each ellipse. Then, the "List Item" component was connected to five "Evaluate Curve" components to separate the ellipse into five sections. Each section was assigned one vertex and the vertex can move on the any location within the section. The slider value shows that the location of the vertex ranges from 0 to 0.2, 0.2 to 0.4, 0.4 to 0.6, 0.6 to 0.8, and 0.8 to 1. (1.0 is the same as 0: the starting point and end point are same as the base curve is an ellipse) A "Polyline" component connects these five vertices and finally, it can be a configuration of the typical plan.
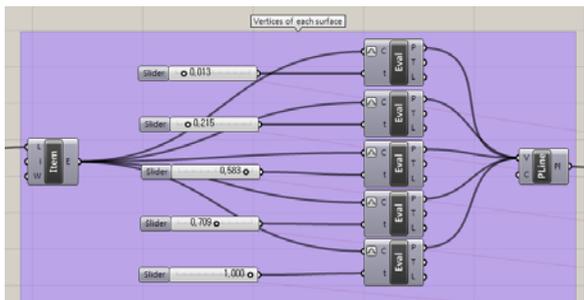

Figure 12 Grasshopper definition: vertices of each surface

Through the resultant poly lines, a "Loft" component created a lofted surface, and then that surface was deconstructed into faceted surfaces. In this process, several components were used: "Explode" to decompose the loft, "Divide Domain" to divide a loft-surface domain into equal segments, "Isotrim" to extract an isometric subset of each surface, and "4Point Surface" to create a surface connecting three vertices (Figure 13).
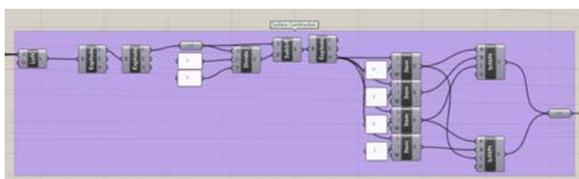

Figure 13 Grasshopper definition: surface construction

3.3 Surface Azimuth and Tilt Angle Extraction

This section of the definition has two different parts: "Surface Azimuth Extraction" and "Tilt Angle of the Surface." Each surface was assigned with an "Evaluate Surface" component to set up the normal vector of the surface. The z-vector from "Plane components″" was

selected and input to the "Vector Decompose" component. Based on the resultant vector, other components such as "Reverse Vector" were used to calculate the surface azimuth and tilt angle of the surface.
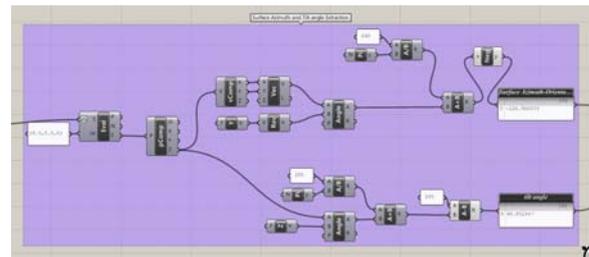
Figure 14 Grasshopper definition: surface-angle information extraction

3.4 Linking the Master Spreadsheet to Grasshopper

Surface-angle information that was obtained from the previous definition was input to an "Excel Write" component to send the information to the master spreadsheet. In Figure 15, two of the light green cells are input cells. When the Grasshopper definition grabs the surface information, the "Excel Write" component directly sends the data to the spreadsheet and the values to these input cells. Then, the spreadsheet automatically calculates the DSHG throughout a year and the DSHG average value. After that, the "Excel Read" component reads the average DSHG value from the spreadsheet and the DSHG value of each surface is multiplied by its surface area. Finally, the total DSHG value is sent to a "Galapagos" component (Figure 16). If the model changes, the spreadsheet result will automatically trigger and update within Grasshopper.

Figure 15 Master spreadsheet input cell location

Figure 16 Grasshopper definition: Excel write and read

3.5 Galapagos; Form-Refining Process

As a final step of definition, Galapagos was added to find a locally optimal solution given the input constraints by users. This algorithm acts as a feed-back loop so architects can have iteration studies without manually inputting numerous options in the simulation programs that may not even be the best solution.

Figure 17 Grasshopper definition: Galapagos

4. Result and Observation

By using the algorithm, a simple test with the first ten floors (20 faceted surfaces) of the building was conducted to check how this system works. The building was located in Phoenix, Arizona and Minneapolis, Minnesota. Figure 18 shows the two resulting geometries of the building for two climates with different criteria: maximum DSHG and minimum DSHG. This form-refinement process is under certain design criteria, (in this case, the building geometry constraints) such as the vertices need to move along with the given ellipse, and there are five vertices on each ellipse. Therefore, this algorithm follows the architect's design intention but at the same time, it gives her a better geometrical design decision by refining the overall shape and tilt of the faceted building.

Figure 18 Form-Refining Trial with the First Ten Floors (20 faceted surfaces)

FUTURE STUDY

There are several methods that could be improved in the next version of the study including more climate specific optimization and keeping the surface area of the building constant.

One issue regarding the maximum and minimum amounts of DSHG should be addressed due to its complexity. DSHG can be added or subtracted based on energy consumption for cooling or heating. For example, the climates of certain places, such as Denver, CO, have relatively hot outdoor temperatures over the summer months, whereas the indoor space needs heating from November to March. In cases like these, DSHG should be minimized only for the summer months and maximized for the winter months. A multi-objective Galapagos study could be conducted that is based on the balance point temperature concept of weighting methods. The balance point is the outdoor air temperature, causing building heat gains to be dissipated at a rate that automatically creates a desired indoor air temperature. For the multi-objective study, a weighting system also needs to be developed congruently and this weighting value for each month can be applied (Figure 19).

Figure 19 Overall Concept of Building Balance Point

The program could also allow the user to keep the total surface area constant when creating the refined forms. Currently, this algorithm can find a form that has minimum/maximum DSHG among various iterations. However, the total surface area is not exactly same in all forms. If the algorithm cannot keep the total surface area the same, the heat gain/loss from conduction would be different from each of the forms. A multi-objective study can be added in regards to this issue.

CONCLUSION

This paper shows a possible integration between a genetic algorithm and the schematic design process.

Rhino, Grasshopper and Galapagos were used to demonstrate one possible method of combining parametric design and energy simulation. Based on the accurate DSHG values calculated from a master spreadsheet, the algorithm acts as a feed-back loop in Grasshopper. By using it, architects can perform iteration studies without manually inputting options in the simulation programs. One of the difficulties in applying energy simulation results to design decisions is that the user cannot do parametric studies easily. The algorithm can show results in real-time iteration studies, while being faster, more user-friendly, and perhaps more intuitive, thus affecting the overall building shape design with regard to the efficient use of DSHG.

The algorithm focused only on the DSHG aspect to find out the refined-form for specific building designs. This approach has several limitations. Energy simulations have to consider many other issues, for example, HVAC systems, schedules, properties of materials such U-value, etc. However, the approach demonstrated in this paper is a first step towards integrating schematic design and energy simulation programs. Future work could focus on the additional layers to the algorithm considering the complex climate conditions and enhancing the user-specified constraints such as geometrical conditions or shaded effect from adjacent buildings.

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