Improving Window Selection:
A New Workflow and Tool for Architects/Engineers

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Abstract

Window selection greatly influences a building's energy performance. Typical methods for choosing high performance windows include following published performance criteria, using simple decision-support tools, and performing customized simulations. This paper demonstrates, through case studies, the shortcomings of existing methods for selecting energy-efficient windows and describes a parametric simulation-based methodology with a new publically-available plug-in called WinEnergy for Grasshopper for Rhinoceros. This plug-in is an interface for the EnergyPlus building performance simulation engine and was developed with a focus on a user-friendly interface and improved data visualization capabilities. WinEnergy was then used in 192 case studies. The results were compared to other window-selection methods, including following the prescriptive fenestration requirements of ASHRAE Standard 90.1-2016 energy code.

Introduction

High performance and efficient window systems can dramatically reduce overall building energy consumption, increase daylight and thermal comfort, reduce HVAC system sizes, and contribute to long-term cost benefits. However, factors such as climate, building orientation, window size, surrounding context, shading, and HVAC systems, all influence the optimal window selection. Furthermore, the variety of glazing types, coatings and frames has increased exponentially over recent years, making the selection process even more difficult. Typical methods for choosing high performance windows include: following prescriptive performance criteria, using simple decision-support tools, and performing customized building simulations, often via specialized consultants.

Path 1- Prescriptive path

Energy codes and standards set prescriptive requirements for fenestration systems[1] Examples include: the American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE) 90.1 Energy Standard for Buildings Except Low-Rise Residential Buildings (2016) and the International Energy Conservation Code (IECC) (2015). Both are model codes adopted by state and municipal governments in the U.S. and beyond for the establishment of minimum design requirements for energy efficiency in buildings. Another standard, ENERGY STAR, developed by the U.S. Environmental Protection Agency (2015), certifies window products that meet certain performance requirements aimed at energy efficiency, including achieving National Fenestration Rating Council (NFRC) certification. All three standards define limits for the U-factor[2] and Solar Heat Gain Coefficient (SHGC)[3] for fenestration systems according to climate zones.[4]

Path 2 - Supportive tools

Web-based tools

Existing web-based tools can help designers choose energy efficient windows in the early design phase and can generate results quickly. In the Efficient Windows Selection Tool (Efficient Windows Collaborative, 2016), shown in Figure 1, for residential buildings, a user chooses from predefined inputs describing climate, house type, window type, orientation, window area, and shading type. The tool outputs a ranked list of window products. The criteria include annual energy consumption, cost and peak load (heating and cooling).

In the Façade Design Tool (Windows for High-performance Commercial Buildings, 2015), used mainly for offices and schools, the user inputs include location, building type, and orientation. The tool simulates the performance of ten generic glazing systems and two retrofit films, representative of the breadth of options

[1] Many codes, including ASHRAE 90.1, include a performance path in addition to the prescriptive path. Therefore, to demonstrate code compliance one can use a detailed energy simulation. Here, we are not discussing paths to code-compliance, but rather the use of prescriptive code requirements as an aid in window selection in early design.

[2] U-factor describes the heat flow rate between interior and exterior due to a temperature difference, taking conduction, convection and radiation into consideration.

[3] SHGC describes the ratio of direct or diffuse transmitted solar radiation to total incident solar radiation.

[4] ASHRAE 90.1 and IECC, also permit an alternative performance compliance path, allowing users to trade-off energy conservation measures, as long as the overall energy performance can be maintained as demonstrated by approved software tools.

available on the market. The result is a ranking of twelve window types based on energy, peak loads, carbon, daylight, glare, and comfort.

Desktop Tools

Desktop tools such as COMFEN and RESFEN support fenestration design. COMFEN (Lawrence Berkeley National Laboratory, 2013), as shown in Figure 2, is a fenestration design tool used for commercial buildings, RESFEN (Lawrence Berkeley National Laboratory, 2012) is used for residential buildings. They allow for more detailed user inputs and provide a larger window library compared to the tools above. COMFEN and RESFEN use either DOE-2 or EnergyPlus as their simulation engines. COMFEN simulations are based on a perimeter zone model, allowing the results to be applied to a whole-building simulation. RESFEN uses two standard house designs as part of its input parameters.

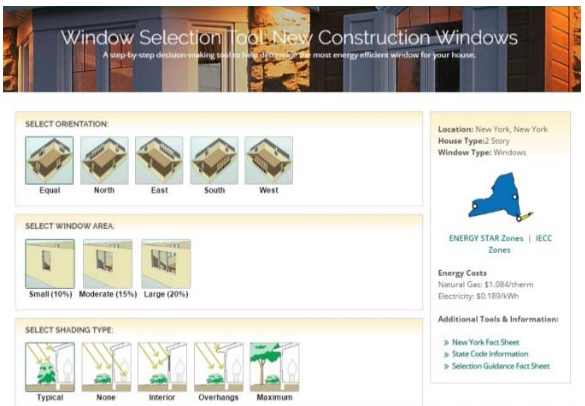

Figure 1: Efficient Windows interface

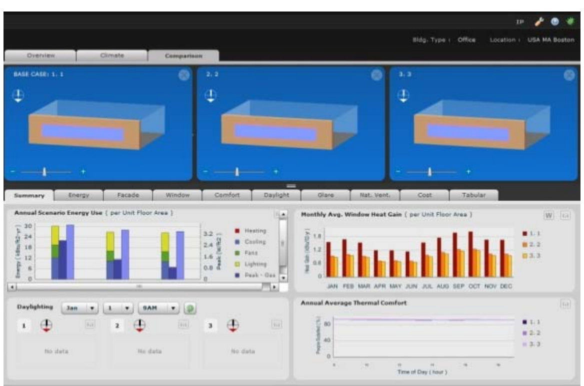

Figure 2: COMFEN interface

The user has the capability to input location, orientation, utility cost, and HVAC system, then to define the fenestration systems, including facade geometry, wall construction, window size, location, and shading systems. The tools allow users to define their own glazing (window as well as shading systems) and provide input possibilities for customized products. After different scenario inputs, the tools are able to calculate and compare multiple fenestration scenarios at the same time. They provide quantitative performance results including the heating and cooling energy use, peak energy demand, CO_2 emissions, window annual and peak heat gain, daylighting and thermal comfort.

Path 3 - Whole-Building Energy Simulation

The third path to energy-efficient window selection is the use of whole-building energy simulation, using software such as EnergyPlus, to test window properties (among other energy conservation measures). This process, often performed by specialized consultants, can provide more flexibility than the tools above, since the inputs (which include envelope construction, HVAC systems, occupancy schedule, etc.) are more customizable.

Limitations of Existing Methods

The methods described above each have limitations, and choosing from the multitude of available fenestration products remains challenging. In the prescriptive path, envelope recommendations are generalized into broad climate zones and building type categories. This method ignores certain variables influencing window performance, such as a building's surrounding context, unique geometry, and solar orientation. The web-based tools are easy to use in the early design phase and allow users to generate simulations quickly. However, their accuracy depends on the degree to which the models, with their limited flexibility, represent the real building. Furthermore, their limited libraries do not depict the full set of available window products. COMFEN and RESFEN enable more customized inputs. However, the user interface may not be intuitive and provides no connection to other software used in early building design. In addition, they lack the capability to model unique geometry and building context compared with customized whole-building simulation.

The third method, whole-building simulation, offers the most functionality and customizability, albeit while requiring the most user expertise. The authors argue that this method needs improvement to fit better into the early design process and more clearly convey information to decision-makers. Furthermore, the traditional workflow, which involves simulating one model at a time, fails to provide an overview of the range of fenestration options. More comprehensive performance information could aid the design process, where energy performance must be evaluated among a number of other design considerations, including budget, aesthetics, product availability, etc.

Research Objectives

Based on the limitations of existing window selection methods, the research objective contains four parts. First, promote an improved custom-simulation workflow for window selection in early design, making the process more informative, less tedious, and faster. Second, better integrate with the early-design process by improving the user interface and results visualizations as well as coordinating with software tools used during this phase. Third, allow for more customized inputs, than currently available in the simplified tools, including building geometry and site context. Fourth, compare performance with existing methods including ASHRAE Standard 90.1 requirements for fenestration systems.

Methodology

Simulation Method

This research proposes a new tool, WinEnergy, to use a parametric simulation workflow and provides performance results for the full range of possible window properties at one time. This allows the user to both find the best window options for a specific project and to understand the trade-offs associated with less-optimal selections.

WinEnergy is developed as a plug-in for Grasshopper, the graphical scripting platform for Rhinoceros, which is a popular 3D modelling software program. In Grasshopper, WinEnergy works together with Honeybee/Ladybug, also a plug-in for Grasshopper, to compute parametric simulation using the EnergyPlus engine. The authors explored methods to simplify window system modelling and to increase simulation speed while maintaining desired accuracy, as described under "Simulation Resolution".

Because heat transfer through glazing is complicated, most energy simulation engines require inputs of window construction details including properties of each layer of glass, film, and infill gas. This contrasts with building codes, standards and the window industry, where window systems are described according to simplified performance indices such as U-factor, SHGC, and visible light transmittance (VT). In response, Lawrence Berkeley National Laboratory has developed a simple window modelling methodology for EnergyPlus so that it can utilize common window indices in whole building simulations (Arasteh et al. 2009), which reflects the integrated properties for window systems including frame materials and glazing, the same as indices as in NFRC labels for window products. This methodology is applied in this research.

Variables and Ranges

The parametric simulation variables are U-factor (including window frames) and SHGC. The U-factor ranges from 0.1-0.9 Btu/(hr·ft²·°F) [0.6-5.1 W/(m²·K)], while the SHGC value ranges from 0.1-0.9. Figure 3 identifies typical values of products on the market.

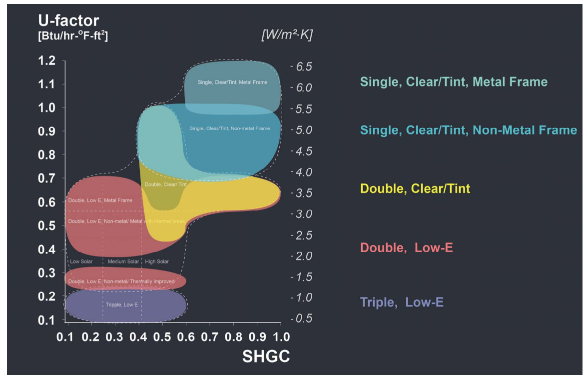

Figure 3: Window's U-factor and SHGC value range

Visible Light Transmittance (VT) - Sensitivity Analysis

VT describes the fraction of visible light transmitted through fenestration. It indirectly influences electric lighting use and, therefore, heating and cooling loads. However, with the development of efficient lighting technology, including LEDs, the impact of VT on energy use has declined. The authors ran a sensitivity analysis to test the impact of different VT values on total building energy consumption. The model studied is a medium office, selected from the U.S. Department of Energy, Commercial Reference Building for New Construction. It is a rectangular office building (long facades facing north and south), built to ASHRAE 90.1-2010 standards with daylighting controls. The results showed that the total energy consumption varied less than 5%, when testing the VT from 0.23 to 0.85, i.e. extreme cases for windows available on the market. Since VT was a relatively minor influencing factor on total energy consumption, and since advances in lighting technology are reducing the energy impact of electric lighting even further, VT was not included as a parametric test variable in this round of research. Thus, the parametric variables are reduced from three to two, U-factor and SHGC, which greatly reduces the number of parametric simulation runs required. In the future, VT could be added as a parametric test variable.

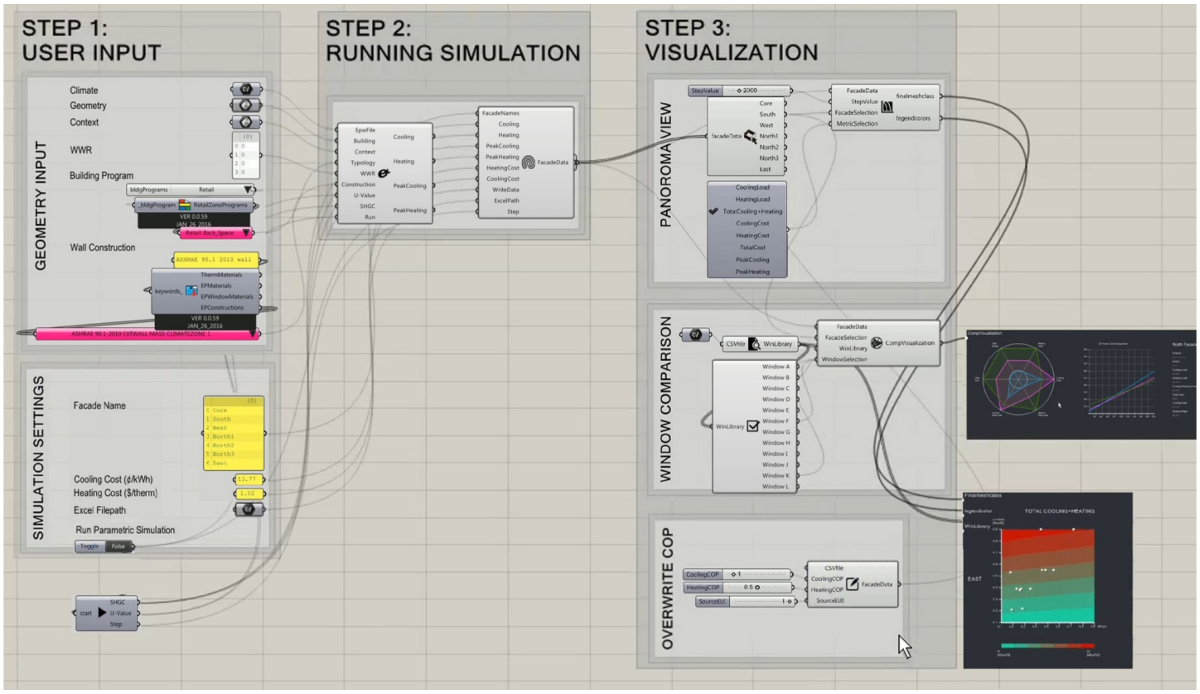

Figure 5: Grasshopper component of proposed tool

Simulation Resolution

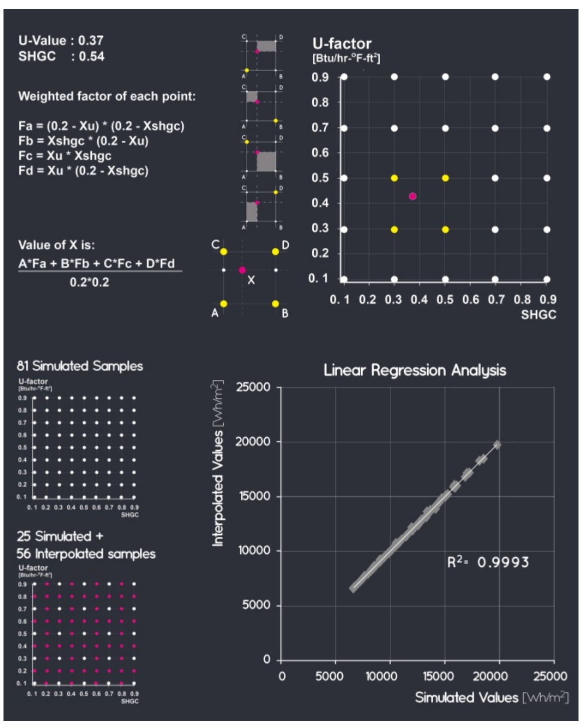

Figure 4: Bi-linear interpolation calculation and linear regression analysis

In parametric simulation, higher resolution, i.e. running each test-variable with smaller perturbations, can generate more accurate results, while also consuming more time. Therefore, the authors used the same reference building as above to test multiple resolutions, and chose intervals of 0.2 Btu/(hr·ft²·°F) [1.1 W/(m²·K)] for U-factor and 0.2 for SHGC. The results of other combinations are calculated by bi-linear interpolation, as shown in Figure 4. The interpolated values at intervals of 0.1 were compared to simulated results. A linear regression analysis of the simulated and interpolated values shows a correlation coefficient of 0.9993, which indicates a strong positive association of these two sets of values. Therefore, only 25 simulations are sufficient to get an overview of all possible window products performance, and the simulation time can be reduced from several hours to approximate around half an hour.

Software

The authors chose Rhinoceros/Grasshopper (McNeel, 2014) as the development platform for the proposed tool, because this software is widely used in architectural firms and schools for 3D modelling. Geometry input and energy simulation use grasshopper built-in components and components from Ladybug and Honeybee (Roudsari, 2016), from which users can directly choose construction settings built to ASHRAE 90.1 standards. The code of WinEnergy is written in C# using Visual Studio Platform and creates 14 Grasshopper components (Figure 5 and 6). The Grasshopper plug-in file is available to the public at https://goo.gl/Xmg7Se.

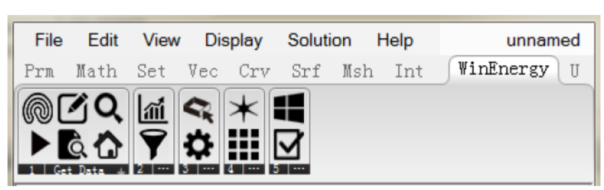

Figure 6: The proposed tool in Grasshopper toolbar

User Inputs and Other Parameters

The user inputs include: (1) Location: Input as an .epw weather file. (2) Building Geometry: Input as Rhino boundary representations (B-reps), including building, building zones, windows, and surrounding buildings. In lieu of inputting window geometry, users can instead type-in specific window-to-wall ratios for various facades. (3) Construction: Can be selected from a library. WinEnergy includes the following default settings: (1) the floor and ceiling are set to be adiabatic to simplify the modelling. (2) The perimeter zone can be automatically generated with a depth of 5 meters. (3) The perimeter zone partition is set to be an air-wall, which will mix air representing a realistic mechanical system.

Results Analysis and Visualization Method

WinEnergy runs whole-building simulation and extracts results of the perimeter zone of the corresponding facades for analysis. It provides six performance metrics: cooling load, heating load, total cooling & heating energy, utility cost, peak cooling load, and peak heating load.[5] Each result is normalized by the respective perimeter zone area, because window performance has relatively minor impact on the energy consumption/load in the core zone. The total cooling and heating energy calculations take user-customizable system coefficient of performance (COP) values into consideration. The total utility cost is calculated based on the simulated total energy result and the local electricity and natural gas utility rate. The default utility rates refer to the average electricity and gas rate of 2014 by U.S. states by Energy Information Administration (EIA), and can be over-written by the user.

WinEnergy provides two modes of visualization. The first visualization mode consists of six graphs, one for each performance metric, e.g. cooling load. Each graph illustrates the whole range of parametric results in a set of gradient colours, depicting different value ranges (Figure 7). The graphs are generated by the following automated method. First, the tool locates the 25 simulation results as points related to a U-factor (y-axis) and SHGC (x-axis) coordinate system. Second, it assigns the performance value (simulation result) as the point's z-axis value. Third, it uses a Delaunay mesh command to generate a 3-dimensional surface to cover all the points. Fourth, the tool uses several planes to cut the surface, the level distance between two planes is a step value. Fifth, it assigns a colour to each surface based on its z-axis value to identify different value ranges. Finally, the coloured surfaces are projected onto a flat plane to generate a graph (Figure 7). In this way, the graph can demonstrate value ranges with specific step value in different colours.

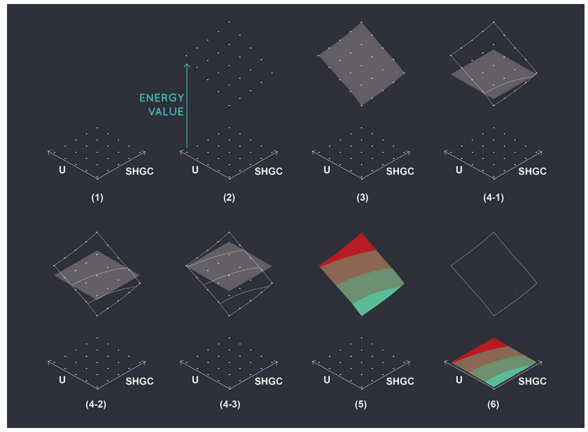

Figure 7: Steps to generate performance graph

Users can set the numerical increment for each colour step and plot window products of interest on the graph to compare their respective performances. In the graph shown in Figure 8, the step value is 2 kBtu/ft^2 [6.3 kWh/m^2], which means that window products falling in the same colour area produce similar results (i.e. within 2 kBtu/ft^2 [6.3 kWh/m^2]. Specific window products can be plotted on the graph for better comparison (Figure 8).

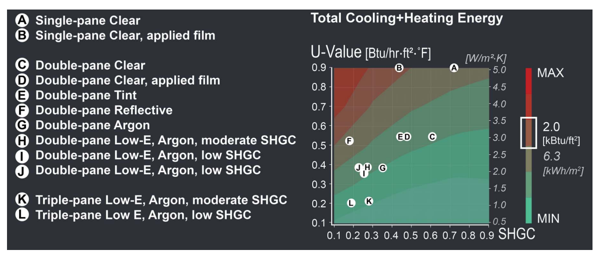

Figure 8: Visualization 1 – Total cooling and heating energy graph

WinEnergy's second visualization mode helps users compare several windows with six different performance metrics. It is composed of three parts. The first is a spider graph, as shown in Figure 9. Here, the performance of three windows are plotted, which illustrates that Window 3, in green, has the lowest heating load, cooling/heat energy, utility cost and heating peak load, while Window 2, in blue, has the lowest cooling load and cooling peak load.

The second part is a cost-benefit graph to help users select the best window in terms of life-cycle cost. It shows the (user-inputted) up-front cost of the selected windows, combined with a 20-year prediction of utility costs, based on the simulation results as described above. Figure 10 shows that Window 3 has a high initial cost, which is offset by lower performance and operational costs over time. Finally, the tool provides a table of results for each window product, highlighting the best value (Figure 10).

[5] The cooling and heating load is defined as the amount of heat energy that would need to be removed from or added to a space to maintain the temperature in an acceptable range. System COP is not taken into consideration.

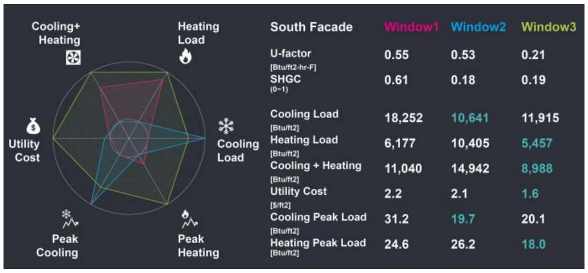

Figure 9: Visualization 2-Windows comparison graph

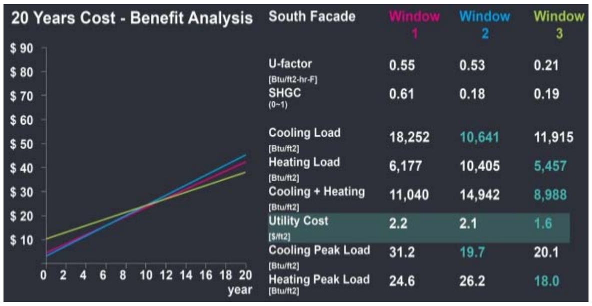

Figure 10: Visualization 2-Window cost-benefit analysis graph

Workflow

The general workflow of using WinEnergy is described as follows: First, build or import the building geometry in Rhinoceros. Second, import the local weather file, assign the geometry in Grasshopper and set up constructions of the envelope, the building type, etc. The U-value and SHGC have default settings which can be overwritten by users. Third, start the parametric simulation, which will take approximately 20-40 minutes based on the model complexity. Fourth, the WinEnergy components take the simulation results and display visualizations on the Grasshopper canvas. The users can input customized utility rates and test various HVAC COP values for further analysis.

Case Studies

The authors performed 192 case study simulations using WinEnergy/EnergyPlus and examined the impact, on window selection and energy performance, of certain variables that are unsupported by the simple tools or standards. The authors then compared the results to both the ASHRAE 90.1-2016 standard requirements for fenestration systems and results derived from the Facade Design Tool.

The cases

The building model inputs used here are based on the U.S. Department of Energy's Commercial Reference Buildings for New Construction. These benchmark models are designed to represent approximately 70% of the commercial buildings in the U.S. The first building type tested is the reference medium office building (Figure 11). The weather files used are Typical Meteorological Year 3 (TMY3) files of a city representing each climate zone. The wall construction and window-to-wall ratio (WWR) (set to the maximum allowable 40%) both meet the ASHRAE 90.1-2016 standard. Window visible transmittance is set to a default 0.5 in WinEnergy, falling within the common range from 0.4 to 0.6. The floor and ceiling conditions are set to be adiabatic. Building context and shading are not considered in the case studies. The HVAC systems are modelled with a cooling COP of 5.5 and heating COP of 0.8. The performance metric is on-site normalized total heating and cooling energy consumption for the south perimeter zone. The numerical increment of the results graphs is set to steps of 2 kBtu/ft² [6.3 kWh/m^2].

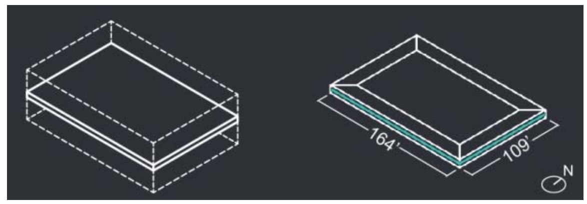

Figure 11: Case study model: medium office building

Comparison with Prescriptive Path

ASHRAE 90.1 has increased the strictness of its fenestration requirements over the past ten years. SHGC requirements remain relatively similar while the requirements of U-factors decreased dramatically, especially in Climate Zones One to Four (of eight). Various influencing factors were studied including climate zones, coefficient of performance and orientation.

Influence of climates

Several case studies, using the above-mentioned settings, were simulated in Climate Zones One through Eight. This first analysis focused on window selection on the south façade.

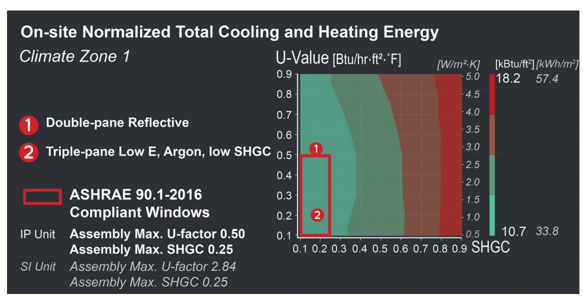

Figure 12: Climate Zone One on-site energy results for south-facing windows

Starting from Climate Zone One (using Miami, very hot and humid, weather), Figure 12 shows the results of total cooling and heating energy, taking COP into account. Such a graph could help a design team visualize the relationships between SHGC, U-factor and energy performance. In this case, SHGC is the most important factor to consider, while U-factor has relatively little impact. By laying out window products on the graph, the tool demonstrates that window 1 (Double-pane reflective) falls in the same performance range with window 2 (Triple-pane Low-Emissivity [Low-E]).[6] These results may not be apparent to a design team using the ASHRAE 90.1 prescriptive requirements (bounded by the red rectangle) alone. In Climate Zone Two (using Phoenix, hot and dry, weather), the results were similar.

In the heating-dominated Climate Zone Five (using Boston, cool and humid, weather), users can see from the graph (Figure 13) that U-factor and SHGC are both

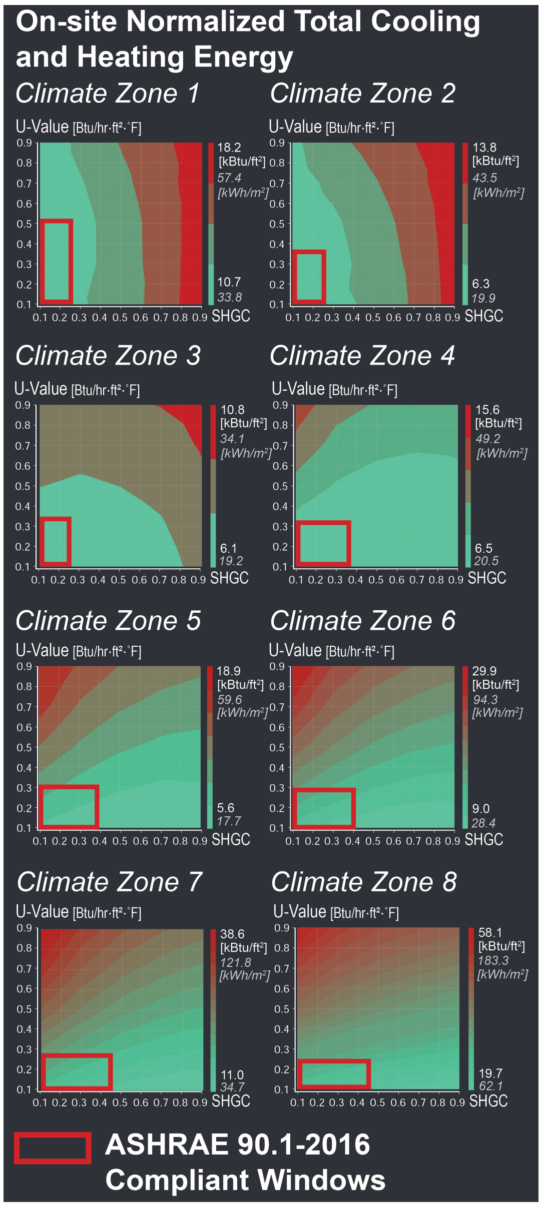

Figure13: Eight climate zones on-site energy results overview for south-facing windows

important window selection criteria in this south-facing perimeter zone. This trend is similar for the test cases in Climate Zones Four-Eight. The results from each climate zone are shown in Figure 13. A user can see how the importance of window selection, in terms of heating and cooling energy performance, increases in the colder (higher numbered) climate zones, as indicated by the graph legend and denser colour gradient. Higher SHGC values appear to be beneficial in the colder climate zones due to passive solar heat gain. However, importantly, the results shown here are for the south-facing zone only, as will be discussed in the Discussion Section.

Figure 14 shows the same results converted from site to source [total cooling and heating] energy, using average U.S. conversion factors per (ENERGY STAR Technical Reference - Source Energy, 2013).

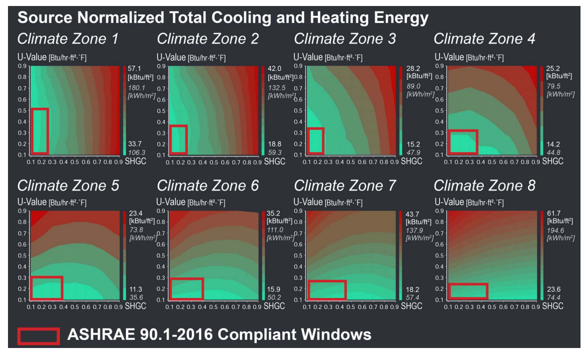

Figure 14: Eight climate zones source energy results overview for south-facing windows

Considering HVAC Efficiencies in the Analysis

The selection of HVAC systems affects the balance of heating and cooling energy consumptions, which, in turn, influences window performance (and vice versa). Yet, the simple decision-support tools mentioned in the introduction cannot consider system efficiencies.

Here, the authors changed the cooling COP to 3 for comparison. The results below are a comparison of total cooling and heating energy use, in a south-facing zone, in Climate Zone Three (Figure 15). By visualizing the results in this way, design teams can quickly demonstrate how the variables of window properties and HVAC system selection interact to impact energy performance in a project. For example, as can be observed in Figure 15, the range of energy performance across the window-selection spectrum becomes smaller when cooling COP values are higher. A tool that allows users to visualize the impact of heating and cooling system COPs along with window properties could be valuable in the early design phase.

[6] The simulation results showed less than 0.8% difference in site heating and cooling energy between the windows, with significantly different construction costs.

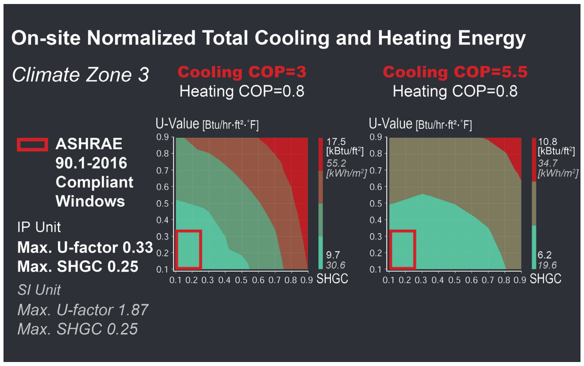

Figure 15: Results of Different COP in Climate Zone 3

Influence of orientation

Orientation plays an important role in building envelope considerations. Simple decision-support tools such as Efficient Windows and the Facade Design Tool cannot consider every orientation. Users can consider any 360° solar orientation with WinEnergy. In order to examine the influence of orientation, the test building was simulated in four orientations (North, East, South, and West) with 40% WWR, no shading, and no context. The results are shown in Figure 16 for Climate Zones One and Five. By visualizing the results in this way, users can see how orientation changes the window performance needs of the project. For example, in Climate Zone One, a user can see that the graph is only divided into two contour intervals for the north-facing façade. This means that the difference in energy consumption between the best and worst performing windows is relatively small. Thus, with its lower received solar radiation; window selection can be more flexible in this orientation.

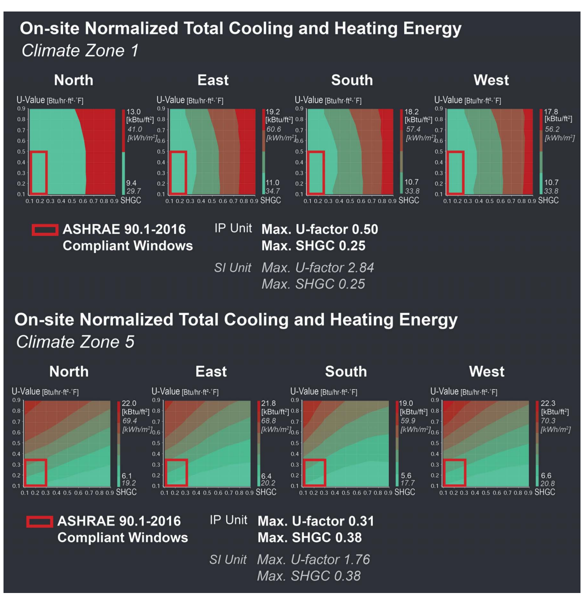

Figure 16: Influence of Orientation in Climate Zones One & Four

Comparison with Web-Based Tools

The authors compared the performance between the proposed plug-in and existing tools. The Facade Design Tool uses EnergyPlus as its simulation engine, and shows results in detail with many metrics. Therefore, the authors chose to compare its result with the proposed WinEnergy tool. The case study is an office building in Boston (US), with 40% WWR without shading devices, without lighting controls, and no urban context. The authors ran simulations in both tools for four facades. The Facade Design Tool provides the results with a ranking of 12 default windows.

Comparing the annual total energy consumption, Figure 17 shows the difference in window rankings between the Facade Design Tool results (in white on the right) and WinEnergy results (in green on the left). The performances of some windows in these two tools are quite different, even though these two tools use the same simulation engine, EnergyPlus.

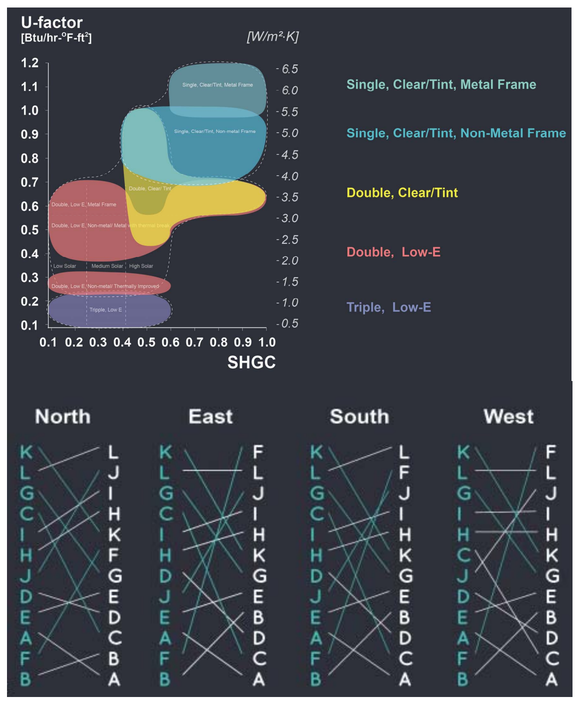

Figure 17: Comparison of window type ranking in annual energy consumption

Multiple factors led to these differences in results. One critical factor is the building modelling method. In the Facade Design Tool, the building is simplified as a unified 15ft*10ft*9ft (5m*3.3m*3m) shoebox model, and all surfaces except the exterior walls are adiabatic. Therefore, a building in the Façade Design Tool is simulated as a perimeter zone, omitting the heat transfer between perimeter and core zones. This approach may not be appropriate for a building with a deep floor plate. In contrast, in WinEnergy the perimeter zone walls are set as air walls. Air between adjacent zones is automatically mixed at a rate of 0.0963 $m^3/s\text{-}m^2$. This number represents a reasonable air mixing rate due to mechanical systems/diffusers.

Another factor is the coefficient of performance (COP) of the HVAC. In the Facade Design Tool, the HVAC COP setting is unknown. Several scenarios with different COP values were conducted in WinEnergy, and the results from the scenarios with cooling COP 3 and heating COP 0.8 were closest to the results from the facade design tool. According to colleagues in practice, they are specifying cooling COPs of 5 to 6 and heating COP of 0.8 for high performance commercial buildings in the Boston area. For such buildings, a tool with a fixed cooling COP of 3 may provide misleading window selection priorities.

Comparison with Desktop Tools

Some desktop tools, for example COMFEN/RESFEN, can run parametric simulations as well. The benefit of WinEnergy is its fast simulation time, due to the embedded algorithm, which enables the user to get an overview of all window products performance with only 25 simulations. The result visulizations are also easier for designers to understand and analyze.

Tool Integration

Another benefit of the proposed tool is its ability to integrate with other professional energy simulation tools. There are 14 components in the proposed tool, one of them is to run the simulation and collect results, which can be replaced by other grasshopper-based simulation software, such as Ladybug, Honeybee etc. Once results produced by such software, including hourly cooling and heating load, are collected, they can be input to WinEnergy for data analysis and visualization, as shown in Figure 18.

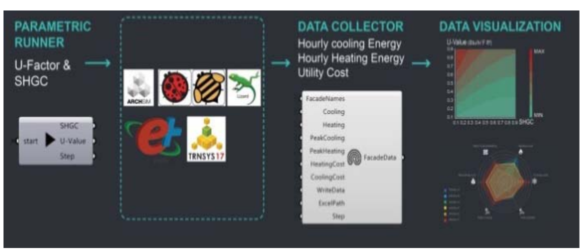

Figure 18: Software integration with WinEnergy

Discussion

The authors believe that the ability to visualize the impact of window properties could be a beneficial aid to the early design process.

Limitations and future work

Simple Window Simulation

This tool can allow developers to integrate better simulation methods as they become available. The simple window simulation used by WinEnergy is an approximate method. As any method to use U-factor and SHGC alone in building simulation software will inherently be approximate. Furthermore, as explained above, future work could incorporate the consideration of visible light transmission values and its resultant energy implications, including electric lighting consumption. Moreover, the tool can be improved by taking non-standard window shapes into consideration.

Single-Zone Versus Whole-Building Approach

As mentioned, the proposed tool displays the results of one zone at a time. However, the tool runs a whole-building simulation, so the interface could be modified to display whole-building results.

Data Analysis Algorithm

The proposed tool uses a bi-linear interpolation method to calculate missing samples in the simulation process. This can be optimized by applying a more advanced algorithm, such as bi-cubic interpolation, or an adaptive sampling method, among others.

For the panorama graph, the tool uses a Delaunay mesh command to generate the mesh in Rhino for the visualization graph. This can be improved by commands such as NURBS (non-uniform rational B-spline) surfaces in Rhino, which can generate more accurate missing values and help to increase the accuracy of the graphs.

More input and output

The proposed plug-in can be further improved by linking window product libraries such as the database available in LBNL WINDOW, and utility rates available online to automatically obtain up-to-date information for analysis.

Thermal comfort and condensation are critical factors for window selection especially in cold climates. Therefore, a future improvement could be to integrate a consideration of glass surface temperature into the tool.

Conclusion

This paper discussed the shortcomings of existing methods for selecting windows based on energy performance, and demonstrated how these shortcomings might lead to poor window selection. A parametric simulation-based methodology was proposed and a new software plug-in was developed in the software platform used by many architects. Within it, users can take into account confounding variables such as specific solar orientations, heating/cooling system COPs, and neighbouring solar obstructions. The proposed tool provides unprecedented results visualization capabilities, allowing the user to view the energy results of the entire set of window choices (based on solar heat gain coefficient and U-factor) as well as individually selected products, and immediately recognize trends in their energy performance.

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