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CALCULATING FENESTRATION SYSTEM U-FACTOR, SHGC, AND VT USING PARTIALLY AUTOMATED WORKFLOWS

Sarah Rentfro
Simpson Gumpertz & Heger Inc., Washington, DC

ABSTRACT

This paper explores current workflows and methodologies used by building enclosure professionals to calculate and report the effective U-Factor, Solar Heat Gain Coefficient (SHGC) and Visible Transmittance (VT) of fenestration assemblies, henceforth referred to as *fenestration performance metrics*, in various stages of design. Topics covered include a review of manual and partially automated calculation and simulation workflows, as well as methods for communicating performance targets and goals with the project team, including a web-based data visualization tool developed by the author's firm.

This paper relies on shared modeling experience informed by building enclosure design and consulting as the basis of the discussion. While multiple means for calculating and reporting fenestration performance metrics exist, this paper focuses on the primary experience of the author and the author's colleagues.

INTRODUCTION

Building enclosure design is an iterative process, shaped by the architect's aesthetic vision and the project team's evolving understanding of each system's impact on the performance requirements of the building. One of those requirements is energy efficiency. Whole building energy efficiency requirements continue to become more stringent, and code officials are becoming more vigilant with enforcement of energy code compliance (Rentfro et al., 2018). Additionally, whole building energy performance plays a significant role in performance-based voluntary certifications such as LEED and Passive House.

The desire for grand views, open office plans and daylighting have contributed to an increased use of fenestration in modern building design, including use of custom glazing assemblies and unitized facade systems. Accurate understanding of heat transfer through fenestration systems is critical, as heat loss/gain through the fenestration often exceeds that in opaque walls and dominates the performance of the building enclosure (Der Ananian et al., 2007). For this reason, minor modifications and improvements to thermal and solar performance of fenestration systems can have a significant impact on a building's overall energy performance. An accurate understanding of the thermal and solar performance of proposed fenestration systems can contribute to efficient use of daylighting, reduced lighting loads and more appropriately sized HVAC systems.

Typical methods for selecting high performance fenestration systems include adhering to published performance criteria, using simple decision-support tools, and performing customized simulations (He et al., 2017). Workflows for calculating fenestration thermal and solar performance have evolved to include custom simulations, computer automation tools and parametric analysis, especially in a project's early design phases. These tools automate the workflow, improve efficiency, reduce human error, and augment the development of an early and open dialogue with the project team.

That said, how fenestration performance metrics are communicated with the project team is of equal importance. The design process is dynamic. Rather than provide a static representation of the performance analysis to clients, the author's firm sought to develop a nontechnical, interactive tool that project team members could use in real time to evaluate the thermal and solar performance impacts of various fenestration design decisions.

This paper explores the development of calculation workflows for U-Factor, SHGC, and VT based on the industry shift toward automation and parametric modeling. Additionally, this paper presents an interactive web-based platform used to communicate results with clients during both early and developed design stages.

FENESTRATION PERFORMANCE METRICS

The following performance metrics define the thermal and solar impacts of a fenestration system on building enclosure performance and overall energy use.

U-Factor

Also known as thermal transmittance, the U-factor is the rate of heat transfer across a component due to conduction, convection, and long-wave infrared radiation (NFRC, 2017a). In North America, this value is calculated in accordance with NFRC 100 – *Procedure for Determining Fenestration Product U-Factors* for transparent and translucent enclosure systems, and ASHRAE Standard 90.1 – *Energy Standard for Buildings Except Low-Rise Residential Buildings* for opaque enclosure systems. The U-factor is used to quantify the thermal performance of a system for comparison purposes. For example, manufacturers can compare against each other's systems or designers can compare against prescriptive code requirements. These values are also used as an input for a whole building energy model. The U-factor may also be used as part of a broader analysis to understand the effects the proposed fenestration system may have on occupant thermal comfort.

Solar Heat Gain Coefficient (SHGC)

The SHGC is defined as the ratio of solar heat gain entering through the fenestration product (as a function of directly transmitted solar heat and absorbed solar radiation that is reradiated, conducted, or convected into the space) to the solar radiation striking the fenestration product (NFRC, 2017b). The SHGC is a number that ranges from zero to one. In North America, this value is calculated in accordance with NFRC 200 – *Procedure for Determining Fenestration Product Solar Heat Gain Coefficient and Visible Transmittance at Normal Incidence*. Similar to the U-factor, the SHGC is used to quantify performance of a given system and to determine compliance with the applicable energy codes, as well as to determine the impacts a given system might have on occupant thermal comfort.

Visible Transmittance (VT)

The VT is defined as the ratio of visible light entering the space through the fenestration product to the visible light striking the surface of the fenestration product (NFRC, 2017b). This value is also a number that ranges from zero to one and is reported as a percentage. In North America, it is calculated in accordance with NFRC 200 and is used to determine compliance with the applicable energy codes, and in daylighting and occupant comfort analyses. For opaque components (e.g., frames, dividers, opaque infill panels), the VT is zero (NFRC, 2017b).

Effective Performance Metrics

As part of the permitting process, project teams are often required to provide documentation to the Authority Having Jurisdiction (AHJ) to show that the proposed performance metrics meet the requirements of the applicable energy code. Some design professionals incorrectly report the glazing manufacturer's published thermal performance values (e.g., center-of-glass U-factor) for the entire fenestration system; however, these glazing values do not account for additional heat flow that occurs through the highly conductive frame components and spacer bar at the edge of the glazing (Der Ananian et al., 2007).

Energy codes are clear in their definitions and require calculation of an "effective" or "overall" value that accounts for the fenestration system as a whole: glazing, spacer bar, and frames (IECC, 2018). Effective values are determined using an area-weighted average of the performance of the fenestration system's component parts (e.g., center of glass, edge of glass, frame, dividers, etc.) over the area of the whole fenestration unit as shown in the following equation for the effective U-factor (NFRC, 2017a):

[Eq.1] $$U_{eff.} = \frac{[\Sigma(U_f A_f) + \Sigma(U_e A_e) + \Sigma(U_{COG} A_{COG}) + \cdots]}{A_{total}}$$

COMPUTER SIMULATION AND AUTOMATION TOOLS

In North America, the National Fenestration Rating Council (NFRC) has defined the methodology to test as well as calculate the aforementioned fenestration performance metrics. The NFRC has approved a few computer simulation tools for performing these calculations (NFRC, 2017a; NFRC, 2017b). Building enclosure professionals and design teams rely on these tools, and are more recently turning to scripting tools to automate these calculations. This paper references the computer software tools outlined in Table 1 below.

Note that there are other computer software tools used for similar purposes, and the list in Table 1 is not intended to be comprehensive. Further, building enclosure professionals also use three-dimensional finite element analysis programs, such as HEAT3 and ANSYS, to perform thermal simulations of discrete components or systems with complex geometry; however, this type of analysis is not covered in this paper. Similarly, Grasshopper and Rhino are not the only tools used for this kind of parametric design. Some others include Dynamo (Autodesk Revit) and GenerativeComponents (Bentley MicroStation) (Aksamija, 2018); however, these tools were not specifically used to develop the basis of this paper.

Table 1: Tools for Partially Automating Fenestration Thermal and Solar Performance Calculations

Program (Developer)	**Description**
Thermal and Solar Performance Simulation Tools	
THERM (Lawrence Berkeley National Laboratory, LBNL)	Two-dimensional (2D), static heat transfer analysis program used to calculate component U-factors of fenestration assemblies (NFRC, 2017c).
WINDOW (LBNL)	One-dimensional (1D), static heat transfer analysis program used to calculate center-of-glazing thermal and solar properties for glazing buildups. WINDOW can also be used to calculate effective U-factor, SHGC and VT for simple fenestration assemblies based on inputs from THERM (NFRC, 2017c).
Optics (LBNL)	Used to calculate optical properties of glazing layers to be input into WINDOW (NFRC, 2017c).
Automation Tools	
Rhinoceros (Robert McNeel & Associates)	Referred to as Rhino. Computer aided drafting program (2D and 3D) that can be used to generate the geometry of fenestration assemblies.
Grasshopper (Robert McNeel & Associates)	Visual programming environment and plug-in to Rhino that is used to automate parametric calculations of 2D and 3D geometry.
Honeybee (Ladybug Tools)	Plug-in for Grasshopper that is used to facilitate interoperability between Grasshopper and energy simulation programs, including THERM.
Excel (Microsoft Office)	Programmable spreadsheet tool, which can be used for performing hand-scripted and macro-enabled calculations.

EARLY DESIGN WORKFLOWS

Integrated project delivery and building information modeling (BIM) have shown that early collaboration between members of the design team as well as between the design and construction teams has a valuable impact on the overall performance and efficiency of the implementation of the project (Construction Users Round Table, 2004). Furthermore, some of the most important design decisions that have significant impacts on building performance are made at the conceptual stage of a project, such as building massing, orientation, volume, shading, daylight strategies, etc. (Aksamija, 2018).

Building enclosure professionals do not often use thermal and solar performance simulation tools to inform decisions in early stages of design (e.g., schematic design) because information about the enclosure systems is limited and not refined enough for thermal modeling to be helpful. For instance, the project team may have a sense of general rough opening dimensions and mullion sightlines but not have chosen a specific product or fenestration assembly. In this early stage of design, rather than modeling based on assumptions, a designer may use published performance data from fenestration manufacturers or industry resources such as ASHRAE Handbook of Fundamentals (Chapter 15, Tables 1 and 4) to provide rough estimates for fenestration performance metrics.

Manual Workflow (Early Design)

For the purpose of this paper, the term "manual workflow" is used to describe calculation procedures in which humans must transfer information and data between individual steps of the process. In early design, the manual workflow procedure is relatively simple, and consists of the following steps also shown in Figure 1 below:

1. Reference published literature (e.g., manufacturer's published data, ASHRAE Handbook of Fundamentals) for fenestration performance metrics (U-factor, SHGC, and VT).
2. If needed, perform numerical calculations to obtain effective performance values.

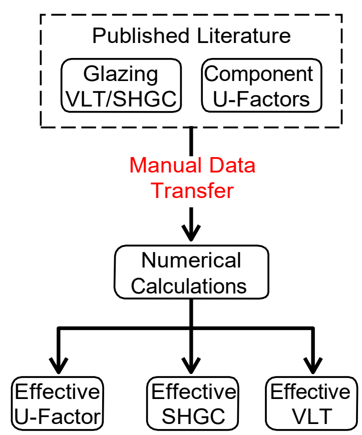

Figure 1 – Manual Workflow in Early Design

Partially Automated Workflow (Early Design)

Automating Calculations

Area-weighted calculations can very quickly become time intensive and are prone to human error. The process often uses spreadsheet tools such as Microsoft Excel to calculate effective performance metrics based on manually input data including fenestration unit sizes and individual component performance metrics. The author's firm and others (see *Reference Procedure for Simulating Spandrel U-Factors* published by the Fenestration Association of British Columbia) have developed macro-enabled worksheets that perform the calculations required to obtain effective thermal and solar performance metrics. This is one means to partially automate the workflow and introduce efficiency; however, it can still be prone to user error associated with manual data input into the worksheet. If not caught early on, transfer errors can contribute to inaccuracies in downstream tasks that rely on building enclosure performance inputs, such as a whole building energy model or envelope trade-off analysis.

Note that while Excel is readily available and prepackaged with in-program scripting capabilities (using Visual Basic for Applications, VBA), building enclosure professionals may choose to use different programmable calculators. The author's firm, for example, has created a tool using the C# programming language to be compatible with an interactive web-based platform for project team members to use (reference Results Reporting section below).

Automation with Parametric Design and Computer Aided Drafting Tools

In the author's experience, parametric design and computer aided drafting tools, such as Grasshopper and Rhino, are well suited for automation and can improve efficiency while analyzing a wider range of design options, generally with improved quality control (QC). This process involves assigning key parameters to various features of the fenestration system, as shown for example in Figure 2 below, that the team anticipates may change as the design develops and are often studied parametrically.

Parametric design studies for building enclosure and fenestration systems most often includes varying the geometric and material properties. For example, designers may want to understand the impact of enlarging a vision glazing panel compared to changing that panel to a shadow box assembly. By integrating the capabilities of parametric design and building performance simulations, multiple design variables can be tested rapidly (Aksamija, 2018). The parametric design approach is most effective when parameters are prioritized early on by the project team.

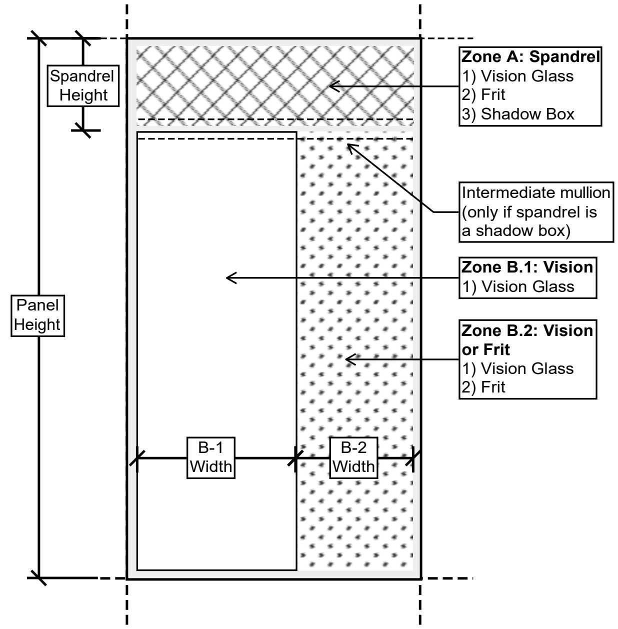

Figure 2 – Example Fenestration System Parameters

The key change in the workflow is the use of a scripted sequence, developed in Grasshopper for example, that controls the workflow with limited user interference. In this case, the resulting workflow, as shown in Figure 3, includes the following steps:

1. Develop a directory (e.g., plain text file or Excel file) of relevant component performance metrics (e.g., manufacturer's published center-of-glass U-factor and frame/edge U-factors from ASHRAE Handbook of Fundamentals).
2. Generate geometry in Rhino. In early stages of design, the geometry built in Rhino typically consists of an elevation with general dimensions (e.g., unit width and height, mullion width, framing member lengths, etc.).
3. Use Grasshopper to apply parameters to Rhino geometry, which can then be manipulated such that downstream calculations can be re-run automatically.
4. Develop a script in Grasshopper to perform the analysis calculations. The script may include sourcing component performance metrics and geometric inputs, performing numerical calculations, and exporting results.
5. Manipulate parameters and run simulation(s).

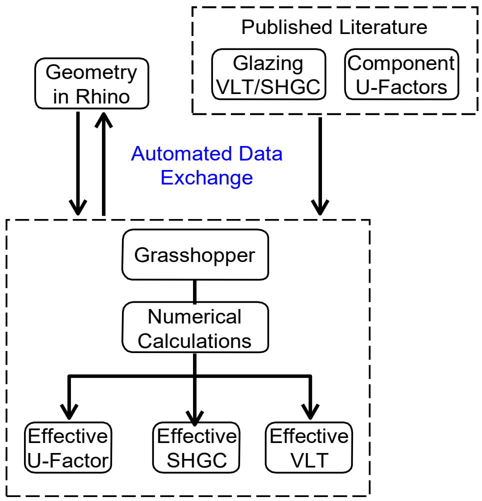

Figure 3 – Automated Workflow in Early Design

By parametrizing the geometric inputs of the model, Grasshopper can automatically update the area-weighted analysis based on the user's preference. In early design, it is also possible to use Grasshopper to evaluate a series of non-geometric modifications to the fenestration system (e.g., glazing build-up, thermal properties of the frame, introduction of an opaque element such as a shadow box, etc.) as long as the user provides the relevant component performance metrics. In some instances, if the proposed system is similar to previously modeled systems, then it may be possible to use past experience or to use previously calculated component performance metrics. However, this should be done with care, as many factors, including adjacent perimeter conditions and dimensional ratios, can affect fenestration performance metrics. These factors can be explored further with the use of computer simulation tools, which generally occurs during later design stages (developed design).

DEVELOPED DESIGN WORKFLOWS

In later stages of design (e.g., Design Development and Construction Document phases), the project team has a more defined vision of the proposed enclosure assemblies, including specific fenestration and glazing systems. In these phases, building enclosure professionals often rely on computer simulation tools such as THERM and WINDOW to calculate refined, project-specific component performance metrics.

Manual Workflow (Developed design)

The manual workflow during developed design, as shown in Figures 4 and 5, includes the following steps:

1. Model the glazing assembly in WINDOW, using OPTICS as required, and manually import it into THERM.
2. Generate frame geometry in THERM, manually assign boundary conditions, and run THERM simulation(s).
3. For simple fenestration configurations, import THERM simulations back into WINDOW to calculate effective performance values (reference forthcoming Automating Calculations section). For more complicated fenestration configurations, manually export component U-factors for frame, edge of glazing and center of glazing from THERM, and perform numerical calculations to obtain effective performance values.

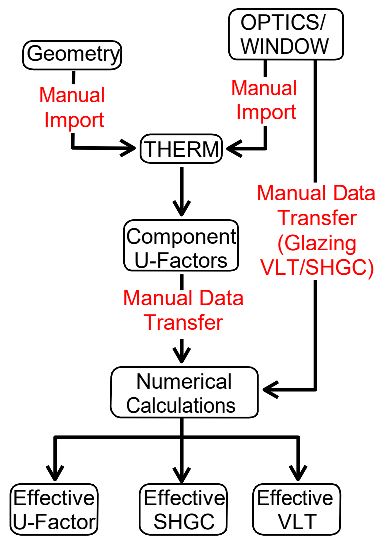

Figure 4 – Manual Workflow in Developed Design

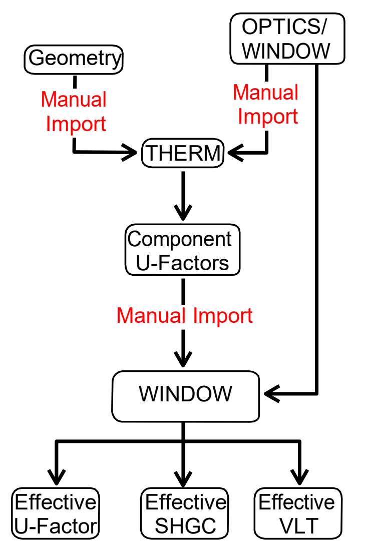

Figure 5 – Manual Workflow in Developed Design Using WINDOW

In later stages of design, the manual workflow requires development of new models for each individual design case. The development of the whole building energy model is typically an iterative process, as the model develops along with the building design (Rentfro et al., 2018). That said, even if a minor modification is made to the fenestration system (e.g., a low-E coating is added to the glazing buildup), the models and inputs must all be updated by hand and the results recalculated, resulting in time lags and decreased efficiency.

Additionally, manual calculation approaches in developed design are more prone to human error associated with the various steps involving manual data transfer.

Partially Automated Workflow (Developed Design)

Automating Calculations

As noted previously, in addition to programmable calculation tools (e.g., Excel), WINDOW can calculate effective performance metrics for simple fenestration system configurations, based on user inputs from THERM. However, the fenestration system geometry is limited to a series of pre-set unit layouts, and the center infill is limited to homogenous glazing systems only. In other words, partial frit patterns, shadow boxes, opaque infill panels, louvers, and insulated spandrels, among other custom fenestration features often cannot be modeled without significant workarounds that, again, involve significant manual inputs. To avoid significant time spent on these exercises, complex systems are often generalized. However, this can become a concern in developed design, where accuracy is of higher importance, since misrepresentation of systems will lead to errors in calculation of whole building energy efficiency (Rentfro et al., 2018) or objections from AHJ's who request supporting documentation for such calculations.

Automation with Parametric Design and Computer Aided Drafting Tools

During developed design, the parametric workflow, as shown in Figure 6, includes the following steps:

1. Generate geometry in Rhino. In later stages of design, the geometry built in Rhino typically consists of specific section details (e.g., through critical heat flow path components such as frames, dividers, etc.) and an elevation with general dimensions (e.g., mullion width, framing member lengths, etc.). Reference Figure 7 for sample details.

2. Use Grasshopper to apply parameters to Rhino geometry, which can then be manipulated such that downstream calculations can be rerun automatically.

3. Develop a script in Grasshopper to perform the analysis calculations. The script may include generating WINDOW and THERM Models, running simulations, exporting data from computer simulation tools, performing numerical calculations, and exporting results. Note that Honeybee is used to communicate between Grasshopper and THERM.

4. Manipulate parameters and run simulation(s).

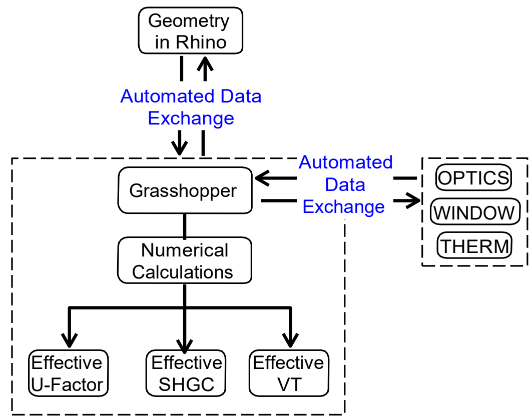

Figure 6 – Automated Workflow in Developed Design

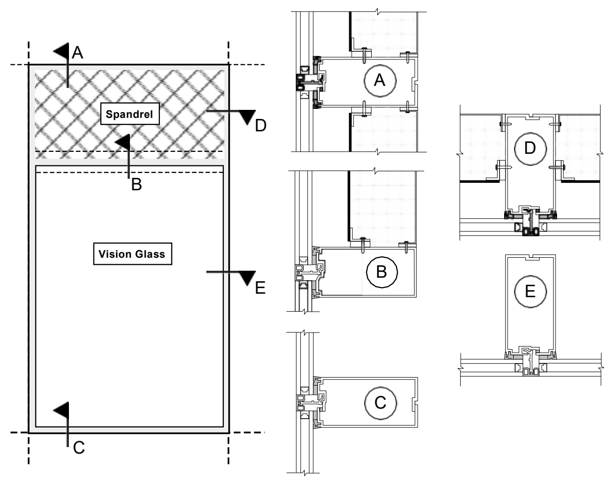

Figure 7 – Example of Fenestration Details in Developed Design

As a visual programming tool, Grasshopper can be used to perform the numerical calculations required to obtain effective performance metrics. In some instances, however, the user may decide to use an alternate means to perform these calculations. Refer to Results Reporting below for an example.

MODEL VERIFICATION

With the use of user-defined scripting tools, such as Grasshopper, and computer aided drafting tools, such as Rhino, building enclosure professionals can accurately model multiple iterations of unique fenestration configurations. The QC process becomes more efficient, as once a working baseline model is verified, iterations of the same model can be made that require less human interference and, therefore, less review time. It is important to note that when working with automated workflows, the results must be verified. In the author's experience, verification is often performed by hand, early on, as part of the QC process.

EXISTING TOOLS TO EXAMINE ENERGY IMPACTS OF FENESTRATION

Various web-based and desktop tools exist to help designers understand the energy impact a proposed fenestration system will have on building energy performance. For example, COMFEN by LBNL is a desktop tool that calculates heating and cooling energy use, associated costs, and peak heating and cooling demand for specific fenestration products based on user-defined inputs such as building type, geographic location, orientation, and window configuration. Users also specify size, shading, and thermal properties of the fenestration system they wish to investigate (LBNL, 2019). Facade Design Tool by Efficient Windows Collaborative is a web-based tool that performs similar analyses. These types of tools can be useful early on in design. However, their accuracy depends on the degree to which the models, with their limited flexibility, represent the building. Furthermore, their limited built-in libraries do not depict the full set of available window products on the market. They also at times lack the capability to model unique geometry and building context (He et al., 2017).

RESULTS REPORTING

As discussed, there are many benefits of using computer software, particularly parametric software, to automate or partially automate the evaluation of thermal and solar performance metrics for fenestration systems. Project teams, however, may not always benefit from such analyses for the following two reasons (Donato et al., 2016):

- Difficulty balancing flexibility, accuracy, and user friendliness of the software tools available for dynamic simulations.
- Difficulty in handling the amount of data and deriving clear recommendations that the design team can follow.

Data Visualization Tool

To address these concerns, which were echoed by clients, the author's firm developed an in-house, web-based data visualization tool customized to integrate with its workflow. These types of tools help to develop a useful dialogue with the project team that can drive the overall design of the building.

The web-based data visualization tool, conceptually depicted in Figure 8 below, provides real-time feedback to project teams regarding the performance impacts of strategic fenestration design decisions. The tool sources data from a direct link library (.DLL) scripted in C#. The .DLL calculates area-weighted effective performance metrics based on input from the web tool and component performance metrics from Grasshopper (Figures 3 and 6). The user can iterate through various design options, and the web tool automatically updates a conceptual rendering of the system as well as the effective thermal and solar performance metrics.

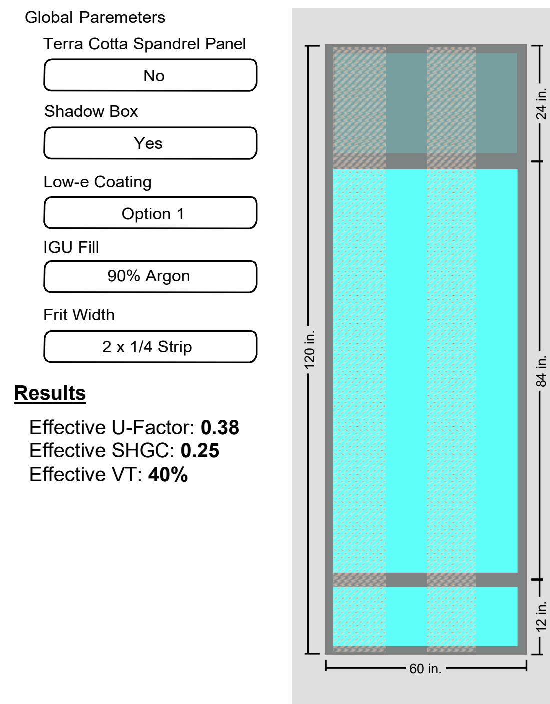

Figure 8 – Example Web Application Output

The author has found that this tool is an effective means for communicating project-specific information quickly, is intuitive for our clients to use, and can supplement traditional design deliverables (e.g., reports), which are often cumbersome.

CONCLUSION

Introducing automation into workflows related to calculation of thermal and solar performance metrics for fenestration systems can improve efficiency and expand capabilities. This process is most effective with early communication with the project team to understand and address specific project needs. Establishing an open dialogue in early design can result in valuable feedback that informs fenestration system selection, aesthetics, architectural layout, and design of the mechanical and electrical systems. This paper provides a summary of how automated processes can affect the overall workflow—and presents a tool that can be used effectively with an automated workflow—to deliver fenestration system thermal and solar metrics to the project team.

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NOMENCLATURE

Symbol	Definition
$U_{eff.}$	Effective U-factor of fenestration product
U_f	Frame U-factor
A_f	Frame area
U_e	Edge-of-glass U-factor
A_e	Edge-of-glass area
U_{cog}	Center-of-glass U-factor
A_{cog}	Center-of-glass area
A_{total}	Total fenestration product area

SOFTWARE RESOURCES

THERM: https://windows.lbl.gov/software/therm
WINDOW: https://windows.lbl.gov/software/window
Optics: https://windows.lbl.gov/software/optics
Rhinoceros: https://www.rhino3d.com/
Grasshopper: https://www.grasshopper3d.com/
Honeybee: https://www.ladybug.tools/honeybee.html
COMFEN: https://windows.lbl.gov/software/comfen
Facade Design Tool: https://www.commercialwindows.org/fdt.php

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