Methods for integrating parametric design with building performance analysis

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ABSTRACT: This paper discusses methods for integrating parametric design with building performance analysis procedures, specifically presenting tools and design methodologies that are suitable for whole building design. In this research, an ideal framework for integration of parametric and performance analysis procedures was developed. Then, the framework was tested using existing software applications, including building information modeling (BIM), non-BIM, parametric design and building performance analysis applications. Current applications that can integrate some form of building performance simulation with parametric modelling include Rhino 3D (non-BIM), Revit (BIM), and SketchUp (non-BIM). Revit and Rhino each have visual programming plugins to aid in the creation of parametric forms. In this research, three different workflows were tested. Specifically, Honeybee and Ladybug (for Rhino 3D), Insight 360 (for Revit) and Sefaira (for Revit) were evaluated. A case study building was used to test and evaluate the workflows, interoperability, modeling strategies and results. Three different building performance aspects were analyzed for each workflow: 1) energy modeling, 2) solar radiation analysis, and 3) daylighting. Simulation results from energy modeling, solar radiation and daylight simulations were recorded and analyzed. However, besides simulation results, the paper compares modeling procedures, parametric capabilities of investigated applications, ease of integration and interoperability. The results show a promising course for integrating parametric design with building performance simulations.

KEYWORDS: Parametric design, building performance analysis, high-performance buildings, BIM, energy-efficiency

INTRODUCTION

Advances in building performance simulations have enabled designers to better understand how environmental factors affect building performance (Aksamija, 2013). Parametric design methods, on the other hand, allow designers to generate and explore geometries of building elements by manipulating certain parameters. There are a number of software platforms that focus individually on environmental analysis or parametric design, but few integrate both. Common parametric design tools include Grasshopper (Rhino 3D), Dynamo (Autodesk Revit) and GenerativeComponents (Bentley MicroStation). Environmental and energy analysis tools include Ladybug and Honeybee (Rhino 3D), DIVA (Rhino 3D), Insight 360 and Green Building Studio (Autodesk Revit), Sefaira (Autodesk Revit + Trimble SketchUp), Radiance, OpenStudio, EnergyPlus, eQuest, DesignBuilder, IES VE, and many others. The most common method of integrating building performance simulations (BPS) into early design work has been by exporting the design model (whole building, partial building, or model of a building component) to a dedicated analysis tool to generate an analysis model, assign inputs necessary for calculations and simulate energy usage, daylighting, or solar radiation. The results from these simulations would be used to adjust the design model in the original design program, and then the model would be exported again, thus repeating the process. By integrating the capabilities of parametric design and building performance simulations, multiple design variables could be tested rapidly, creating a more cohesive design process. These following research objectives were addressed in this study:

- Investigation of methods for integrating performance-based design with parametric modelling, focusing on whole building design.
- Investigation of tools and software programs that can seamlessly integrate performance-based design with parametric modelling, particularly focusing on energy analysis, solar radiation analysis and daylight simulations.
- Testing the procedures on a specific case study and documenting the results.

1.0 BRIEF LITERATURE REVIEW

Typical energy modeling programs are often complex for architects to use during the early stages of design, resulting in building performance analysis being performed at later stages (Bazjanac 2008; Schlueter and Thesseling 2009). The architectural profession lacks established methodologies and protocols that incorporate performative analyses into the early stages of design (Pratt and Bosworth, 2011). However, 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. Tools that shift the building performance assessment back into conceptual stages of design will have a bigger effect on building performance (Rahmani et al., 2013). This introduces the concept of performance-based design, where the environmental performance becomes the guiding factor in the design process. However, most current design software applications are not capable of integrating the results from performance-based simulations back into the design model. It is the designer who interprets the results and optimizes the model based on simulation results (Oxman 2008).

Parametric modeling relies on geometric representation of a design with components and attributes that can be parametrically varied, where each geometric configuration that derives from parametric variations is called an instance. Instances represent a unique set of transformations based on parametric inputs, generating design variations and different configurations (Turrin et al., 2011). Parametric modeling has the potential to overcome current design process limitations and to facilitate the revelation and comparison of performative solutions. Parametric modeling initially lacked applications in architectural design; however, new architectural tools have been developed, allowing for new directions. The ability to produce many instances that result in unique configurations of the same geometric component is the main advantage of parametric modeling.

Integrating parametric modeling with building performance analysis procedures could enable architects and designers to analyze impacts of design decisions on building performance from the earliest stages of the design. Testing multiple design strategies in an efficient way, and reducing the time necessary for modeling and analysis procedures are the main benefits of integrated performance-based and parametric design.

2.0 FRAMEWORK FOR INTEGRATION OF PERFORMANCE-BASED AND PARAMETRIC DESIGN METHODS

The ideal framework for integrating parametric and performance-based design is shown in Figure 1. Parametric modelling, geometric preparation and analysis preparation should be streamlined and connected to performance analysis. This would combine parametric control of building geometry and building systems with analysis and visualization of results.

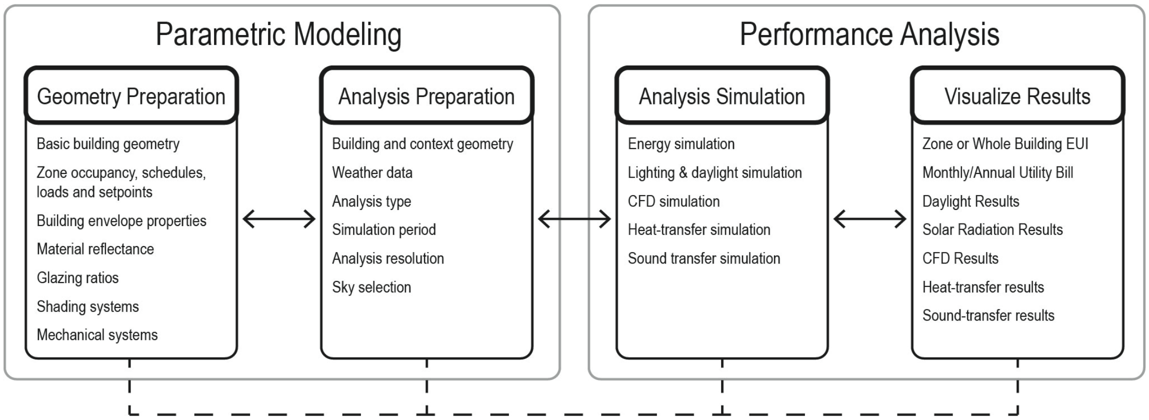

Figure 1: Ideal framework for parametric and performance-based design. Source: (Author 2017)

Current software applications that integrate some form of BPS with parametric modelling include Rhino 3D, Revit, and SketchUp, as shown in Figure 2. Revit is a BIM-based design tool, while Rhino and SketchUp are non-BIM based. Revit and Rhino each have visual programming plugins to aid in the creation of parametric forms. And, a variety of BPS tools are available that address different aspects of performance analysis, including solar radiation analysis, energy modeling and daylight analysis. This research investigated three different workflows, including integration of both BIM and non-BIM design platforms with parametric modeling and BPS. Specifically, Rhino 3D (with Grasshopper, Honeybee and Ladybug plugins) and Revit with Insight 360 and Sefaira workflows were investigated in this research. Figure 2 shows details of all three investigated workflows, and relationships among software applications. The parametric and performance tools discussed are run within Rhino (Ladybug and Honeybee) or Revit (Insight 360 and Sefaira). Honeybee and Sefaira use the same simulation engines for running analysis (Daysim, Radiance, EnergyPlus and OpenStudio). Insight 360 also uses EnergyPlus for energy analysis, but Revit has its own engine for lighting simulations, which has been validated against Radiance. Since all plugins use EnergyPlus as the energy simulation engine, any variations in results are caused by geometry and input differences between the three plugins.

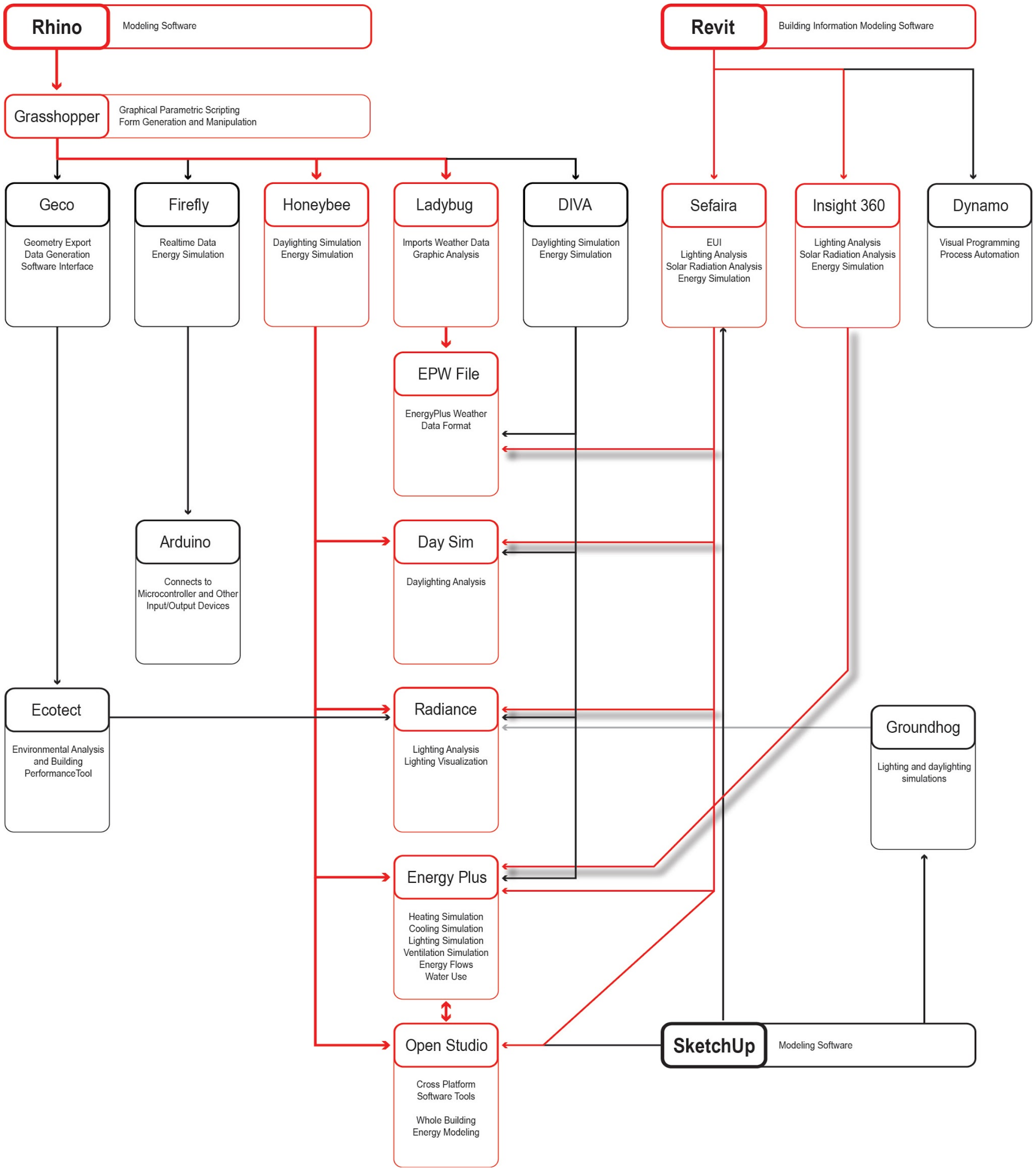

Figure 2: BPS and parametric workflows for Rhino, Revit and SketchUp. The workflows and software applications explored in this research are shown in red. Source: (Author 2017)

The next section reviews a case study, which was used to evaluate this framework.

3.0 EVALUATION OF THE FRAMEWORK AND CASE STUDY

A prototype building located in the financial district of Boston was used as a case study to evaluate the above discussed framework, and the building site is shown in Figure 3a. The evaluated workflows included Honeybee and Ladybug (Rhino 3D), Insight 360 (Revit) and Sefaira (Revit) software applications. The building is divided into a low-rise portion of five stories, and a high-rise portion of 15 stories. Floor-to-floor height was 3.7 m (12 ft), with a total height of 73.2 m (240 ft). The perimeter zone depth was 14.6 m (48 ft). The surrounding buildings were modelled from GIS data, and were included in the site model. Figure 3b shows Rhino model with surrounding buildings, and Figure 3c shows Revit model. Energy, solar radiation, and daylight analysis were run for the case study building using the three investigated workflows.

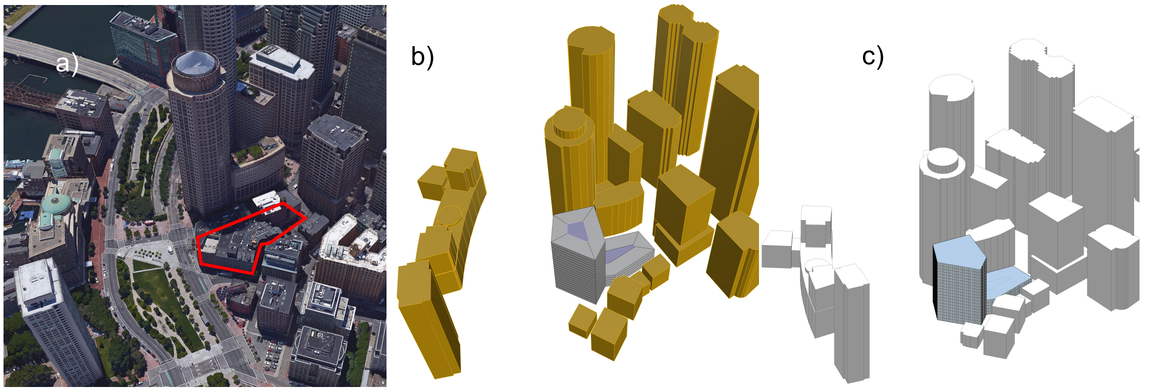

Figure 3: a) Case study building site outlined in red; b) Rhino model of the case study building, with surrounding buildings; and c) Revit model of the case study building, with surrounding buildings. Source: (Author 2017)

3.1 Rhino, Grasshopper, Ladybug and Honeybee Workflow

Figure 4 shows the Grasshopper definition used for the analysis and simulations within Rhino. Due to the graphic nature of Grasshopper, the organization of components is vital for understanding the user's own definition. As more components and connections are added to the canvas, the file becomes increasingly visually complex. The components are divided into four stages: geometry preparation, analysis preparation, analysis simulation and visualization of results.

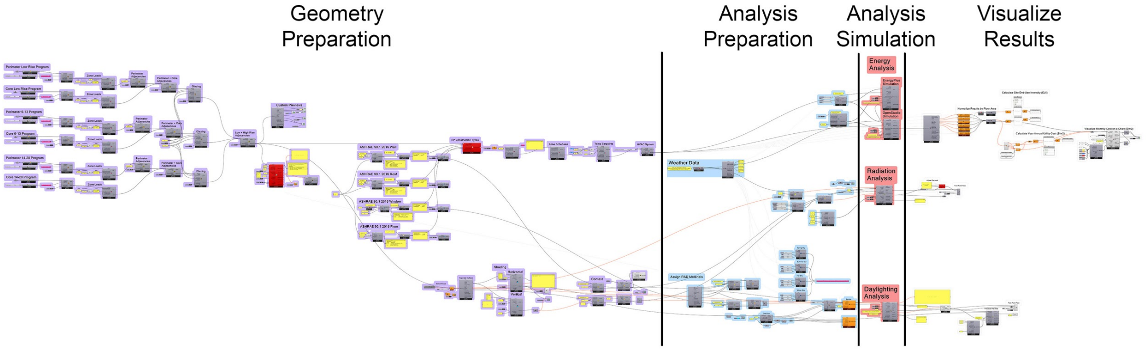

Figure 4: Grasshopper definition used for the analysis. Source: (Author 2017)

Honeybee exports model geometry and settings to EnergyPlus, which performs the energy simulation. The simulation options that were parametrically controlled in Honeybee included window-to-wall ratio (WWR), temperature set-points, wall and roof R-values, glazing U-values, SHGC and Vt, infiltration rates, HVAC systems, and lighting power density. Since the building geometry was complex, each run ranged from taking 20 to 60 minutes to complete. The number of windows had a direct impact on simulation time. Table 1 shows properties of investigated models and respective EUI results.

Table 1: Energy simulation results (Rhino and Honeybee).

Run Name	Variables	EUI kWh/m^2 (kBTU/ft^2)
Baseline	50% WWR; VAV w/ Reheat, 72°F/78°F Set-points; Wall: R-19; Roof: R-30; Window: .45/.38/.42 (U/SHGC/VT); Infiltration: .8 ACH; Lighting power density: 10.54 w/m^2	216.7 (68.7)
Low WWR	30% WWR	205.1 (65)
High WWR	80% WWR	237.8 (75.4)
Setpoints	68°F/82°F Set-points	161 (51)
Higher R-Values	Wall: R-40; Roof: R-60; Window: .2/.38/.42 (U/SHGC/VT)	185.7 (58.9)
Infiltration	Infiltration: .2 ACH	129.5 (41)

Lighting Power Density	Lighting power density: 3 w/m^2	212.4 (67.3)
HVAC Alternate	Fan coil units + DOAS	127.3 (40.4)
Best Case	50% WWR; Wall: R-40; Roof: R-60; Window: .2/.38/.42 (U/SHGC/VT); Fan coil units + DOAS, 68°F/82°F Set-points; Infiltration: .2 ACH; Lighting power density: 3 w/m^2	45.3 (14.4)

The Ladybug Radiation Analysis Tool uses the location of the sun for every hour of the year to determine how much radiation the exterior surfaces receive. Surrounding buildings are taken into account during this analysis. Simulation options that were parametrically controlled in Honeybee included analysis period, sky type, grid size, grid distance off surface, and legend (low and high bound). Results are shown in Figure 5a. Honeybee exports model geometry and settings to Radiance, which performs daylight simulations. The simulation options that were parametrically controlled in Honeybee included analysis period, sky type, grid size and distance off surface, radiance rendering parameters, and simulation type (illuminance, radiation, luminance). Typical results are shown in Figure 5b.

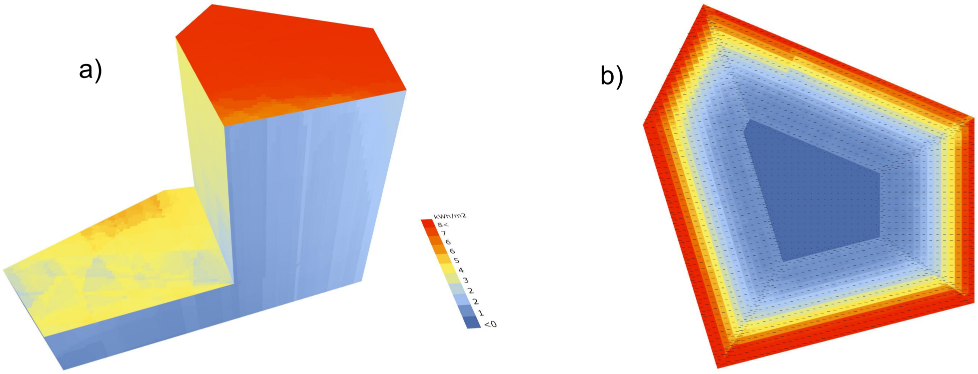

Figure 5: a) Solar radiation analysis results (cumulative, June 21); b) Daylight simulation results (June 21, WWR 80%). Source: (Author 2017)

3.2 Revit and Insight 360 Workflow

Two Revit models were built to simulate the same conditions that were set up in the Rhino model, primarily for the lighting analysis. One contained individual windows to simulate WWRs between 20% and 50%, while one large window per facade orientation was needed for a WWR ratio of 80%. The solar radiation analysis model utilized the massing model, as radiation results were desired for multiple facades, and not detailed elements. Revit exports the model geometry and settings to the cloud, where the simulations are run through EnergyPlus. Alternative design factors can be simulated by varying building loads, model geometry and systems. Table 2 includes a series of options that represent all of the alternate design factors that were simulated.

Table 2: Energy simulation results (Revit and Insight 360).

Run Name	**Variables**	**EUI kWh/m^2 (kBTU/ft^2)**
Baseline	50% WWR, no shading; ASHRAE VAV; Wall: R-19; Roof: R-30; Slab: R-23; Window: Double Low-E; Infiltration Rate: .8 ACH; Lighting: 1.1 W/SF; Daylighting: None; Building Type: Office, Schedule: 12/6	225 (79.1)
Low WWR	30% WWR	245 (77.6)
High WWR	80% WWR	271 (86)
Higher R-Values	Wall: R-38; Roof: R-60; Slab: R-23; Windows: Triple Low-E	241 (76.4)
Infiltration	Infiltration Rate: .17 ACH	233 (73.7)
Daylighting	Daylighting and occupancy Controls; Horizontal shading south and west (¼ window height); Lighting: 3 w/m^2	232 (73.7)
HVAC	High Efficiency VAV	218 (69.2)

HVAC alternate	High Efficiency Package System	144 (45.7)
Best case	30% WWR; Horizontal shading south and west (¼ window height); HVAC: High Efficiency Package System; Wall: R-38; Roof: R-60; Slab: R-23; Windows: Triple Low-E; Daylighting and occupancy Controls, Lighting: 3 w/m^2	87.5 (27.7)

The solar analysis tool was used to study the south facade of the building for average, cumulative and peak insolation. Figure 6a shows cumulative insolation values for June 21, where the effects of adjacent buildings can be seen on the low rise portion of the building. Insight 360 uploads the Revit model to the cloud, where daylight simulations are run. The 10th floor was simulated according to the LEED v4 EQc7 opt 2 analysis type, which measures the percentage of floor area that is between 300 and 3,000 LUX at 9am and 3pm on the equinox averages. Figure 6b shows the results of daylight simulation.

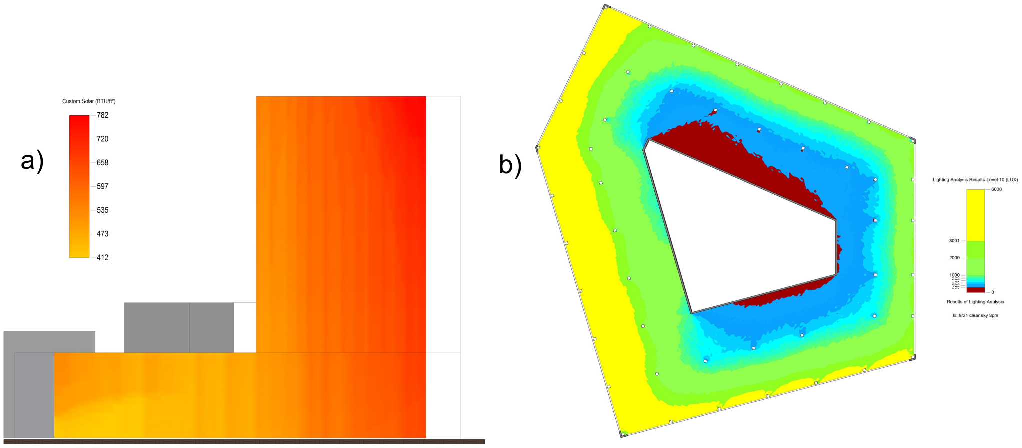

Figure 6: a) Solar radiation analysis results (cumulative, June 21); b) Daylight simulation results (June 21, WWR 80%). Source: (Author 2017)

3.3 Revit and Sefaira Workflow

Sefaira is able to use the same Revit model as Insight 360, with some changes. The total number of glazing planes cannot exceed 1,500. The window design for WWR of 30% and 50% had to be changed to one window per orientation, instead of multiple windows, so that Sefaira could process and run the analysis. When an energy analysis is run, the model is uploaded to the cloud, where it is run through EnergyPlus. The results are either displayed in the web-based application, or within the plugin in Revit. On average, it takes three to five minutes for each energy analysis run. Runs utilizing thermal comfort or natural ventilation factors take significantly longer to process. Runs can be cloned to use as alternates with different design options within the same model. Results are shown in Table 3. Solar radiation analysis cannot be performed in Sefaira. Radiance and DAYSIM are used to perform daylight simulations, and an example is shown in Figure 7.

Table 3: Energy simulation results (Revit and Sefaira).

Run Name	**Variables**	**EUI kWh/m^2 (kBTU/ft^2)**
Baseline	50% WWR, no shading; VAV - Return Air Package; Wall: R-19, Roof: R-30; Slab: R-23; Window: .45/.38 (U/SHGC); Infiltration Rate: .8 ACH; Lighting: 3 W/m^2	290 (92)
Low WWR	30% WWR	290 (92)
High WWR	80% WWR	296 (94)
Higher R-Values	Wall: R-40; Roof: R-60; Slab: R-23; Window: .2/.38 (U/SHGC)	271 (86)
Infiltration	Infiltration Rate: .17 ACH	148 (47)
Shading	.3 m horizontal shades; Internal blinds	296 (94)
HVAC Option 1	Fan coil units and central plant	243 (77)
HVAC Option 2	Radiant floor	180 (57)

HVAC Option 3	Active Chilled Beams	252 (80)
Best Case	50% WWR, no shading; Wall: R-4; Roof: R-60; Slab: R-23; Window: .2/.38 (U/SHGC); Infiltration Rate: .17 ACH; HVAC: Radiant floor	76 (24)

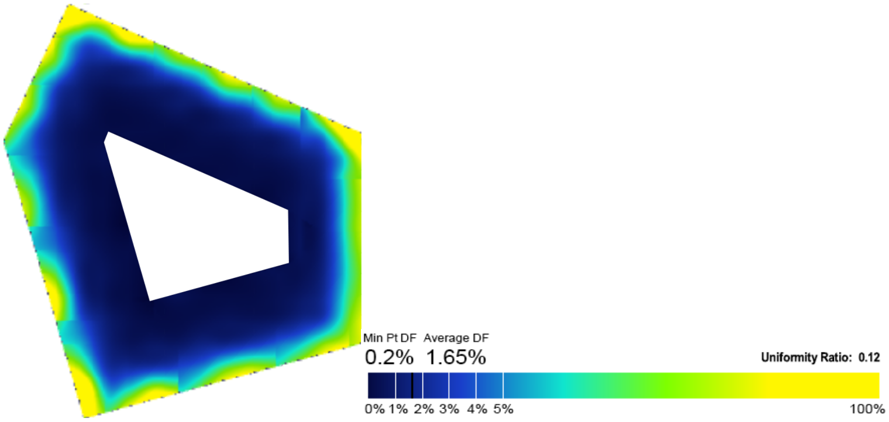

Figure 7: Daylight simulation results showing daylight factor. Source: (Author 2017)

4.0 DISCUSSION OF RESULTS

All simulations followed similar procedures for geometry preparation and visualization of results. Rhino, utilizing Grasshopper, Ladybug and Honeybee, provides significant customizability for parametric control of geometry, and offers different simulation types. The parametric nature of Grasshopper means that there is an infinite number of forms and strategies that can be investigated. One major drawback of this workflow is that the components have to be configured before the initial use. Once they are configured, the Grasshopper definitions can be repeatedly used on the same or different projects. Another drawback is the learning curve required to use the software. While other software programs utilize a series of dialog boxes to configure the parametric and simulation options, this workflow requires the user to set up all the components before visualizing the results. In terms of BIM-based workflow, Revit is the widely adopted BIM software, but both Insight 360 and Sefaira have certain benefits and drawbacks. Learning curve for Insight 360 is fairly light. With the energy and daylight simulations being run in the cloud, the results are quickly generated. The customizability of the daylight and solar radiation analysis is adequate, but the energy simulation parameters are limiting. Further, the lack of parametric tools to generate different WWRs or shading methods based on building orientation is a shortcoming. Additionally, the parametrically generated energy model cannot be used for daylight or solar radiation analysis. Sefaira is easy to install, as well as to use. The organization of energy analysis options within the web-based application makes tracking model changes straightforward. Sefaira's use of the cloud for simulations decreases the time necessary for calculations. The daylight analysis tool is excellent for analyzing the overall light levels and daylighting metrics, although its capabilities for showing specific values on a floor plan are limiting. Additionally, the plugin lacks support for solar radiation analysis.

Although the accuracy of the simulations was not the focus of this research, the energy analysis results were compared to each other, as shown in Table 4. All three program use the same engine, EnergyPlus, for the energy calculations. The only differences between the three tools are variation in inputs and geometry discrepancies between Rhino and Revit. The EUI results from Honeybee and Insight 360 were compared to Sefaira, and the differences were expressed as a percentage. Insight 360 and Sefaira results were the closest to each other, with the EUI results for Insight 360 baseline run being 16% lower than the Sefaira run, and the best case run 15% higher. The Honeybee baseline EUI result was 34% lower, while the best was 66% lower. The parameters for daylight and occupancy controls cannot be set in Sefaira. Insight 360 does not allow for control of the temperature set-points. Ladybug and Honeybee have support for both of these variables, but daylight and occupancy sensors were not simulated. The results from the daylight analysis are difficult to compare since detailed illuminance values were not collected for Sefaira. In addition, the reflectance values of floors, walls and ceilings cannot be set in Sefaira, so the illuminance values would not match even though the simulation engine is the same. Further testing would be needed to compare the accuracy of the daylighting analysis for Honeybee, Insight 360 and Sefaira.

Table 4: EUI results comparison (Honeybee, Insight 360 and Sefaira).

Run Name	EUI (kBTU/ft^2, kWh/m^2)	Difference (%)
Honeybee Baseline	68.71 (216.74)	-34%
Insight 360 Baseline	79.1 (225)	-16%
Sefaira Baseline	92 (290)	0%
Honeybee Best Case	14.4 (45.3)	-66%
Insight 360 Best Case	27.7 (87.5)	+15%
Sefaira Best Case	24 (76)	0%

CONCLUSION

The objective of this research was to investigate methods for integrating parametric design with building performance analysis. An ideal framework for integration of parametric and performance analysis procedures was developed. Then, the framework was tested using existing software applications, including BIM-based and non-BIM design software, parametric design and building performance analysis applications. Specifically, Honeybee and Ladybug (for Rhino 3D) were evaluated as a non-BIM workflow, while Insight 360 (for Revit) and Sefaira (for Revit) were evaluated as BIM-based methodologies. A case study building was used to test and evaluate the workflows, interoperability, modeling strategies and results. Three different building performance aspects were analyzed for each workflow: 1) energy analysis, 2) solar radiation analysis, and 3) daylighting. The framework applied to Rhino, Grasshopper, Ladybug and Honeybee offers a lot of options and customization for the parametric and simulation options. The lack of BIM integration in this framework is a drawback, which means that many designers may use it for conceptual and/or schematic design, but will migrate to a BIM-based software for schematic and design development phases. Insight 360 is able to integrate building performance simulations within a BIM environment. However, Insight 360 has only been available for a short time, and the functionality of the tool has its limits. Sefaira takes the customizability of Ladybug and Honeybee and the accuracy of Insight 360 and integrates it into a BIM environment. The energy and lighting analysis can be simulated quickly. The daylighting simulations have a few drawbacks, which include lack of support for detailed illuminance values at specific points on the floor plan, an analysis grid that cannot be adjusted by the user, as well as the inability to modify reflectance values of materials. Solar radiation analysis is also not included in Sefaira. However, the overall results show a promising course for integrating parametric design with building performance simulations. This would allow designers to evaluate the effects of design decisions earlier in the design stages. Moreover, by integrating the capabilities of parametric design and building performance simulations, multiple design variables can be tested rapidly, creating a more cohesive and effective design process.

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