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02.

BUILDING SIMULATIONS AND HIGH-PERFORMANCE BUILDINGS RESEARCH:

Use of Building Information Modeling (BIM) for Integrated Design and Analysis

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ABSTRACT

High-performance, energy-efficient buildings require a different design approach than conventional buildings. Building performance predictions, use of simulations and modeling, research-based and data-driven design process are the key elements in the design of high-performance buildings. This article discusses relationships between building performance simulations and design, as well as the role of building performance research in architectural practice. The first part of the article discusses Perkins and Will Tech Lab, its research focus and research activities relating to the design of high-performance buildings. The second part of the article focuses on the role of performance simulations, best methods for integrating analysis procedures with the design, as well as case studies.

KEYWORDS: high-performance buildings, simulations, modeling, decision-making, integrated design and analysis

1.0 INTRODUCTION

What are the appropriate strategies for designing extremely low-energy or net-zero energy buildings? Methods for high-performance buildings require use of passive design strategies, use of advanced building technologies and renewable energy systems. Passive design strategies include shading, response to building orientation and site, utilization of thermal storage and natural ventilation, and use of daylight. Active design strategies include use of energy-efficient building systems and advanced building technologies where appropriate, such as mixed-mode ventilation, radiant heating and cooling systems, dynamic windows (for example, using electrochromic glass), and combined heat and power systems. Passive strategies should be utilized to the fullest extent since their cost is minimal and their effect on energy efficiency is significant. Advanced building technologies should be used to increase energy efficiency measures when and where applicable.

Lastly, renewable energy should be used to supplement energy demand with renewable sources, such as wind power, photovoltaic systems and geothermal energy.

Why do we need to use simulations and building performance analysis for the design of high-performance buildings? Building performance simulations are an integral part of the design process, since they help in investigating different options and simulation of design decisions¹. Quantifiable predictions during the different stages of design process help establish metrics that can be used to measure improvements associated with these different types of strategies. It is important to note that improvements in building efficiency that are obtained through passive and active measures reduce the energy consumption, thus reducing the needs for renewable energy sources. Therefore, understanding effects of design decisions on building performance is crucial in achieving low and zero energy buildings.

The objectives of this article are to illustrate how performance predictions and simulations can assist in identifying strategies for reducing energy consumption and improving building performance by rigorous analysis process. The first part of the article discusses Perkins and Will Tech Lab, whose primary research objective is to advance the performance of project designs through dedicated research. Tech Lab's primary research methods include computational simulations and modeling, where different design scenarios are investigated, as well as their effects on building performance. The second part of the article discusses best methods for integrating performance simulations with the design, specifically addressing relationships between Building Information Modeling (BIM) and analysis software applications. Two specific case studies are discussed to illustrate these processes. The first case study discusses a specific architectural project and different types of studies that were performed during the design to improve building performance. The second case study discusses research on advanced computational design methods, and development of custom applications that allow parametric control of BIM elements based on environmental performance data.

2.0 TECH LAB RESEARCH

Tech Lab was initiated in 2008 as a research entity within Perkins and Will to enhance project designs through dedicated research. Tech Lab's research agenda focuses on advanced building technologies, materials, sustainability, high-performance buildings, renewable energy sources and computational design. Tech Lab monitors developments in building systems, materials, and information technology; reviews and analyzes emerging technologies that can have a direct impact on the course of architectural design, and investigates building systems and technologies that can significantly improve the value, quality and performance of architectural projects.

Examples of Tech Lab's research projects are:

- Performance and life cycle cost analysis for building integrated photovoltaics
- Performance of double skin walls
- Renewable energy systems optimization
- Advanced thermal comfort modeling
- Daylight analysis
- Parametric modeling
- Thermal analysis of exterior wall assemblies
- High-performance building envelopes
- Selection of renewable energy sources.

Primary research methods include simulations and computational modeling, which are used to investigate different design scenarios and strategies. Typical research process involves: 1) determination of research objectives and questions based on the needs of specific architectural/design projects; 2) identification of appropriate research methods; 3) identification of the timeline, schedule and research procedures; 4) execution of the study; and 5) dissemination and implementation of research results. Besides implementation of research results on architectural and design projects, sharing and dissemination of findings with the larger architectural and design community is a key aspect of Tech Lab's objectives. Publications of research data and methods, analysis processes and results benefits the entire field, therefore, research studies and results are shared through Tech Lab Annual Reports, shown in Figure 1.

For example, Tech Lab Annual Report 2009 includes studies such as building envelope performance analysis and daylight optimization, life-cycle cost analysis of building-integrated photovoltaic system, building envelope studies and daylight analysis, relationships between thermal comfort and outdoor design elements, study of facade options and building integrated photovoltaics, and a feasibility study for stand-alone self-powered exterior signage lighting system². Tech Lab Annual Report 2010 includes facade energy studies, photovoltaic system energy performance and cost analysis studies, curtain wall heat transfer analysis, and exterior wall thermal transfer study³. Tech Lab Annual Report 2011 includes studies relating to high-performance building facade, dew point analysis of a typical exterior wall assembly, hygrothermal analysis of exterior walls, and facade energy performance and daylight analysis studies⁴. Tech Lab Annual Report 2012 includes thermal analysis studies for exterior wall assemblies⁵. These reports also include selected white papers that are written on building technology topics, as well as published research articles and research reports.

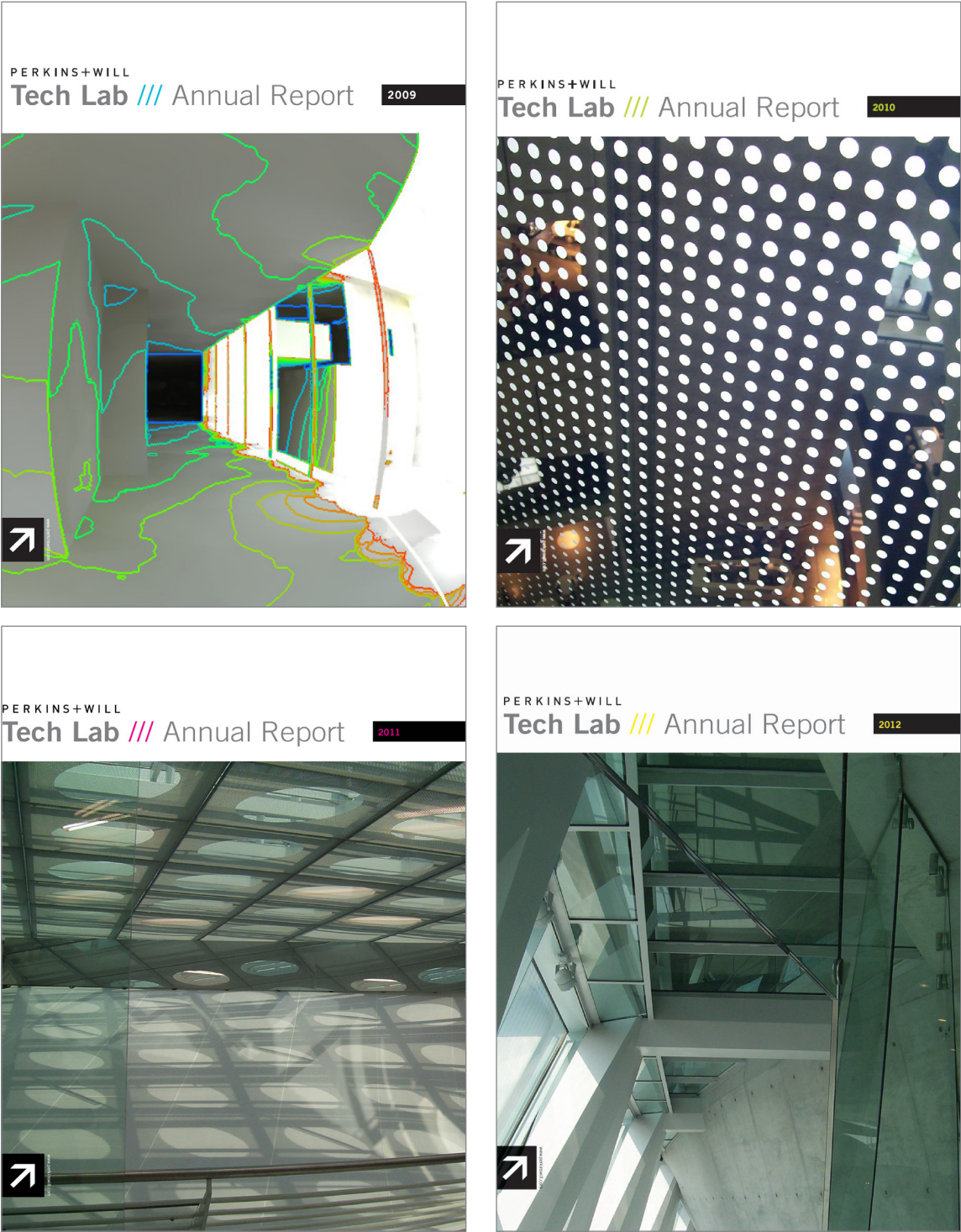


Figure 1: Dissemination of research results through Tech Lab Annual Reports.

3.0 BIM, BUILDING PERFORMANCE ANALYSIS AND DESIGN PROCESS

In order to evaluate and optimize the building performance, different analysis cycles supported by simulations should be part of an integrated design process. This is the basis for **performance-based design method**. However, this is challenging paradigm when compared to a traditional design method⁶:

- 1) **Traditional Method** has deficiencies because (1) it may include simplified assumptions based on rules-of-thumb which can be inaccurate; (2) it may force an aesthetic feature without considering performance impacts; and (3) it may not provide performance measurement/evaluation of a certain design solution.
- 2) **Building Performance-Based Design Method** has an ability to estimate the impact of a design solution since: (1) performance measures are investigated with actual quantifiable data and not rules-of-thumb; (2) it uses detailed building models to simulate, analyze and predict behavior of the system; (3) can produce an evaluation of multiple design alternatives.

Past research on utilization of simulation tools during architectural design process indicates that despite the increase in number of available tools in the last decade, some architects and designers are finding it difficult to use these tools, since they are not compatible with their working methods and needs, or the tools are judged as complex and cumbersome^{7, 8}. To remain competitive, design professionals must weigh the value of information gained through simulation tools against the invested time, resources and against the value of comparable information that might be gained through the use of other or no tools⁹. So, why do we need to use simulations in the first place? Quantifiable predictions through simulations and modeling can help in identifying strategies and methods to improve building energy efficiency and building performance, and help in the decision-making process for sustainable design. They must be integrated with the design process from the earliest stages of the design.

Starting point for the schematic design is site analysis, where environmental factors must be systematically examined. Typical information about environmental conditions of the site includes topography, context, solar orientation, climatic characteristics, surrounding structures, and infrastructure¹⁰. Building orientation plays a significant role in providing access to daylight, as well as solar exposure. Solar radiation introduces passive solar heat gain, which can be advantageous in heating-dominated climates and unfavorable in cooling-dominated¹¹. While passive solar gain can be harnessed to decrease heating demand in winter, gains during summer months create the need for cooling.

Building Information Models (BIM) can be used for energy and performance simulations, where the analysis process can be integrated with the design process. Figure 2 shows the basic types of performance analysis in relation to the project stages indicating what types of analysis should be performed when and how they relate to the BIM development process. The top part of the diagram shows the impact of decisions on actual building performance and relationships to project stages. As early as conceptual phase, the analysis should focus on the bigger design picture such as climate information, orientation, passive strategies and building massing. Then at the schematic stage, the analysis should explore the shading methods, solar access and building envelope options. For example, the iterative cycle of different design options of sun shades can be analyzed at this stage. During the design development stage, optimization of shading devices, daylight and glare studies, energy performance studies, thermal analysis and optimization should take place. However, BIM design authoring software programs and analysis applications are currently distinct and require exchange of data and building information. To successfully use BIM design models for environmental and performance analysis, it is important to consider the Level of Development (LOD) of BIM design models, what type of information is needed from them to develop BIM analysis models, and data exchange mechanisms and workflow between different software programs. LOD refers to the amount of information embedded in BIM design models, and widely accepted example is the American Institute of Architects (AIA) document E202¹².

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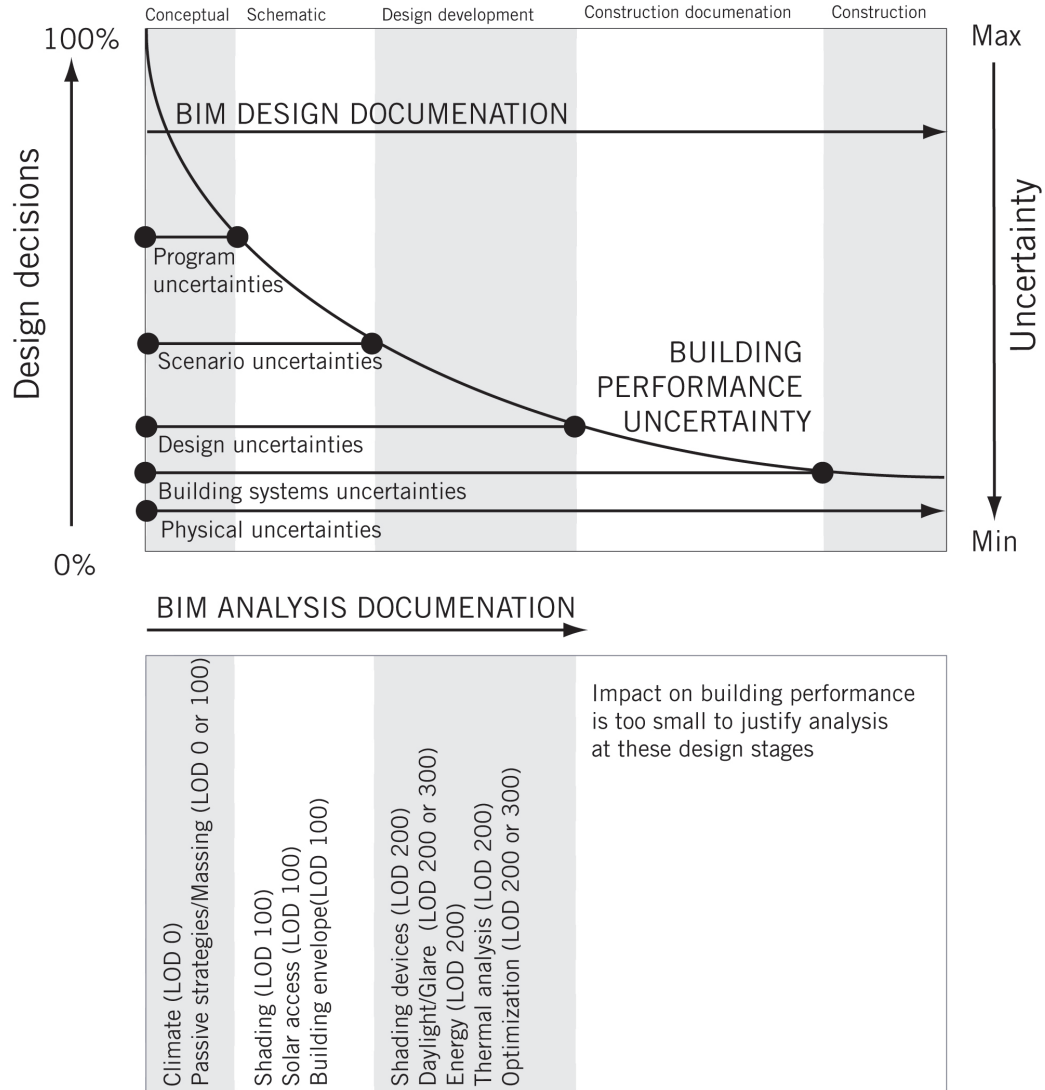


Figure 2: Design decisions and uncertainty for building performance. Relations between “BIM design” and “BIM analysis” process and documentation, indicating recommended level of development (LOD) to be embedded in the BIM models corresponding to each simulation type/analysis.

For example, LOD 100 should include overall building massing, area, height, volume; and can be used to analyze building orientation. LOD 200 includes model elements as generalized systems or assemblies, and may include non-geometric information, such as material properties. BIMs at this stage of development can be used for performance analysis of shading devices, daylight/glare analysis, basic energy analysis, as well as thermal studies. LOD 300 includes model elements that are accurate in terms of quantity, size, shape, location

and orientation, and the amount of information embedded in the models is equivalent to construction documentation. BIMs at this stage of development can be used for detailed daylight/glare analysis, energy analysis, as well as optimization of systems. It is important to note that these types of studies have the greatest impact on the building performance if they are conducted early in the design process (conceptual, schematic and design development).

4.0 METHODS FOR INFORMATION EXCHANGE BETWEEN BIM AND ANALYSIS APPLICATIONS

Best practices for data exchange between BIM and environmental analysis software depend on the analysis objectives and what type of information/data is needed. For example, for determination of building massing that minimizes solar exposure or incident solar exposure on

the facade, data exchange through DXF file format is adequate. For these types of studies, geometric properties of the building massing or component under analysis (for example, part of the facade with shading devices) are sufficient, as developed in LOD 100 model. Examples are shown in Figure 3, where the building massing and form are optimized based on incident solar radiation for different building orientations.

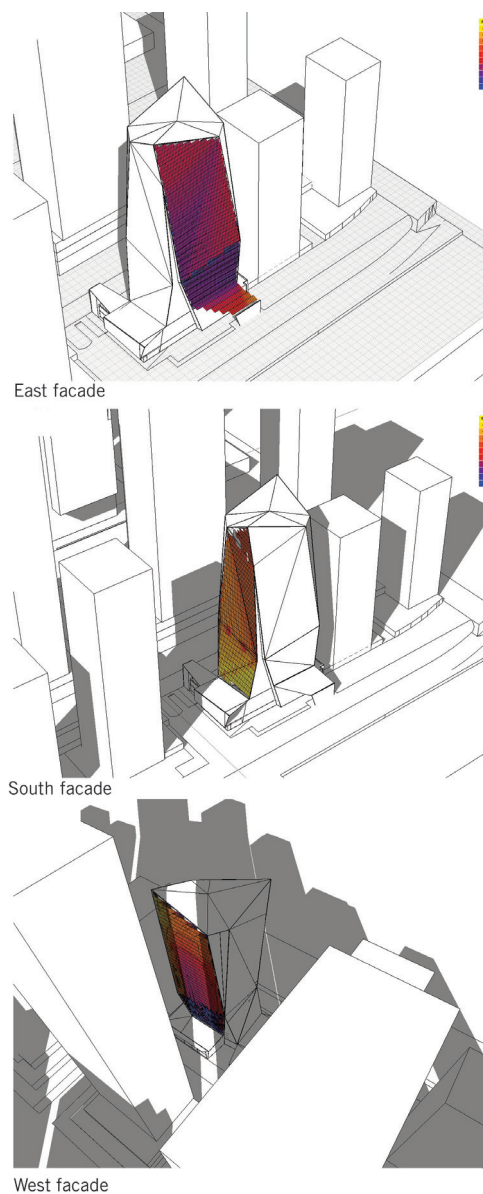


Figure 3: Optimization of building form based on incident solar radiation (LOD 100 model).

For other types of studies, such as daylight or thermal analysis, enriched information about interior spatial organization and zones, material properties and properties of shading surfaces is needed. Therefore, information stored in “design” BIM needs to be exported as “analysis” BIM. For example, Ecotect analysis software is designed to be used during the early stages of the design process and can be effectively used for variety of analysis functions such as shadow analysis, shading, and solar exposure studies. Data exchange between Revit and Ecotect can be performed through Green Building XML (gbXML) schema, a computer language specifically developed to facilitate transfer of building properties stored in BIM to analysis tools.

Basic structure of gbXML consists of elements such as rooms, walls, floors, ceilings, shading surfaces and windows, which inherit properties embedded in the model (actual numeric values) and transfer to analysis applications. The following model parameters are essential for data exchange and are useful in utilizing BIM models for environmental analysis:

1. **Rooms** are the basis of the gbXML file. The hosting structure, location and properties must be specified in the model since all the other data is associated with these elements. Only significant spaces, corresponding to thermal zones, should be defined as rooms. Smaller supportive spaces (elevator shafts, storage spaces, mechanical spaces, etc.) of minimal impact should be grouped. Rooms must be fully bounding, and setting up correct heights and dimensions is important.

2. **Analytical surfaces (Floors, Walls, Roofs):** Building elements must be bounding and connected.
3. **Openings:** Windows and skylights should be defined and their properties and technical details (such as material properties) can be modified in Ecotect (thicknesses, U-values, visual transmittance, solar heat gain coefficient).
4. **Shading surfaces:** Shading surfaces are treated as analytical surfaces (walls, floors or roofs) not bounding a room and are exported as simple surfaces.

These basic elements can be embedded in the model from the earliest stages of the design process (LOD 100), and developed in LOD 200 for studies of different design options and scenarios through environmental analysis. It must be noted that these elements must be properly defined and embedded in the BIM design models if this data exchange mechanism is to be used for translation of building information from design to analysis applications. Also, some modification of translated geometry or element properties may be required in the analysis software application.

Figure 4 shows an example of a Revit file (upper right) with information needed for the analysis imbedded in the model (rooms, their dimensions and properties), which get transferred by gbXML file to analysis engine. The gbXML file containing exactly the same information, but showing a different, data-based view is shown on the left. The lower right image displays analysis model created in Ecotect from the gbXML file.

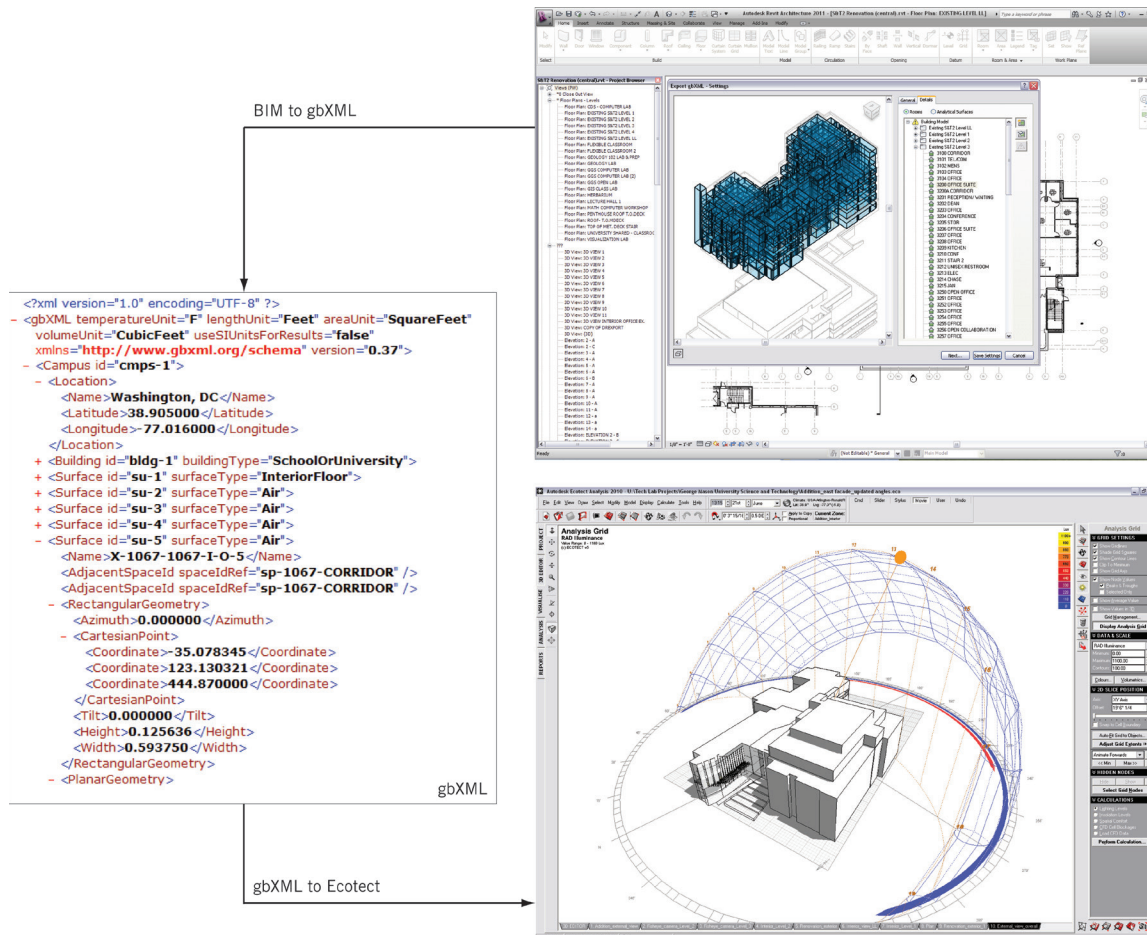


Figure 4: Revit “design” BIM with LOD 200 (upper right); gbXML file structure and data-centric view of the same properties (left); Ecotect “analysis” model generated from the gbXML file (lower right).

5.0 CASE STUDY 1: SIMULATIONS OF DESIGN OPTIONS AND BUILDING PERFORMANCE ANALYSIS

The first case study reviews results of a study that was conducted during the design of a commercial building located in Boston. Building performance analysis and simulations were used during the schematic design to investigate different facade design options, and their effects on energy performance and available daylight. BIM-based and non-BIM based simulation tools were used. For example, EnergyPlus was used for energy modeling, in order to assess the effects of different facade design options on energy consumption. Ecotect was used to study solar exposure for different facade options, and Radiance daylight simulation tool for daylight analysis. The study considered different facade

orientations of the building, and different design strategies for improving energy performance and occupants' visual comfort.

5.1 Facade Design and Energy Modeling

The plan for a typical floor of the building is shown in Figure 5, indicating facade orientations that were investigated. Two different facade types are used along the east orientation (type 1 encloses a double-story atrium, and type 2 encloses single-story office space). South and west oriented facades enclose a double-story atrium space. Three different design options were investigated for each orientation, and specific characteristics are listed in Table 1. In summary, these following scenarios were investigated:

- **East orientation (type 1):**
 - Base case: curtain wall

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- Option 1: curtain wall with 50% of vision area glass covered with ceramic frit pattern
 - Option 2: similar to option 1, with added vertical fins to provide shading
 - **East orientation (type 2):**
 - Base case: curtain wall with spandrel
 - Option 1: similar to base case, with 50% of vision area covered with ceramic frit pattern
 - Option 2: similar to base case, with vertical fins
 - **South orientation:**
 - Base case: curtain wall (Figure 6)
 - Option 1: curtain wall with spandrel
 - Option 2: curtain wall with horizontal shading elements (Figure 7)
 - **West orientation:**
 - Base case: curtain wall
 - Option 1: curtain wall with vertical fins
 - Option 2: curtain wall with horizontal shading elements, identical to option 2 for south orientation.
- All scenarios considered thermally broken aluminum mullions for curtain wall framing, and the properties of the glazing units are listed in Table 2.

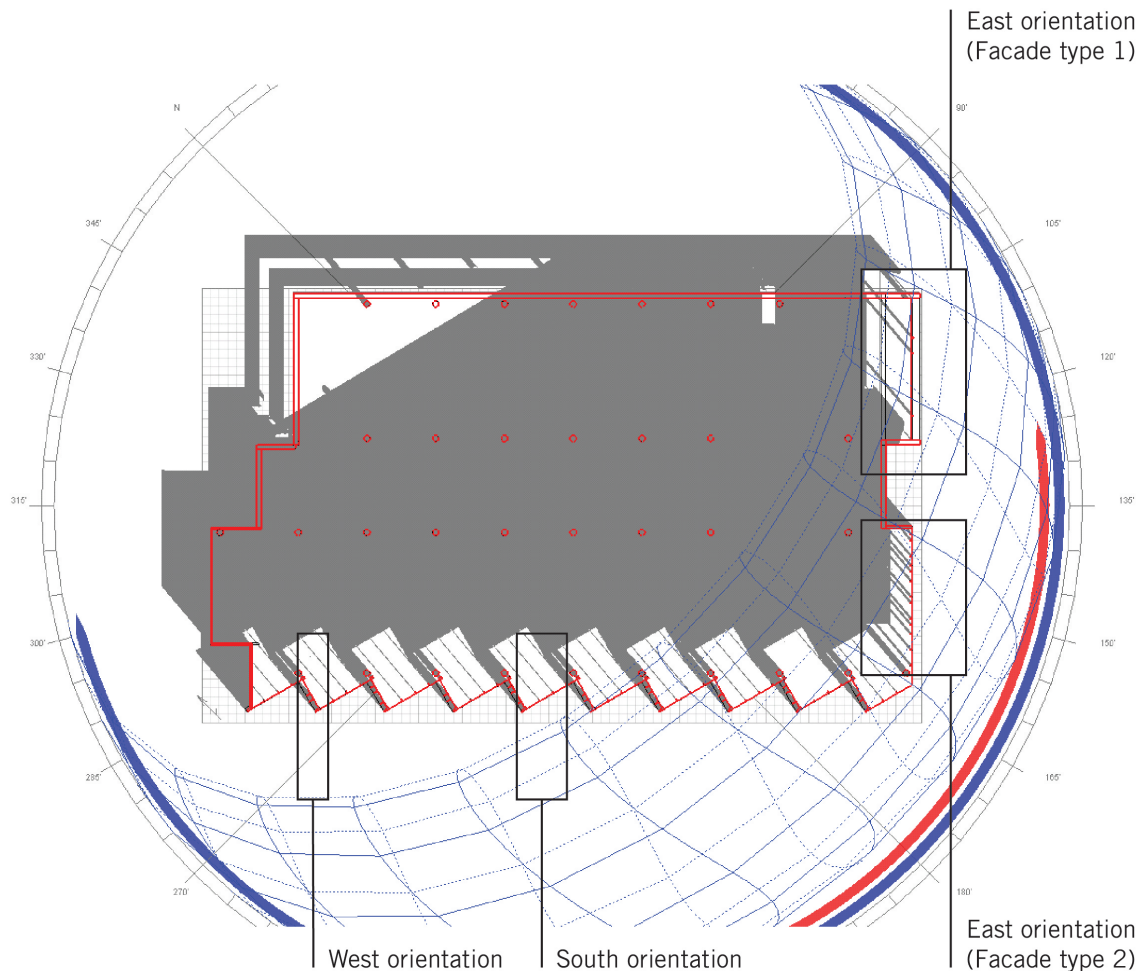


Figure 5: Building plan indicating different facade orientations.

Table 1: Different facade design options considered in the study and their characteristics.

Facade orientation	Design options	Characteristics
East facade type 1 (enclosing two story atrium)	Base case	Fully glazed curtain wall with low-e IGU
	Option 1	Fully glazed curtain wall with low-e fritted IGU (frit pattern covering 50 percent of the vision area)
	Option 2	Fully glazed curtain wall with low-e fritted IGU (frit pattern covering 50 percent of the vision area), and 1.5 ft deep exterior shading elements (vertical fins) spaced 2.5 ft apart
East facade type 2 (enclosing one-story interior space)	Base case	Curtain wall with low-e IGU and 2.5 ft high spandrel with R-17 h-ft ² -F/Btu (window-to-wall ratio 70 percent)
	Option 1	Similar to base case, with added 1.5 ft exterior vertical fins spaced 2.5 ft apart
	Option 2	Similar to base case, with frit pattern covering 50 percent of the vision area
South	Base case	Curtain wall with low-e air IGU (window-to-wall ratio 95 percent), as seen in Figure 6
	Option 1	Curtain wall with low-e IGU and 2.5 ft high spandrel with R-17 h-ft ² -F/Btu (window-to-wall ratio 85 percent)
	Option 2	Curtain wall with low-e IGU, horizontal overhang (3 ft deep) and an interior light-shelf, and horizontal shading elements (0.5 ft wide fins spaced 1 ft apart below the overhang, and 2 ft above the overhang), as seen in Figure 7
West	Base case	Curtain wall with low-e IGU (window-to-wall ratio 95 percent)
	Option 1	Curtain wall with low-e air IGU and 1.5 ft deep vertical fins spaced 2.5 ft apart
	Option 2	Curtain wall with low-e IGU, horizontal overhang (3 ft deep) and an interior light-shelf (also 3 ft deep), and horizontal shading elements (0.5 ft wide fins spaced 1 ft apart below the overhang, and 2 ft above the overhang), identical to south facade option 2

Table 2: Properties of the glazing units.

Glass properties	Base case	Options 1 and 2 (fritted glass)
U-value (Btu/h-ft ² -F)	0.29	0.29
SHGC	0.38	0.60
Visual transmittance	0.70	0.48

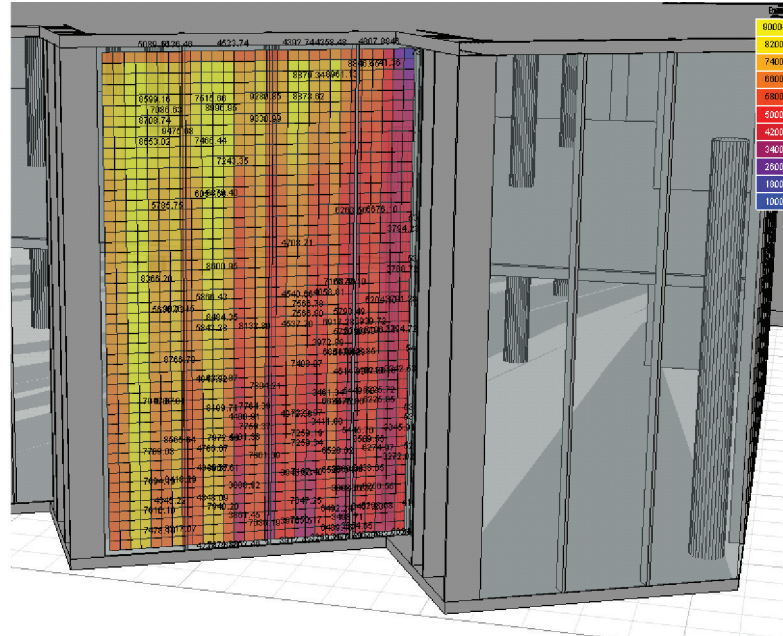


Figure 6: Incident solar radiation for south-oriented facade (Base case).

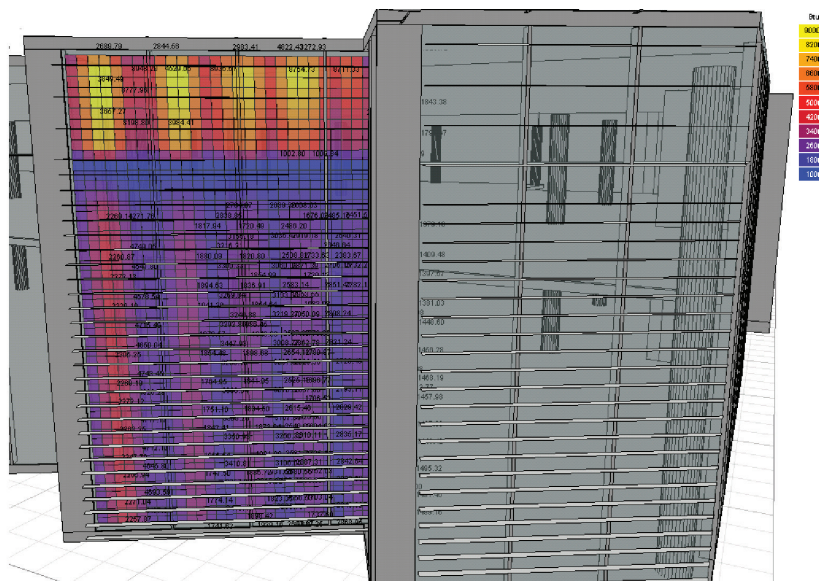


Figure 7: Incident solar radiation for south-oriented facade (Option 2).

Figures 6 and 7 show incident solar radiation for the south facade (base case and option 2 with horizontal shading elements). Ecotect simulation software was used to calculate incident solar radiation for these sce-

narios, and results indicate that horizontal shades work really well in reducing incident solar radiation for this facade. Figure 8 shows results for hourly solar heat gain (all three options for south facade).

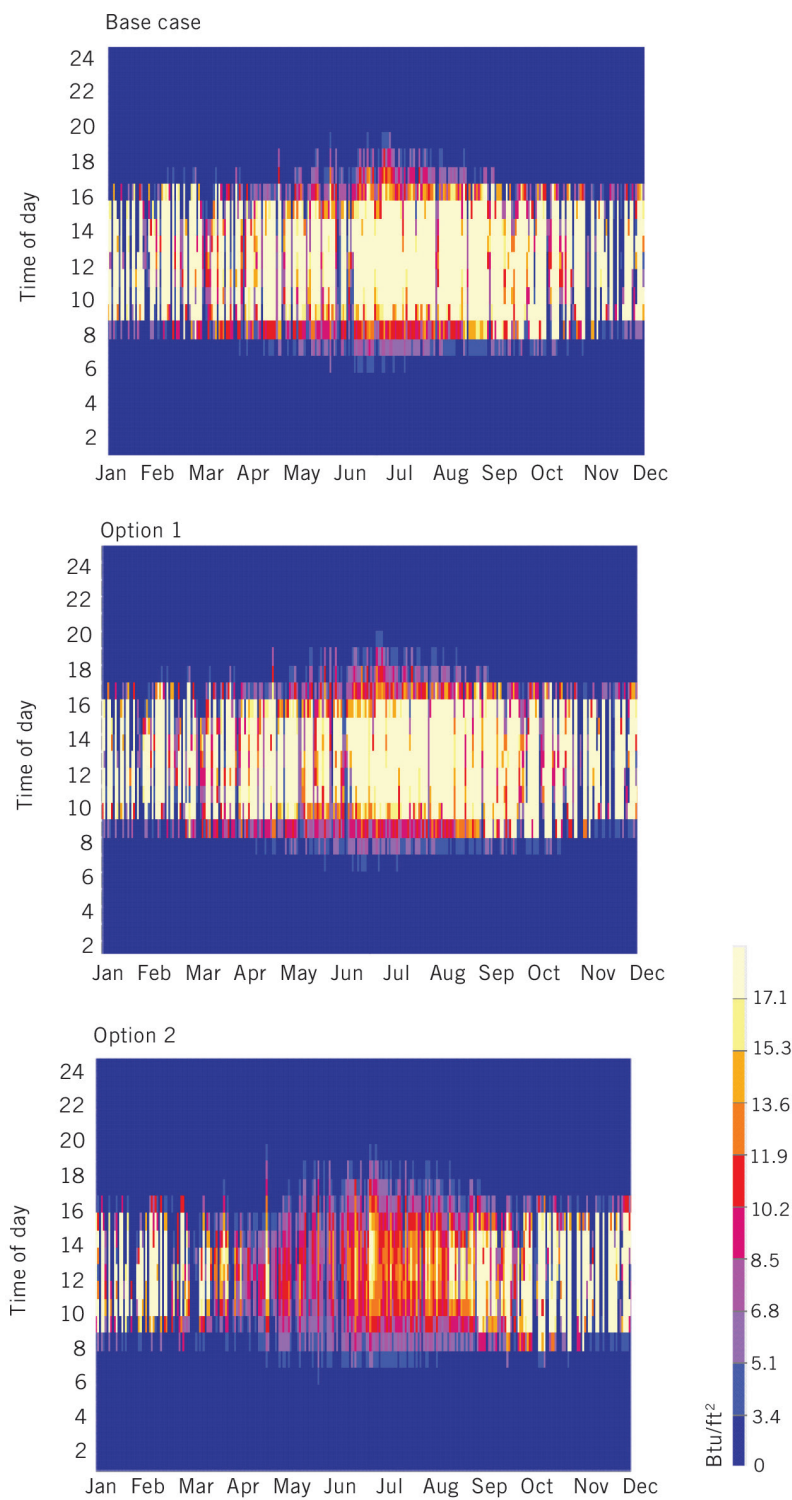


Figure 8: Comparison of hourly solar heat gain for south-oriented facade design options.

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Figure 9 shows summary results for energy consumption for all building orientations and design options. These simulations were performed using EnergyPlus, which is non-BIM based energy modeling software. The

results indicated that options 2 would be the best design scenarios (all four orientations) for improving energy performance.

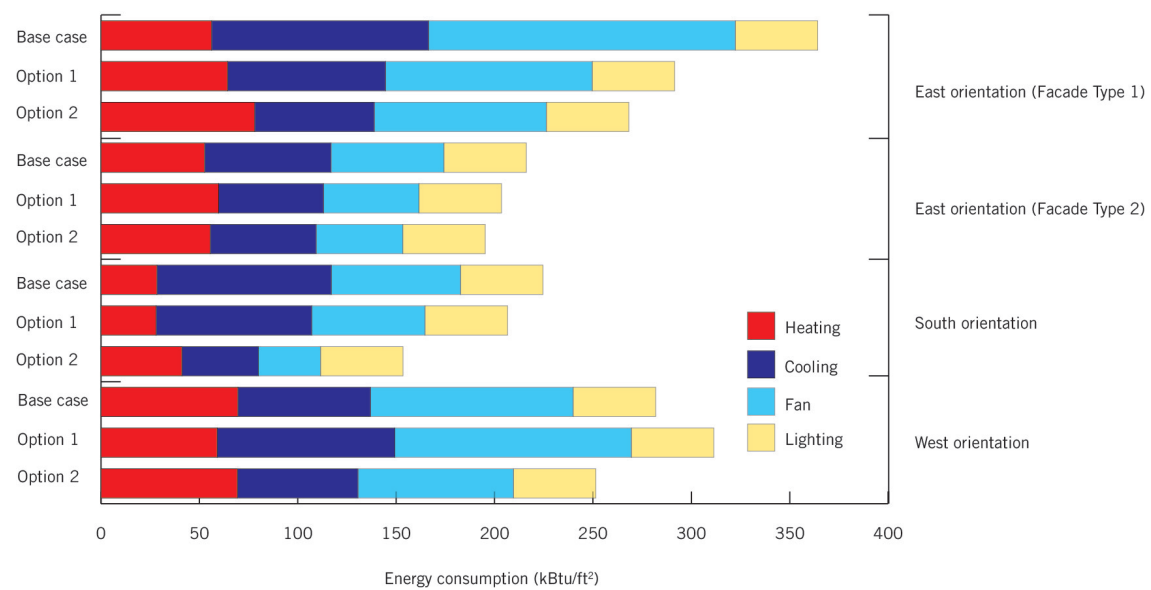


Figure 9: Comparison of energy consumption for all design scenarios.

5.2 Daylight Analysis

Daylight simulations were performed to investigate availability of natural light reaching the interior space. Since it was found that the best-performing design scenarios for the south and west orientations include horizontal overhang, horizontal shading elements and a light-shelf for reducing energy consumption, these design options have been used to study availability of natural light. They were compared to two other design options:

- **Base case:** flat south-west facade
- **Option 1:** serrated south-west facade without any shading elements or light-shelves
- **Option 2:** serrated south-west facade with a 3 ft deep horizontal overhang, horizontal shading elements (0.5 ft wide fins spaced 1 ft apart below the overhang, and 2 ft above the overhang) and 3 ft deep interior light-shelf.

Daylight analysis was performed for September 21 at noon, with sunny sky conditions, using Radiance simulation software. This date was selected in order to investigate representative conditions for fall equinox, and this specific time was selected based on the relative orientation of the analyzed space. Daylight simulations can also be performed for other times of the year (such as June 21 for summer, and December 21 for winter conditions).

Since this facade adjoins two-story interior space, the purpose of the analysis was to compare daylight levels on both levels. Specifically, light redirecting mechanisms for the office space located on the second floor were investigated, since this space is located approximately 20 ft from the facade, and is separated from the atrium by a glass partition wall. These different options are shown in Figure 10, as well as the daylight simulation results.

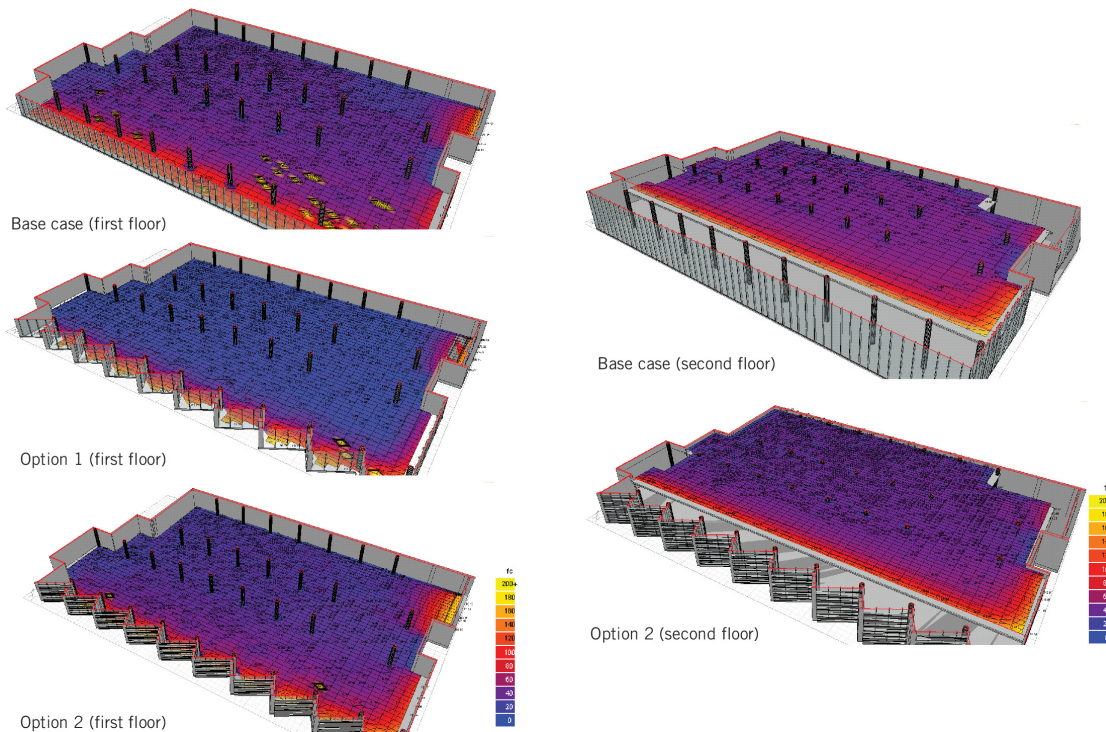


Figure 10: Design options and daylight levels.

Generally, the base case scenario has highest daylight levels along the first floor; however, this option is the worst from energy performance perspective. Comparison between options 1 and 2 shows that option 2 would provide more daylight, since the shading elements and a light-shelf would redirect light within the interior space. For the second floor, daylight levels are compa-

table for both options, although the actual values are higher for the base case scenario. Since option 2 is the best performing design scenario in terms of energy performance, the addition of light-shelves would balance the effects of shading elements on the availability of natural light. Figures 11 and 12 show detailed results of the daylight analysis.

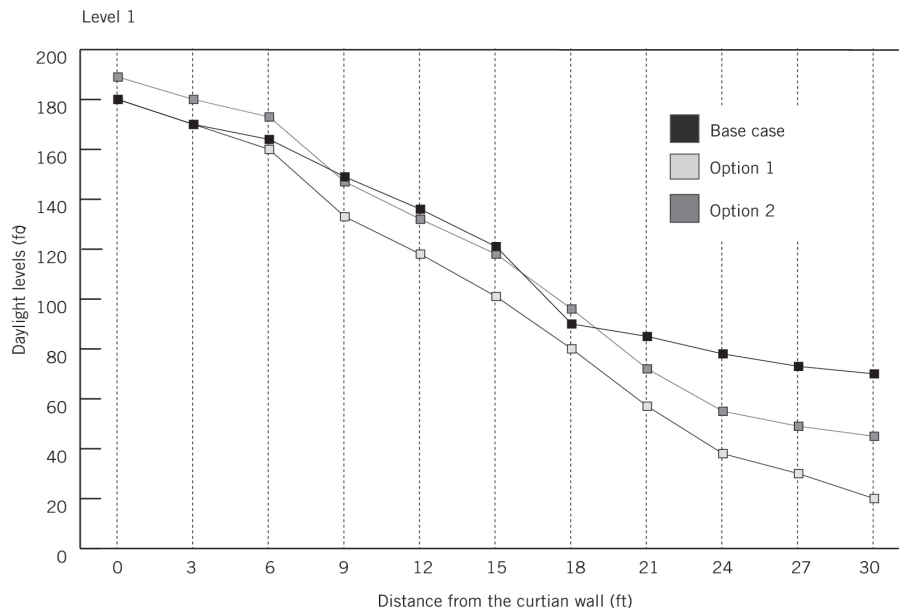


Figure 11: Daylight analysis results (first floor, September 21 at noon).

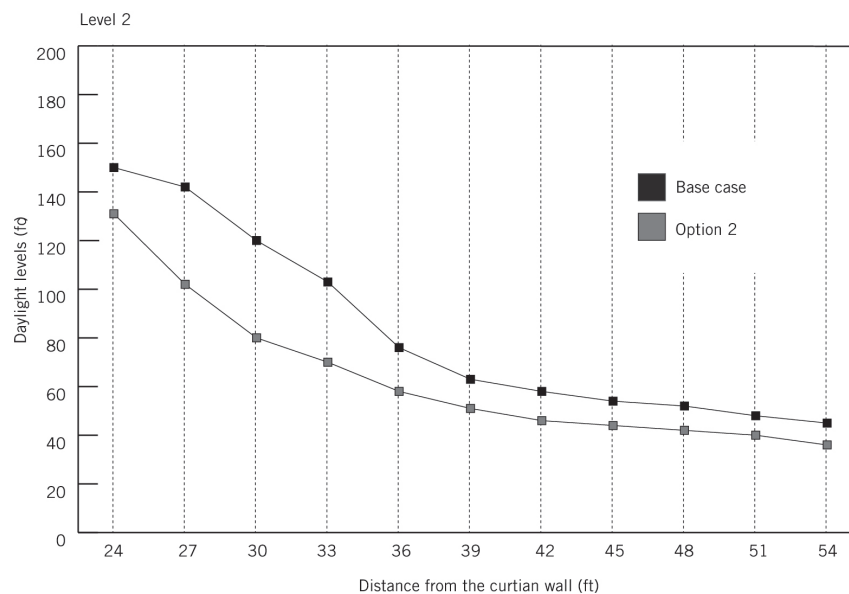


Figure 12: Daylight analysis results (second floor, September 21 at noon).

This case study illustrates how research process, as well as use of building performance analysis can be beneficial for design decision-making. Having these results and quantifiable data allowed the design team to make informed decisions regarding the facade treatment for this specific project, as well as daylight harvesting strategies. At the same time, documenting results and sharing research processes, objectives and results is beneficial for the design community at large since these results can also be applied to other similar projects or design problems.

The next case study reviews how advanced computational design approaches that use analytic data for parametric modeling can be beneficial. Currently, while data exchange between BIM and analytical software can be accomplished, importing the results of the analysis back into the BIM and controlling the geometry of its elements based on the results is extremely challenging. Therefore, custom applications, advanced computational design tools and methods that fully integrate BIM design and analysis software programs are necessary to accomplish this.

6.0 CASE STUDY 2: PARAMETRIC DESIGN, BIM AND PERFORMANCE ANALYSIS

Using analytic data as a driver to parametrically control the geometry of BIM elements is currently a promising method for modeling design elements, such as sun shades, that respond to environmental constraints, such as incident solar radiation or solar angles. This can be done qualitatively, but evaluating multiple options with many variables can be time consuming. A preferred method is to use analytical data, coming from applications such as Ecotect, to parametrically control BIM elements. A previously published article reviewed in detail customization of the Autodesk Revit BIM authoring software to allow for data exchange between BIM design and analytical applications (Revit and Ecotect), where analytic data is used to control the geom-

etry of BIM families¹³. Major points and findings are summarized in this section, and a specific case study is discussed to illustrate innovative approach for parametric modeling and data-driven form optimization based on environmental analysis data.

A BIM provides a common database of information about a building, including its geometry and attributes. It is an integrated, comprehensive building model that stores the information contained in traditional building documents, such as drawings, specification, and construction details, as well as additional 3D information and metadata, in a centralized or distributed database. The goal of BIM is to provide a common structure for information sharing that can be used by all agents in the design process and construction. It virtually simulates design and construction, and provides groundwork for collaborative design, since all the relevant information, such as spatial organization, building components, building systems (mechanical, electrical, plumbing, HVAC) can be incorporated into building descriptions.

Typical workflow and data exchange between BIM and environmental analysis applications requires export of model geometry from BIM to analysis applications, as discussed in previous sections of this article. Appropriate methods for data exchange between BIM and environmental analysis software depend on the analysis objectives and what type of information/data is needed.

As stated above, data exchange between BIM and analytical software can be accomplished, but importing the results of the analysis back into the BIM and controlling the geometry of its elements based on the results is challenging. Therefore, a custom-built plug-in for the Revit platform was developed that allows import of analytical results, such as solar radiation, into BIM design model¹³. It enables importing of data via Excel spreadsheets and parametric control of Revit families based on the numeric values contained in the imported data. The process is shown in Figure 13.

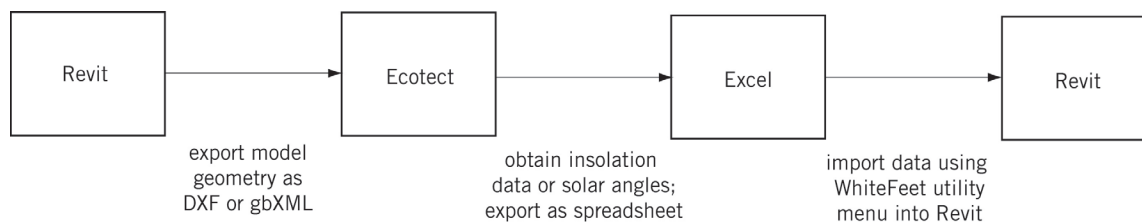


Figure 13: Process diagram showing data exchange between different applications for parametric control of BIM elements based on performance analysis data.

It was tested in relation to building envelope design, as seen in Figure 14, specifically focusing on optimizing design of shading devices along a complex surface based on solar radiation data obtained from Ecotect. In order to align the Ecotect data with individual instances of Revit panel families, several instance parameters can be created within the family. This allows the subdivision of families to be logically ordered in order to align them with Ecotect. After creating a surface in the conceptual design environment, the surface can be subdivided into a desired number of divisions, which can then be exported into a DXF file. This geometry can be imported into Ecotect to analyze incident solar radiation, and obtain solar radiation values based on building location and specific orientation of the panel. These values can be exported from Ecotect into an Excel spreadsheet, as

seen in Figure 14. Once the solar radiation data is obtained and imported in Excel spreadsheet, it must be normalized based on minimum and maximum solar radiation values (in this case, it is normalized into values from 0 to 1). This normalized data is imported into Revit using WhiteFeet utility menu, and used to control the geometry of Revit panel families. This is achieved by matching the normalized values to the correct panel position on the complex curved surface, and using the normalized value from 0 to 1 to control the position and geometry of the shading element relative to the center-point of each panel. The resultant is shown in Figure 15, showing a surface where the shading elements for the curtain wall panels respond to solar radiation striking this surface.

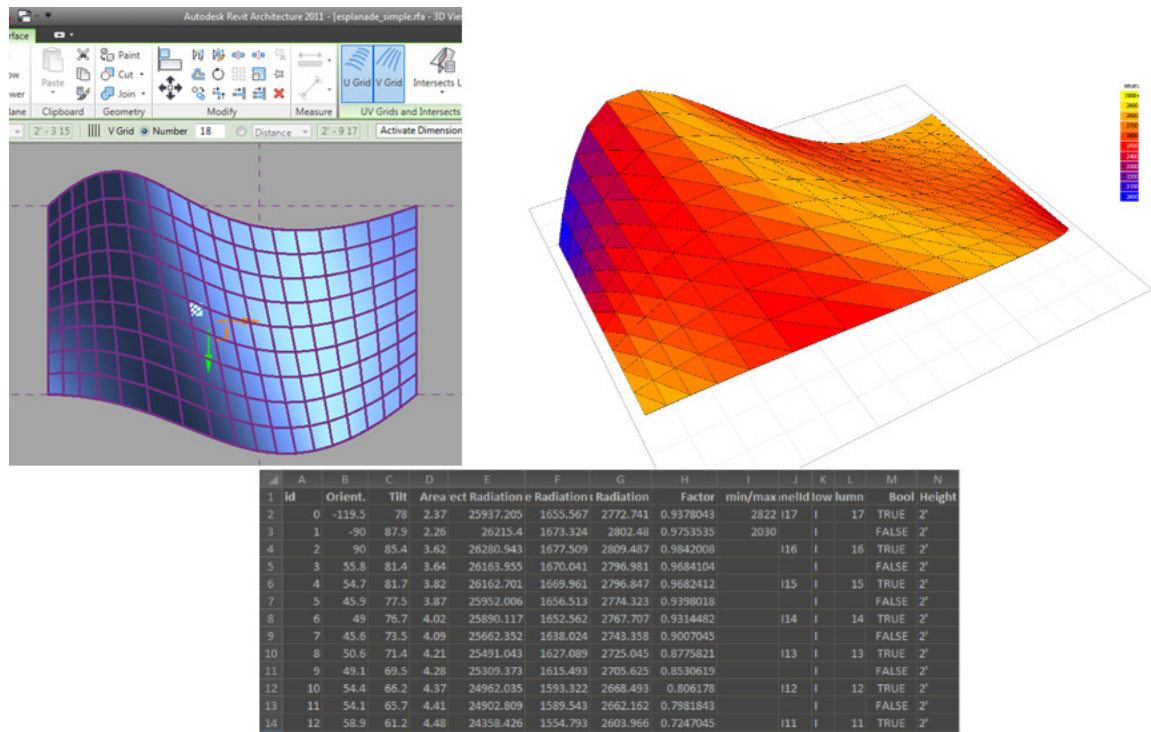


Figure 14: Example of curved surface in Revit and solar radiation analytic data from Ecotect, used to parametrically size and position shading devices along the curved surface.

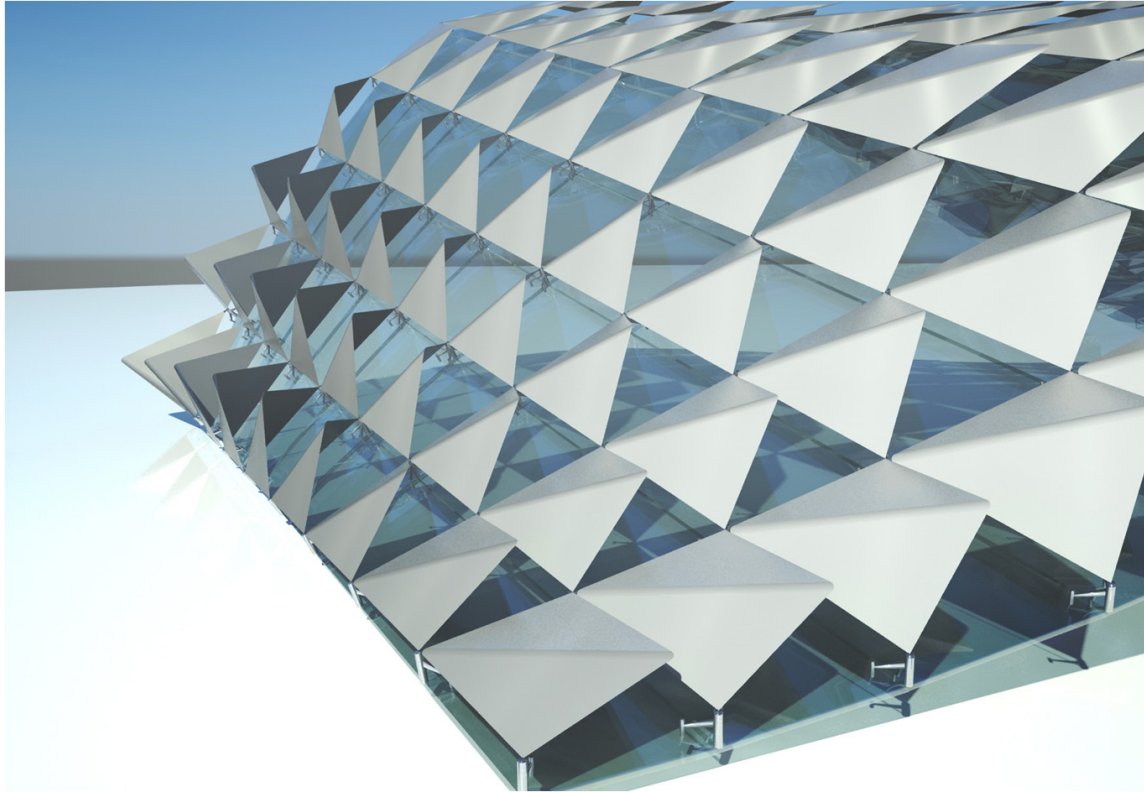


Figure 15: Example of parametric control of shading elements in Revit.

7.0 CONCLUSION

This article discussed relationships between building simulations and design process, and how performance predictions can assist in identifying strategies for reducing energy consumption and improving building performance. The first part of the article discussed why we need to “quantify” design decisions—in order to achieve extremely low and net-zero energy buildings, quantifiable predictions are needed at every step of the process, which evaluate the benefits of using passive strategies, advanced building technologies and renewable energy sources. We need to quantify the benefits of each individual methodology, and relate them to a specific design problem, building, its climate and the context. We also discussed objectives of Perkins and Will Tech Lab and its research projects. Tech Lab’s primary research methods include computational simulations and modeling, where different design scenarios are investigated, as well as their effects on building performance.

We also reviewed methods for data exchange between BIM and environmental analysis software applications, emphasizing the importance of differentiating between “design” BIM models and “analysis” models. Interoperability between BIM-based design and simulation tools can improve the workflow between design documents and analysis applications, where information contained in the models can be used for analysis process as well. However, BIM-design model and the BIM-analysis model need to be managed and properly developed, considering the LOD and the required information necessary for performance analysis. It is important to track what type of information is needed for a particular analysis, and how effectively to use BIM to simulate design decisions. We also demonstrated this by reviewing two specific case studies. The first case study discussed building performance analysis that was performed during the design of a commercial building, methods and results. The second case study discussed advanced computational design methods for integration of environmental performance data with the design.

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