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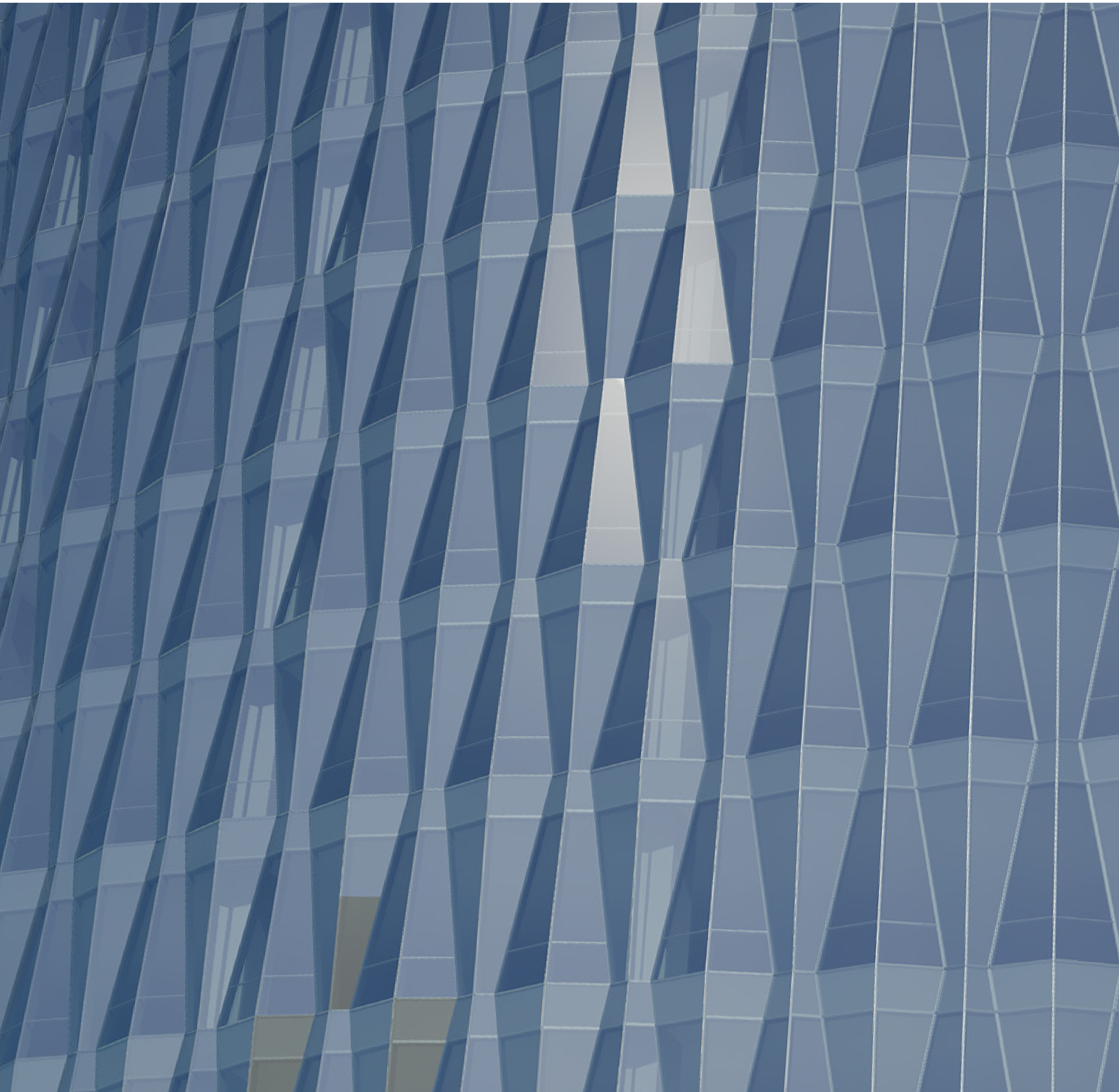

01.
BUILDING PERFORMANCE PREDICTIONS:
How Simulations Can Improve Design Decisions

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ABSTRACT
This article discusses relationships between building performance simulations and design decisions and how building performance predictions can improve the design outcomes. The first part of the article discusses why we need to quantify building performance and predict how a building as a whole or its components will function. Then, relationships between Building Information Modeling (BIM) and analysis software applications are discussed, where best practices for developing BIM models that are suitable for different types of simulations are discussed. Lastly, two case studies are used to illustrate this process. The first study reviews curtain wall energy performance for a healthcare facility located in a mixed humid climate and daylighting analysis. The second case study discusses comprehensive analysis for an academic research building focusing on site and orientation studies, solar exposure, investigation of performance of shading devices and daylighting analysis.

KEYWORDS: building envelope, energy efficiency, daylight, BIM, solar exposure

1.0 INTRODUCTION

Developments in information technology are providing methods to improve current design practices, where uncertainties about various design elements can be simulated and studied from the initial starting point of the design. Energy and thermal simulations, improved design representations and enhanced collaboration using digital media are currently being utilized. In terms of sustainable design practice, building performance simulations are an integral part of the process since they help in investigating design options[1]. Quantifiable predictions can help in identifying strategies and methods to improve building energy efficiency and overall building performance.

Methods for achieving extremely low-energy 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, under-floor air distribution, dynamic windows (electrochromic glass, suspended particle devices), radiant heating and cooling and combined heat and power systems. Figure 1 shows these design strategies in relation to the overall cost. Passive strategies should be utilized to its 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. Quantifiable predictions during the different stages of design process help establish metrics that can be used to measure improvements by using 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 thereby reducing the need for renewable energy systems.

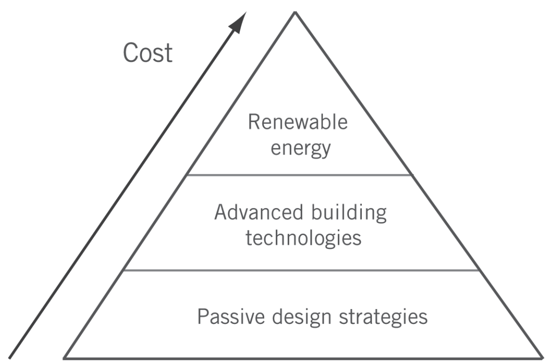


Figure 1: Design strategies for low and net zero energy buildings in relation to cost.

This strategy is applicable for the design of low energy buildings and currently is a viable approach for achieving net zero energy buildings, as it was found by a recent study[2]. The study considered buildings contained in the Commercial Buildings Energy Consumption Survey (CBECS) 2003 database, which includes energy consumption data, energy sources, costs and building characteristics for all US climate types[3]. Building types in the CBECS database include educational facilities, food sale and service facilities, healthcare, hotels, retail, office spaces, public assembly, public order and safety, religious buildings, service buildings and warehouses.

Research method included prediction of lowest energy usage for all of the building types in CBECS database by modeling energy requirements. The study considered currently available building technologies and projections of future improvements in building systems. Also, the study considered inclusion of photovoltaic systems, and the percentage of buildings that can meet zero energy goals. It was found that 62 percent of current commercial sector could reach net zero energy goals by 2025. Figure 2 presents results of the study, represented by the number of buildings and floor area. These following characteristics indicate scenarios that were investigated and energy-efficiency measures:

- Base and photovoltaic system: examined current commercial building stock by applying performance criteria complying to ASHRAE Standard 90.1-2004 and photovoltaic system covering 50 percent of roof area for every building.
- Low energy buildings: examined what can be achieved when current practices are applied (passive and advanced building technologies).
- Low energy buildings 2025: predicted energy savings of low energy buildings with higher component performances reflecting advancements in technology (increase in PV performance, improvements in HVAC systems, reductions in lighting power density).
- Low energy buildings 2025 and reduced lighting

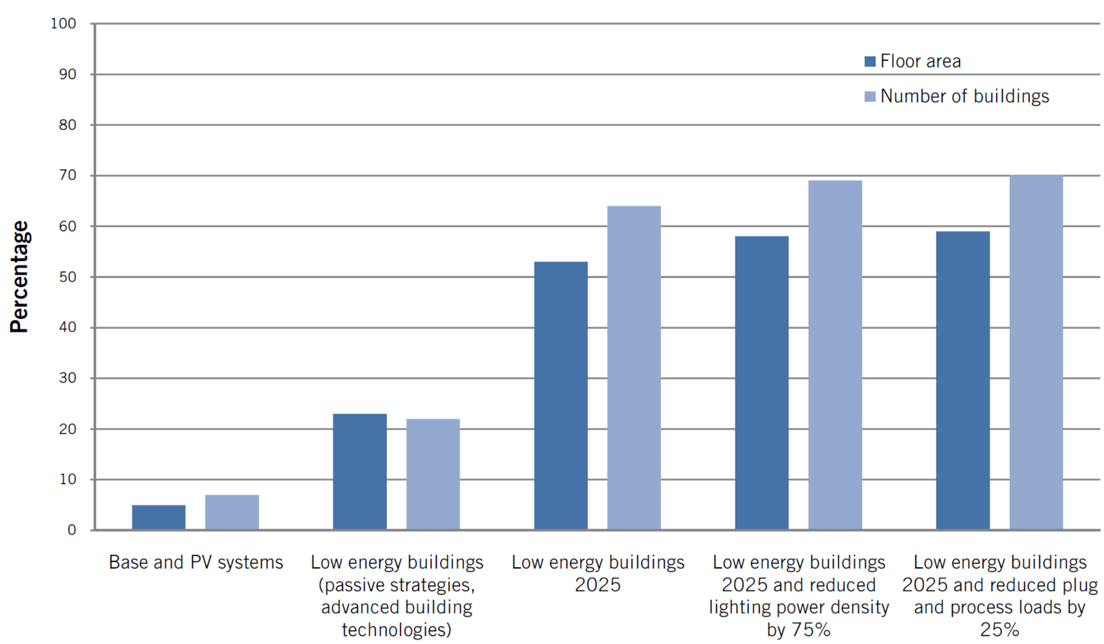


Figure 2: Percentage of US commercial sector that can reach zero energy goals.

- power density by 75 percent: similar to option above with increased reduction of lighting power density.
- Low energy buildings 2025 and reduced plug and process loads by 25 percent: examined reduction in energy use by appliances and electrical equipment compared to other models.

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 why we need quantifiable predictions, followed by the discussion of climate-driven design strategies. Then, relationships between Building Information Modeling and analysis software are discussed, particularly focusing on the best practices for developing models that are suitable for different types of simulations and workflow between BIM and analysis software applications. Lastly, two case studies are discussed to illustrate this process. The first study reviews curtain wall energy performance for a healthcare facility located in a mixed humid climate and daylighting analysis. The second case study discusses comprehensive analysis of an academic research building, focusing on solar exposure studies based on building orientation, investigation of performance of shading devices and daylighting analysis.

2.0 BACKGROUND AND LITERATURE ON BUILDING PERFORMANCE ANALYSIS

2.1 Why Do We Need to Quantify Our Design Decisions?

Past research on the utilization of simulation tools during the 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

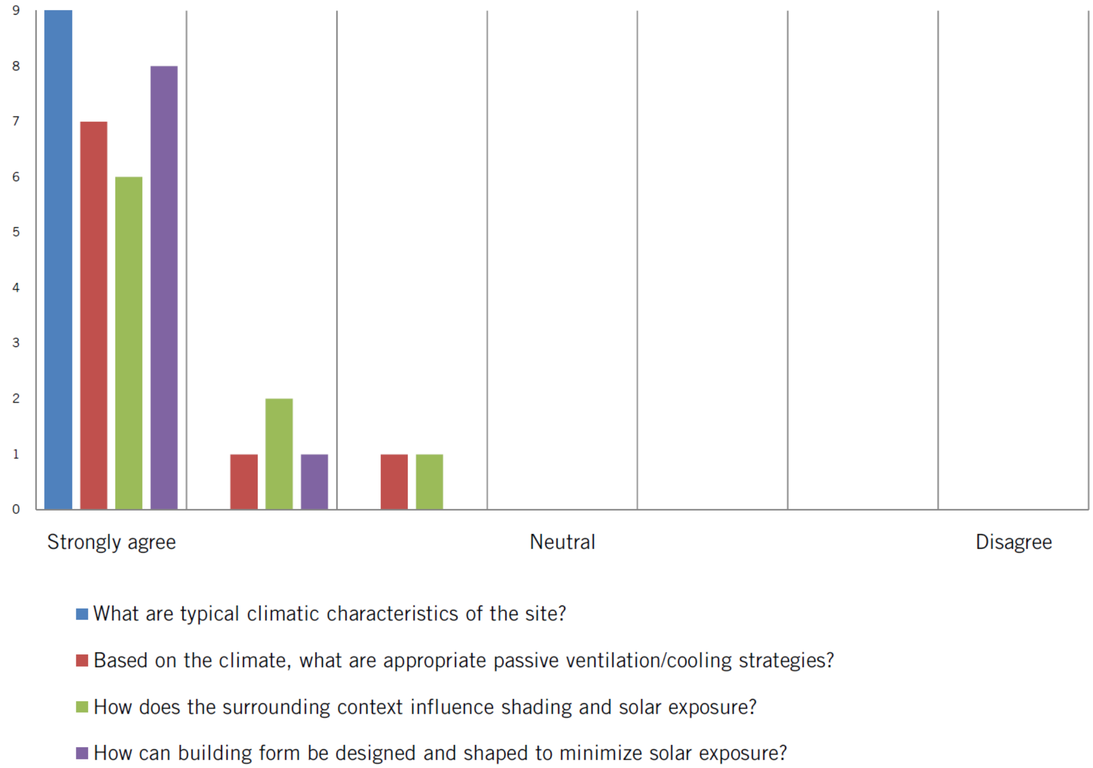


Figure 3a: Survey results rating importance of different questions during conceptual design phase.

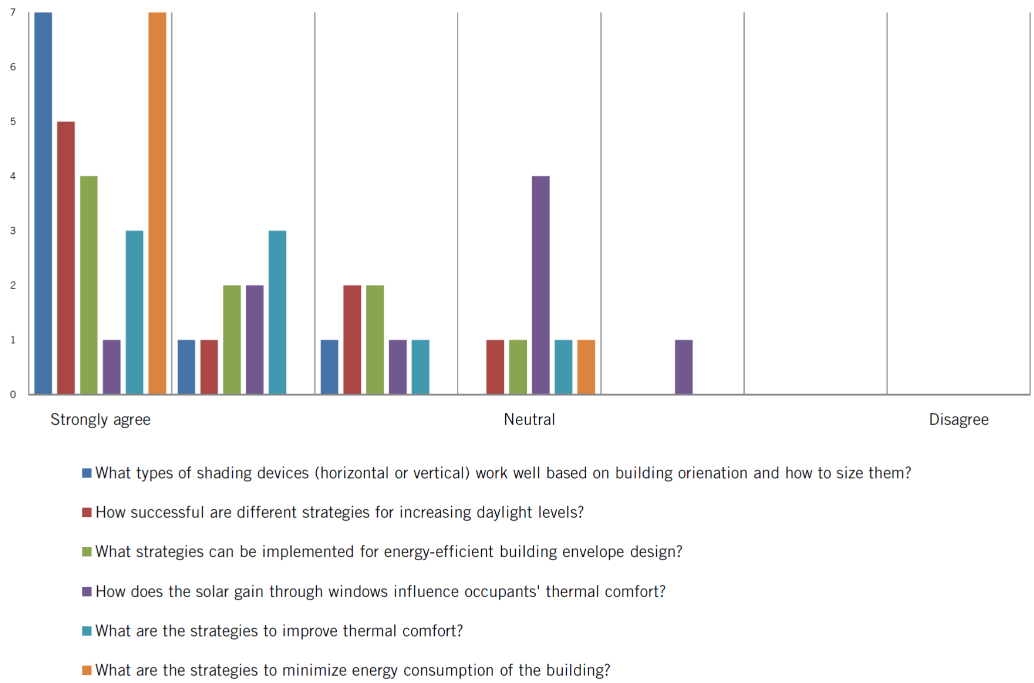


Figure 3b: Survey results rating importance of different questions during schematic design phase.

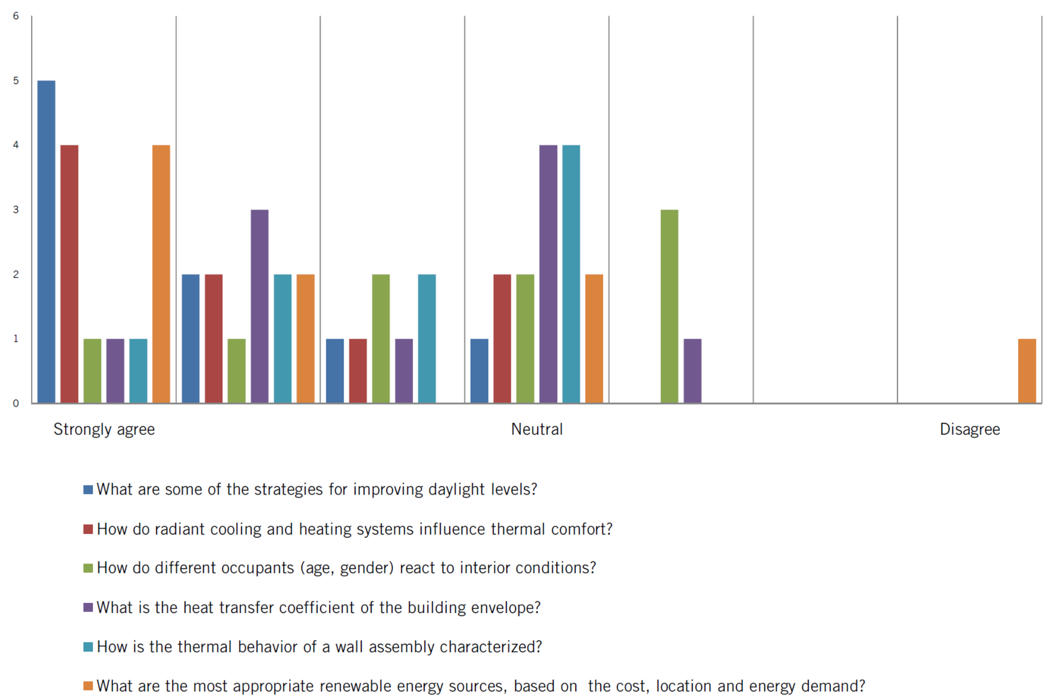


Figure 3c: Survey results rating importance of different questions during design development phase.

with the working methods and needs or the tools are judged as complex and cumbersome[4, 5]. To remain competitive, design professionals must weigh the value of information gained through simulation tools against the invested time, resources and the value of comparable information that might be gained through the use of other or no tools[6].

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. As it is shown in Figure 1, the objectives for attaining extremely low and zero energy buildings rely on several strategies including the use of passive methods, advanced building technologies and renewable energy sources. Therefore, we need to quantify the benefits of each individual methodology and relate them to a specific design problem, building, its climate and the context. Quantifiable predictions during the different stages of the design process help establish metrics that can be used to measure improvements by using these different strategies.

A survey has been conducted at two Perkins and Will offices to investigate relative importance of typical questions raised during the design process that can influence building performance. The objective of the questionnaire was to assess applicability of analysis tools and their relevance in helping address or answer these questions. The survey instructed respondents to rate the relative importance of each question on a 7-point Likert scale indicating whether they agree or disagree that this specific aspect is important during the specific design phase and whether analysis tools should be used to establish specific metrics.

Figure 3a shows questions associated with the conceptual design phase (influences of climatic characteristics, appropriate cooling strategies, surrounding context and solar exposure and derivation of the building form to minimize solar exposure). The majority of respondents agree that these aspects are important for the design and that analysis tools should be used to help during the design process.

Figure 3b shows questions that are associated with the schematic design phase (dimensioning and selection of shading devices, methods for improving daylight levels, strategies for designing energy efficient building envelopes, effects of solar heat gain and strategies to minimize overall building energy consumption). For these questions, the majority of the respondents have indicated that selection of shading devices and determination of their typology (vertical versus horizontal types and dimensions) and determination of strategies to minimize overall energy consumption of the building are very important. Strategies for designing energy efficient building envelopes and methods for improving daylight levels have also been identified as important parts of the design. These aspects require quantifiable predictions and simulations in order to have a significant impact on the design rather than relying on rules-of-thumb.

Figure 3c shows responses and questions that are associated with the design development phase. The types of questions focus on advanced methods for improving daylight levels, thermal comfort and influence of radiant cooling and heating systems, thermal behavior of exterior building envelopes and selection of renewable energy sources. Reponses show that the most important aspects are advanced methods for improving daylight, strategies for improving occupants' thermal comfort and selection of appropriate renewable energy systems. Again, all of these aspects require predictions through simulations, especially in this stage since more information about the design is available.

2.2 Climate-Driven Design and Impact of Simulations

The starting point for the schematic design is site analysis, where environmental factors are systematically examined. Typical information about environmental conditions of the site includes topography, context, solar orientation, climatic characteristics, surrounding structures and infrastructure[7]. 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-dominated. While passive solar gain can be harnessed to decrease heating demand in winter, gains during summer months create the need for cooling.

In a climate-sensitive design approach, it is necessary to account for local solar radiation, temperature, wind and other climatic conditions. Different design strategies are required for different climatic regions and basic concepts that are suited for a particular climate type are outlined in Table 1. Heating dominated climates can benefit from solar collection and passive heating, heat storage and conservation through improved insulation and use of daylight to reduce lighting demand. For cooling-dominated climates, opposite strategies can be applied, where protection from sun and direct solar

Table 1: Climate-dependent design strategies.

Climate type	Design strategies that can achieve reductions in energy demand
Heating-dominated climates	Solar collection and passive heating: Collection of solar heat through the building envelope Heat storage: Storage of heat in the mass of the walls and floors Heat conservation: Preservation of heat within the buildings through improved insulation Daylight: Utilization of natural light sources
Cooling-dominated climates	Solar control: Protection of the building from direct solar radiation Ventilation: Movement and replacement of air within occupied spaces Minimization of internal gains: Reduction of heat from occupants, equipment and artificial lighting Reduction of external gains: Protection from solar heat gain by infiltration (factor for building enclosure design), and conduction (factor for shading design) Cooling: Possible utilization of natural ventilation where climatic characteristics and building usage permit this method Daylight: Utilization of natural light sources while minimizing solar gain by utilization of shading devices and light-shelves
Mixed climates	Solar control: Protection of the building from direct solar radiation during warm seasons Solar collection and passive heating: Solar collection during cold seasons Daylight: Utilization of natural light sources

radiation is advantageous as well as reduction of internal and external heat gains, use of natural ventilation where permissible and use of daylight. In mixed climates, combined strategies need to be implemented balancing solar exposure and access to daylight.

Daylighting and shading are one of the aspects of façade design for high-performance building facades. Facades not only offer the aesthetic look and the building's architectural expression, but should be advantageously used to control the internal conditions of the building. Methods for design of high-performance building envelopes include:

- Enhanced sun protection and cooling load control while improving thermal comfort and providing most of the needed light with daylight.
- Enhanced air quality and reduced cooling loads using natural ventilation schemes employing the façade as an active air control element where permissible.
- Reduced operating costs by minimizing lighting, cooling and heating energy use by optimizing the daylighting and thermal trade-offs.

There are several key parameters that influence performance of building façades, but location and climate are prevailing considerations. Design strategies need to adapt according to the climatic conditions and take into account local characteristics in order to minimize loads and energy consumption. Perfection of a building envelope design depends on the appropriate solutions for the various parameters of visual, thermal and acoustical comfort[8].

Maximum advantage of daylight can be achieved by shaping the plan arrangement of a building to suit the activities within by properly sizing windows and by including light-shelves and selecting interior material finishes that reflect light. Spaces that utilize control systems for artificial lighting (occupancy sensors and photosensors) can significantly reduce lighting loads, accounting for 25 to 40 percent of energy savings for interior lighting[9]. Daylight simulations can help in selection of appropriate strategies, especially for mixed climates since provision of shading devices can negatively affect availability of natural light.

Reinhart and Fitz conducted a study on the utilization of daylight simulations and their impact on building design[10]. A survey was administered to architectural designers (31 percent), engineers (38 percent), researchers (23 percent) and other building professionals (8 percent) totaling 169 participants. Results show that utilization of simulation tools for assessment of daylight potentials was significantly higher during design development than during schematic design and that shading types and controls were the number one design aspects that were influenced by the daylighting analysis. Also, window size, glazing type and choice of lighting controls were identified as important aspects that can benefit from daylighting analysis, followed by building orientation, interior surface properties and room dimensions.

2.3 The Need for Integrating Analysis into the Design Process

In order to evaluate and optimize building performance, different analysis cycles should be part of an integrated design process. Figure 4 shows the basic types of performance analysis in relation to the project stages, particularly focusing on building envelope design. The top part of the diagram shows the impact of decisions on actual building performance and relationships to project stages. As can be seen, as early as the programming

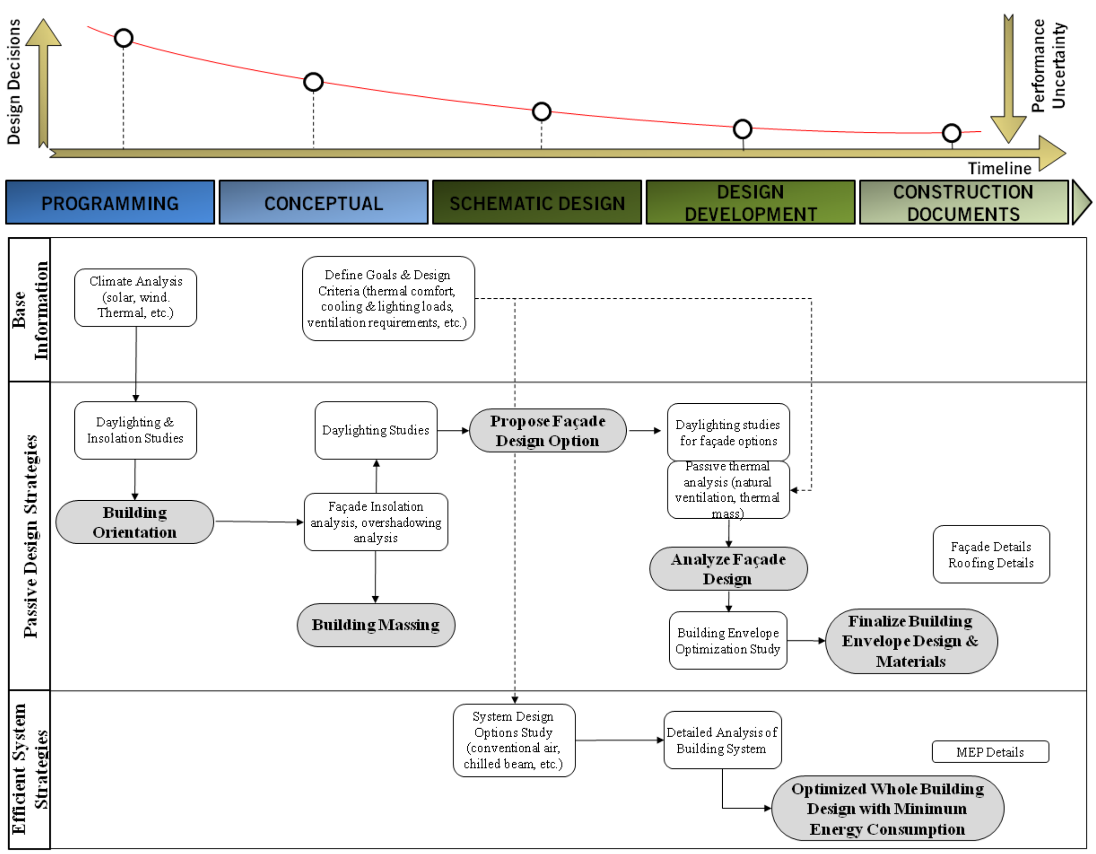


Figure 4: Design performance analysis flow with a focus on building envelope optimization (Adapted from Kohli, 2008)[11].

phase the analysis focuses on the bigger design picture such as climate information, orientation and building massing. Then, at conceptual and schematic phases the analysis observes the whole sun shading method proposed for the façade in alignment to overshadowing of surrounding buildings. Generally, an iterative cycle of different design options of sun shades are analyzed as well as daylighting studies. The decisions here are of high impact on the design because they influence the exterior design character of the project, potential energy use reduction and affect the comfort levels inside the spaces.

The design method that integrates energy and environmental analysis at early design stages suggests a procedure to follow in order to reach a particular solution to a design problem. This is a challenging paradigm when comparing between the traditional and building performance-based design methods:

1. *Traditional Method:* has some deficiencies because: (1) it includes simplified assumptions based on rules-of-thumb that can be inaccurate (e.g. forcing an aesthetic feature); and (2) not accurate in relation with performance measurement of design solution.
2. *Building Performance-Based Design Method:* has power in predicting a design solution because it: (1) uses performance measures with actual quantifiable data and not rules-of-thumb; (2) aims to develop a 'simplified' model of a complex physical system; (3) uses the model to analyze and predict behavior of the system; and (4) produces a more realistic evaluation of the design.

It is important to distinguish between different steps that are associated with performance-based design method, associated design phases and types of design decisions that can be influenced.

2.4 BIM-Based Building Performance Analysis Using Revit and Ecotect

Current design representations offer improved communication and interoperability between design documentation and analysis applications. Best practices for data exchange between BIM Revit® platform and Ecotect® analysis software are discussed to illustrate this process. Ecotect analysis is designed to be used during the early stages of the design process and can be effectively used for a variety of analysis functions such as shadow analysis, shading, solar exposure studies, lighting and daylighting studies[12]. Data exchange between Revit and Ecotect is performed through Green Building XML (gbXML) schema, a computer language specifically developed to facilitate the transfer of building properties stored in BIM to analysis tools. The basic structure of gbXML consists of elements such as rooms, walls, floors, ceilings, shading surfaces and windows. It inherits properties imbedded in the model (actual numeric values) and transfers to analysis applications. The following model parameters are essential for data exchange and are useful in utilizing BIM models for environmental analysis:

1. *Rooms:* Since rooms are the basis of the gbXML file and its structure (all the other data is associated with these elements), their location and properties must be specified in the model. Only significant spaces should be defined as rooms (corresponding to thermal zones) and smaller supportive spaces (elevator shafts, storage spaces, mechanical spaces, etc.) can be grouped. Rooms must be fully bounding, therefore, 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) that are not bounding a room and are exported as simple surfaces.

These basic parameters can be embedded in the model from the earliest stages of the design process and used for environmental analysis. Figure 5 shows an example of a Revit file with information needed for the analysis imbedded in the model (rooms, their dimensions and properties), which get transferred by gbXML file to analysis engine. Figure 5b shows an excerpt of the gbXML file containing exactly the same information, but showing a different, data-based view. Figure 6 shows the analysis model created in Ecotect from the gbXML file.

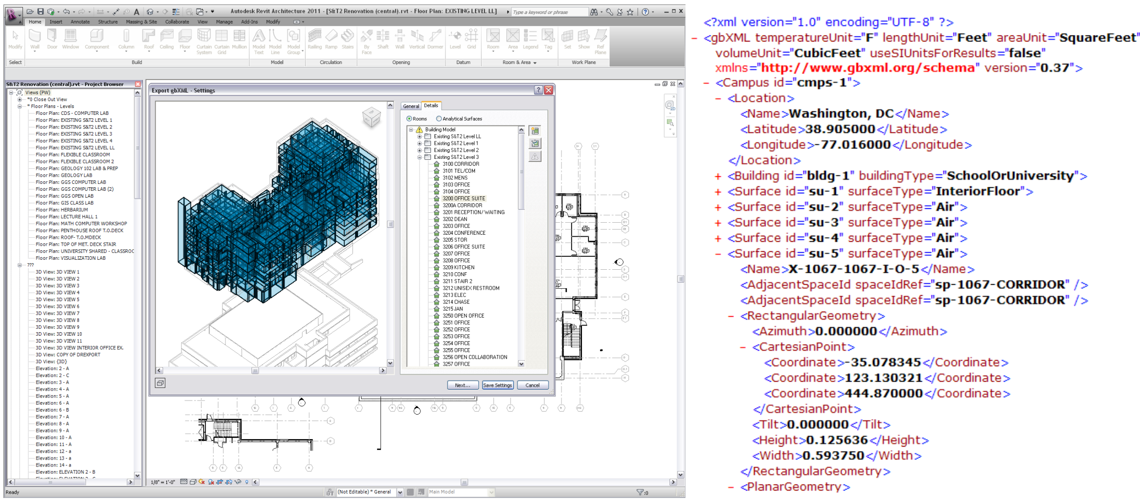


Figure 5: a) Example of Room properties inside a Revit gbXML 3D model, b) gbXML data file structure.

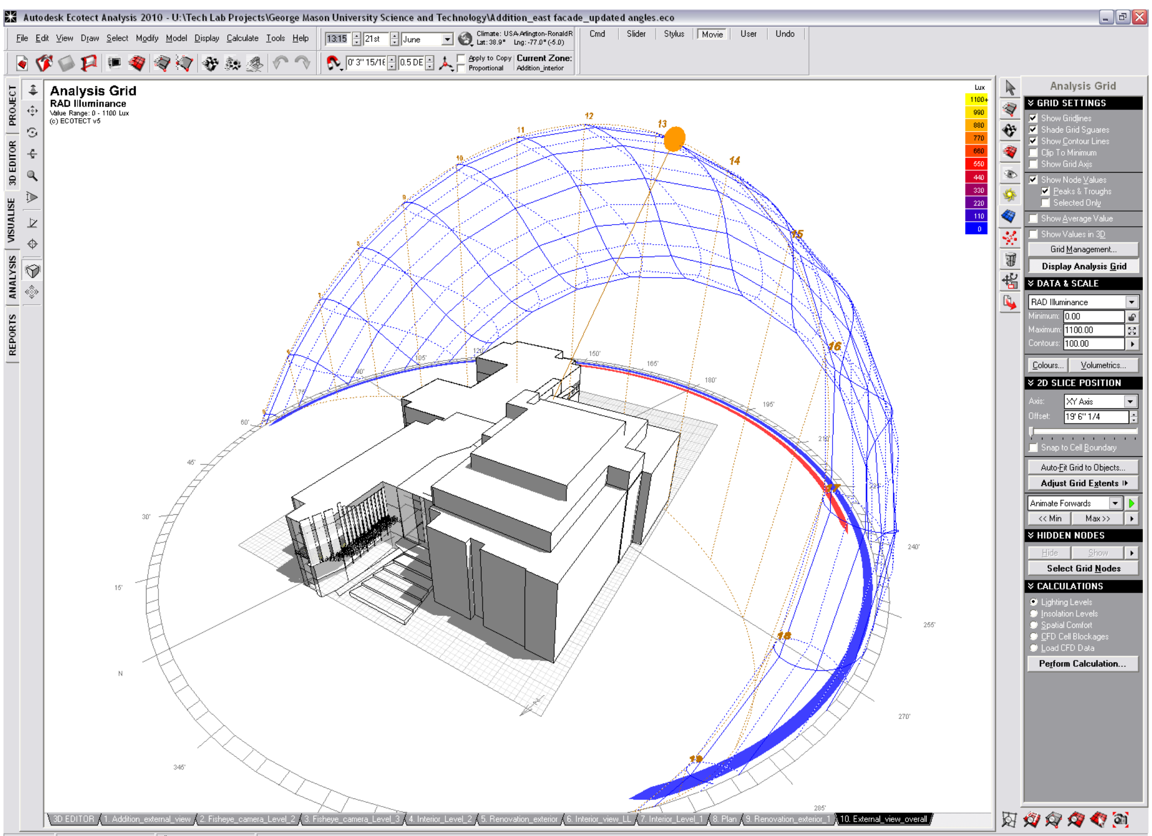


Figure 6: Ecotect model (based on the import of the gbXML file shown in Figure 5).

2.5 The Work Context for Building Performance Analysis

It has become important that designers evaluate building energy performance at early and schematic project phases before a detailed whole-building energy model is produced. This saves the project from drastic changes due to misguided energy goals. However, building performance analysis can be long, tedious process and the authors believe that it is important to demystify such process. This article proposes that building performance analysis can be performed in two primary stages, which can be parallel or complement each other. The first method is a lightweight energy analysis performed at early project phase. We refer to this method as a *Design-Performance Energy Analysis* whereby it could follow two stages and each is utilizing the appropriate tool. In some cases we have noticed that a whole building energy analysis is hard to accomplish at this early stage due to many operational and logistical reasons. Most importantly, certain energy attributes such as detailed information about building systems are not known and are needed for populating a whole-building energy model. This is why isolating components that are known (e.g. building envelope options, skylight options, etc.) work well. The two stages within the *Design-Performance Energy Analysis* method are[13]:

1. *Understanding some energy target goals and design scenarios:* the aim is to establish early in the project some meaningful energy performance targets in order to assess against the different design schemes. With this, early design characteristics and decisions are understood such as: the site, building orientation, climatic conditions, shadow ranges, basic solar exposure and its directionality and passive strategies based on the location. One of the tools that can be used is COMFEN tool, which allows analysis of key fenestration variables on energy consumption, peak energy demand and thermal and visual comfort. Other tools like Autodesk® Green Building Studio® can assist in calculating energy target goals.
2. *Design solutions and optimization:* occurs when the project progresses into design development phase. For example, the building envelope undergoes cycles of performance analysis based on the exterior skin configurations. In this approach different design options are tested utilizing a more detailed "3D prototype model". The analysis tool that can be used here is Ecotect Analysis, which aids the team in performing iterative analysis to assess:
   - Façade solar exposure to determine total solar radiation: Understanding the total radiation assists in understanding insulation needs in the building, which is done by evaluating different wall construction materials' properties.
   - Sunshade design and optimization: The tool helps us optimize the size of sunshades as well as understand the shaded area of exposed glass.
   - Natural daylight levels, which are analyzed at various critical spaces of the building (for example, classrooms, patient rooms, public spaces and lightwells).

The *Energy Modeling* is the second method and it focuses primarily on sizing and selection of mechanical equipment and prediction of annual energy consumption through the "whole building" approach[13].

For the purpose of the work presented in this article, the authors are focusing on the *Design-Performance Energy Analysis* method and application to the two case studies.

3.0 CASE STUDY (1): DUKE MEDICINE PAVILION BUILDING ENVELOPE ANALYSIS

3.1 Project Overview and Analysis Objectives

The objectives of this study were to investigate building envelope design options and the effects on energy consumption, visual and thermal comfort and daylight strategies for Duke Medicine Pavilion, located in Durham, North Carolina. Durham is characterized by a mixed-humid climate. Climatic conditions indicate that high air temperatures and high humidity levels are predominant during the summer months while relatively low temperatures are predominant during the winter months.

As shown in Figure 7, the hospital building is part of a large campus (approximately 350,000 square feet floor area). The first two levels contain the imaging department and public access areas, the third floor is the surgery level, levels four and five contain mechanical open floors and roof garden with two patient towers above them.

Annual solar path, building orientation and shade provided by surrounding buildings were investigated to de-

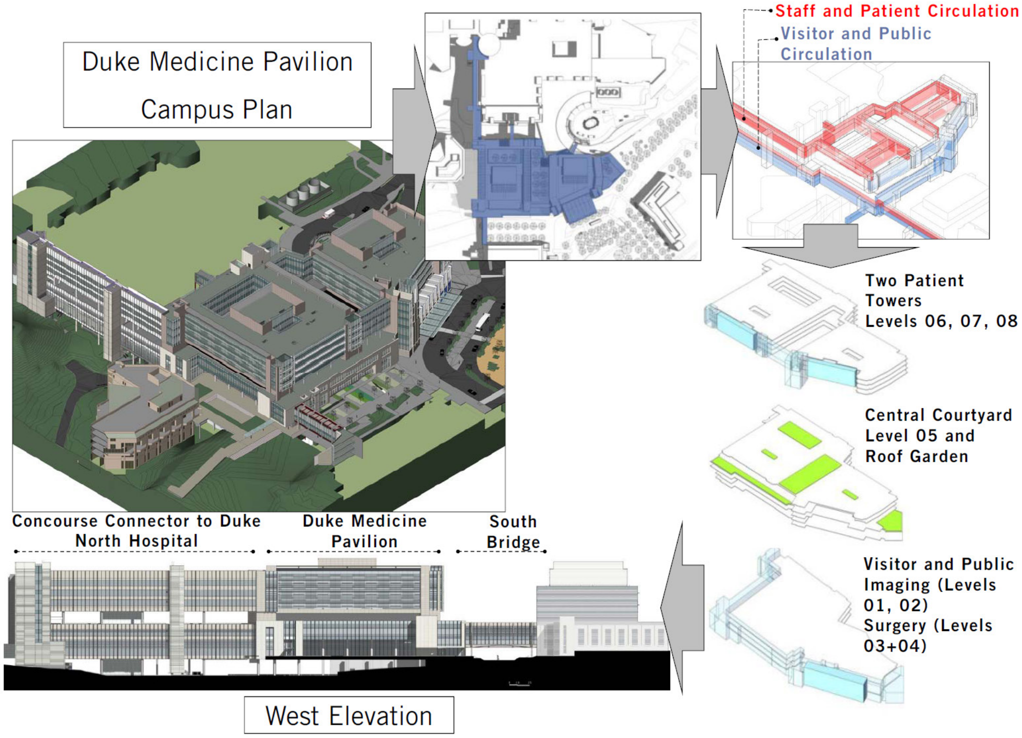


Figure 7: Duke Medicine Pavilion project within campus context and 3D Revit model.

termine critical areas where shading devices are needed as seen in Figure 8. East, south-east and south orientations are critical and require shading devices. West orientation is shaded by the adjacent existing building.

These following aspects were investigated:

1. Energy performance for south and south-east oriented curtain wall and the effects of glass properties (varying U-values, SHGC, visual transmittance), configuration and dimensions of shading devices and daylighting controls.
2. Design of shading devices and light-shelves and their effect on available daylight in the public waiting areas along the south and south east orientations.

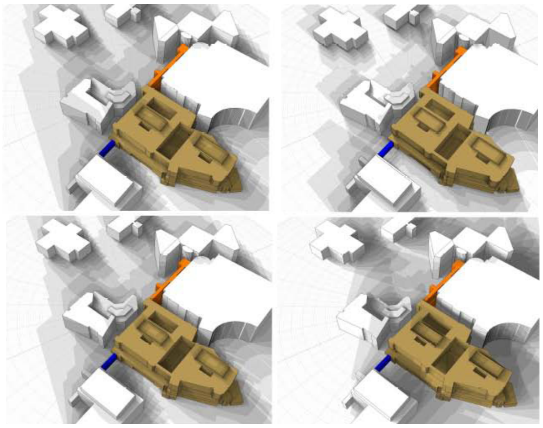


Figure 8: Projections of shadows from surrounding buildings on March 21, May 21, September 21 and December 21.

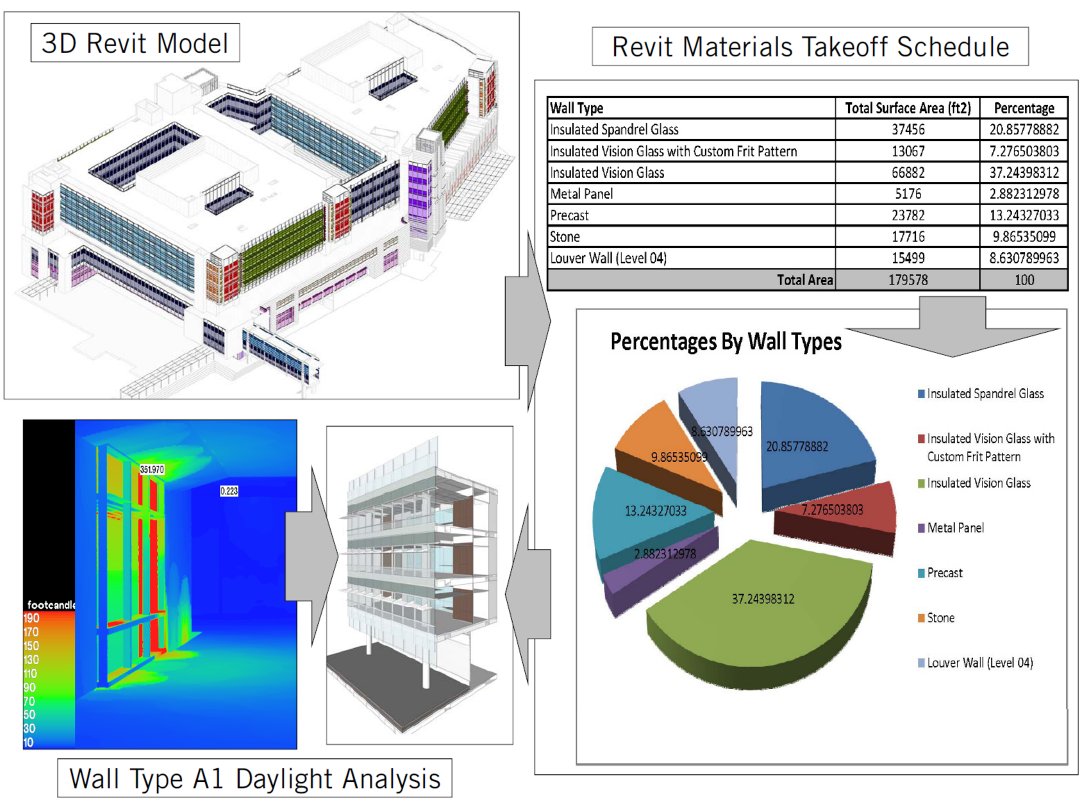
3.2 Building Envelope Design Elements and Effects on Energy Consumption

A number of curtain wall types have been used for this design, but only curtain wall Type A1 is discussed in this article, located on the south and south-east facades (Figure 9). The objective of the study was to analyze different design options (properties of glass and shading devices) that can be applied to minimize energy consumption. The elements of the curtain wall Type A1 are portrayed in Figure 9, where horizontal shading elements are used to block solar radiation and two different types of glass are used (low-e vision glass and insulated spandrel glass). The facade system delivers the greatest performance to the building owner and occupants when it becomes an essential element of a fully integrated building design in a manner that reduces operating costs for a building and increases comfort and productivity for occupants.

Basic guidelines for building envelope design located in a mixed-humid climate are as follows:

- Sun protection should be enhanced while providing most of the needed light using daylight.
- Operating costs should be reduced by minimizing artificial lighting, cooling and heating energy by optimizing the daylight.

For this particular climate, the reduction in cooling loads and provision of daylight are the most important strategies for the reduction of overall energy consumption. Therefore, glass that exhibits higher visual transmittance (Tv) and lower solar heat gain coefficient (SHGC) is preferable, but should be analyzed in order to understand the correlation between heat gain and provision of natural light. Table 2 shows properties of glass types, where GL 1 and GL 2 are low-e, double air-insulated glazing units studied for the vision-areas of the curtain wall. GL 3 and GL 4 are used for spandrel areas and the type of glass is identical, but GL 3 includes ceramic frit to reduce solar heat gain.



Wall Type	Total Surface Area (ft2)	Percentage
Insulated Spandrel Glass	37456	20.85778882
Insulated Vision Glass with Custom Frit Pattern	13067	7.276503803
Insulated Vision Glass	66882	37.24398312
Metal Panel	5176	2.882312978
Precast	23782	13.24327033
Stone	17716	9.86535099
Louver Wall (Level 04)	15499	8.630789963
Total Area	179578	100

Figure 9: Visualizing curtain wall types in Revit and showing material areas/percentage calculation in the model.

Table 2: Glass properties.

Glass type	Visual transmittance (Tv)	Solar Heat Gain Coefficient (SHGC)	U-value (Btu/hr-sf-°F)	U-value (W/hr-m²-°C)
GL 1	0.71	0.38	0.29	1.65
GL 2	0.62	0.29	0.28	1.59
GL 3 (40% white frit coverage)[9]	0.27	0.19	0.30	1.70
GL 4 (No frit)	0.38	0.25	0.30	1.70

One set of simulation scenarios focused on different cases for wall Type A1 (south orientation) and the properties are listed in Table 3. Types of glazing units and shading elements were varied to analyze the effects of their properties on energy consumption (heating, cooling, lighting loads), daylighting and thermal comfort. Moreover, comparison to wall types without shading devices and daylighting controls was performed. Simulation set for south-east orientation also included similar scenarios. Also, vertical shading elements were introduced for the south-east orientation. The study investigated a single bay per floor and a single zone, where associated annual energy demand for heating, cooling and lighting loads for these four cases were calculated.

Table 3: Characteristics of analyzed curtain wall options.

South orientation	South-east orientation
• Vision glass: GL 1 • Non vision glass: GL 3 (40% frit coverage) • Horizontal overhang 4' depth (1.2m) • Mullion extensions 6" (0.15m)	• Vision glass: GL 1 • Non vision glass: GL 3 (40% frit coverage) • Horizontal overhang 4' depth (1.2m) • Mullion extensions 6" (0.15m)
• Vision glass: GL 2 • Non vision glass: GL 3 (40% frit coverage) • Horizontal overhang 4' depth (1.2m) • Mullion extensions 6" (0.15m)	• Vision glass: GL 2 • Non vision glass: GL 3 (40% frit coverage) • Horizontal overhang 4' depth (1.2m) • Mullion extensions 6" (0.15m)
• Vision glass: GL 2 • Non vision glass: GL 3 (40% frit coverage) • Horizontal overhang 4' depth (1.2m) • Mullion extensions 1' (0.3m)	• Vision glass: GL 2 • Non vision glass: GL 3 (40% frit coverage) • Horizontal overhang 4' depth (1.2m) • Mullion extensions 1' (0.3m)
• Vision glass: GL 2 • Non-vision glass: GL 4 • Horizontal overhang 4' depth (1.2m) • Mullion extensions 1' (0.3m)	• Vision glass: GL 2 • Non vision glass: GL 4 (40% frit coverage) • Horizontal overhang 4' depth (1.2m) • Mullion extensions 1' (0.3m) • Vertical fins: height=9' (2.7m), depth=1' (0.3m), thickness=3" (0.08m)

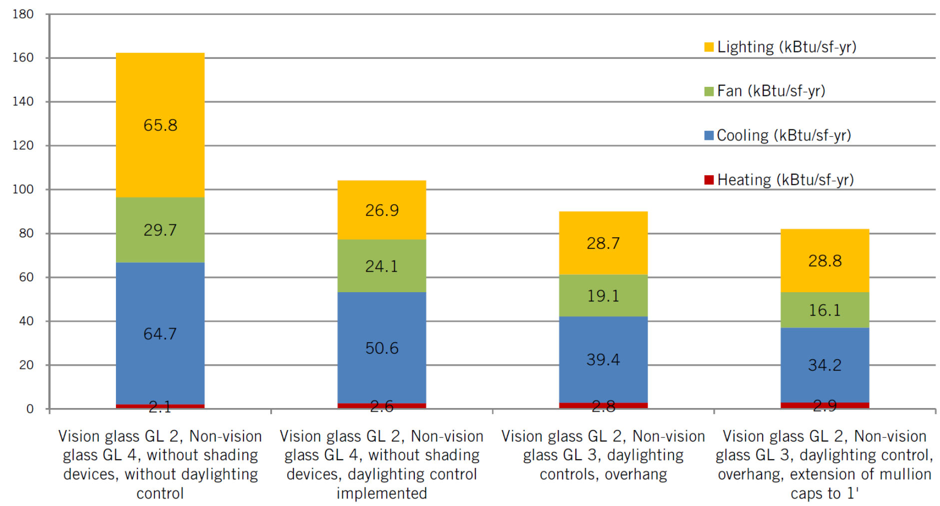


Figure 10: Calculated energy demand for different design options (south-oriented curtain wall).

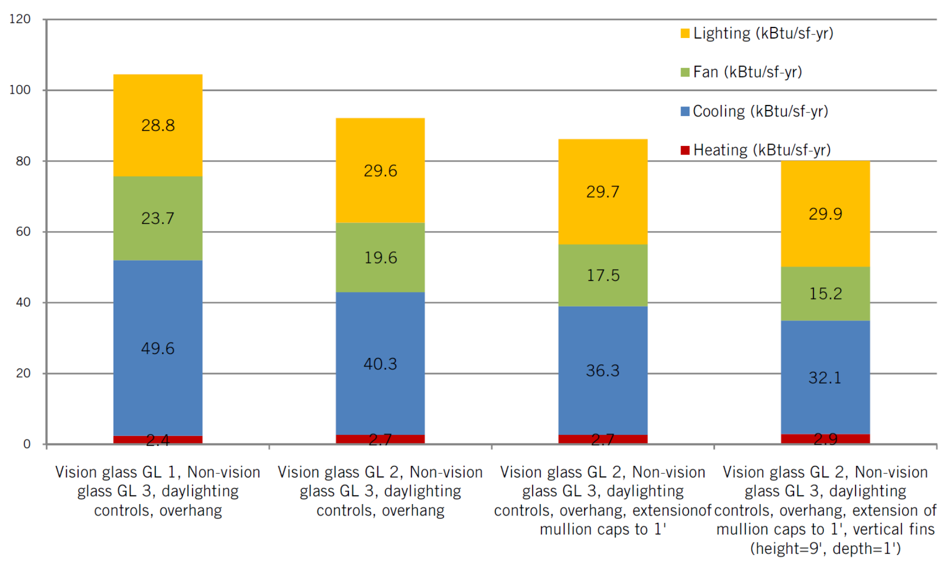


Figure 11: Calculated energy demand for different design options (south-east oriented curtain wall).

Figure 10 shows results for selected scenarios (south orientation), illustrating demand for south perimeter zones only. It was found that glass with lower visual transmittance and lower solar heat gain coefficient used for vision glass (GL 2) would results in reduced cooling loads, therefore, all the shown options show those scenarios. Implementation of lighting controls would significantly reduce lighting loads. Also, use of fritted glass for non-vision areas would reduce solar gains. The optimum design scenario utilizes GL 2 type for vision area, fritted glass for non-vision area, daylighting controls, horizontal overhang and extended horizontal mullion caps to provide additional shading. This scenario would result in 50 percent reduction in energy demand compared to a scenario that utilizes the same type of glass for vision area, but excludes fritted glass for non-vision area, shading devices and daylighting controls.

Figure 11 shows results for selected scenarios (south-east orientation). For this orientation, optimum design scenario also uses GL 2 for vision area, fritted glass for non-vision area and vertical fins are introduced to block early morning sun (besides horizontal overhang and extended mullion caps).

3.3 Effects of Design Options on Occupants' Thermal Comfort and Glare

The effects of the above discussed design options on thermal comfort and glare has also been investigated using COMFEN/EnergyPlus. Controlling glare is necessary for occupants' visual comfort. Average discomfort glare index is based on a subjective response to brightness within one's field of view. In this analysis, the average annual glare index was computed for a person facing the south wall, sitting five feet from the window. A glare index of ten is the threshold for just perceptible glare while a glare index of 16 is the threshold where glare is just acceptable.

Thermal comfort analysis, following Predicted Mean Vote-Percentage of People Dissatisfied (PMV-PPD) method, was used to study the interior thermal comfort conditions for the design options. This method is based on human body energy balance and is combined with an empirical fit to thermal sensation. PMV is based on a seven-point, cold-to-hot sensation scale for a large population of people exposed to a certain environment. PPD is the "Percentage of People Dissatisfied" at each value (PPD indicates the probability that an average person will be dissatisfied with his/her thermal comfort).

PMV-PPD statistically indicates the number of individuals that would express satisfaction by comfort conditions and ASHRAE 55-2004 Standard (Thermal Environmental Conditions for Human Occupancy) recommends that PMV value should be between -0.5 and +0.5, which corresponds to PPD of ten (or ten percent of dissatisfied persons)[14]. It also defines acceptable thermal environment as one in which there is 80 percent overall acceptability, basing this on ten percent dissatisfaction criteria for general thermal comfort, plus an additional ten percent dissatisfaction that may occur from local thermal discomfort.

Comparison of average discomfort glare index and thermal comfort PPD index is listed in Table 4 for south and south-east orientations. Results show that design options that result in improved energy efficiency for both south and south-east orientations are also best candidates for minimizing glare. All design options meet the recommended 80 percent acceptability threshold, but options that improve energy efficiency are also preferable for improving thermal comfort.

Table 4: Glare index and thermal comfort.

	Option 1	Option 2	Option 3	Option 4
South orientation				
Average discomfort glare index	5.30	5.80	4.60	5.10
Thermal comfort (PPD index)	16.83	15.40	14.11	13.40
South-east orientation				
Average discomfort glare (glare index)	5.20	5.00	5.00	4.30
Thermal comfort (PPD index)	14.57	14.24	14.23	14.38

3.4 Daylighting Analysis and Results

Daylight is the best source of light for the public space. The analyzed curtain wall adjoins waiting areas of the hospital. In order to understand the effects of different design options on daylight levels, subsequent daylight analysis was performed. Ecotect and Radiance programs were used for the study. Sixteen different options were investigated (varying window to wall ratio, configuration of shading devices and ceiling geometry). These studies were limited to evaluation of natural light under overcast sky conditions.

Properties of glazed portions of the building envelope were constant as obtained from the best scenarios from energy analysis presented in the previous section. Figure 12 shows three different options and results for south and south-east orientations. The properties are as follows:

1. Base design: vision glass GL 2 (7'-10"), Shading device depth = 4', shading device elevation = 7'-10", flat ceiling at elevation = 12'
2. Option 1: vision glass GL 2 (7'-10"), shading device depth = 4', shading device elevation =

7'-10", interior light shelf, sloped ceiling (sloping down from the curtain wall from 12' elevation to 10'), and with 2' fritted glass band placed 2' above shading device.

3. Option 2: vision glass GL 2 (7'), shading device depth = 3', shading device elevation = 7', sloped ceiling (sloping up from the curtain wall from elevation 10' elevation to 12'), 2' of fritted glass at base.

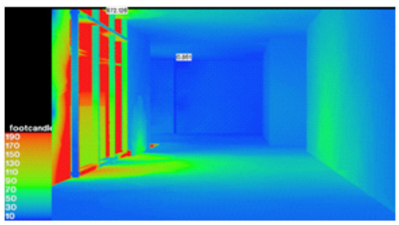
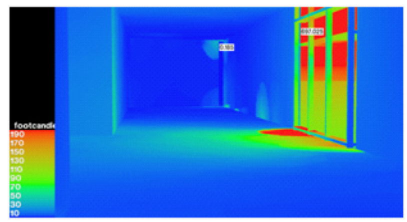
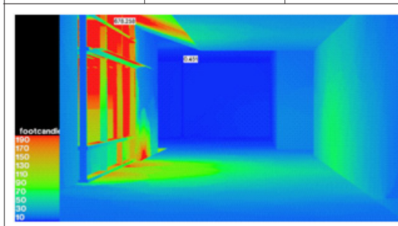
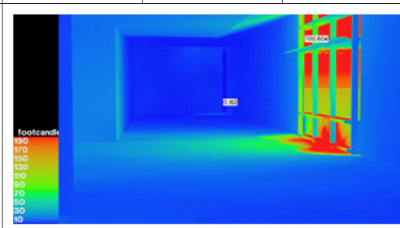
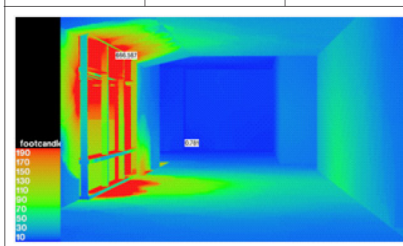
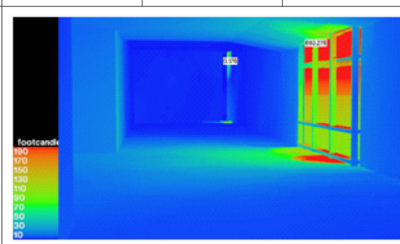
June 21 at 12:00 (South / South East)	At Window		At Middle Space		At Back Wall	
Measurement Distance	1'	1'	8'	10'	14'	17'
Base Design Option (fc)	130	115	70	45	35	10
						
Monthly Transmitted Solar Radiation (Btu/ft²)	41,834; No Shade = 288,249; Glass Area = 181 ft²			125,832; Glass Ares = 181 ft²		
Monthly Average Shade Percentage	75 No Shade = 64			69		
Option (1) (fc)	130	135	60	35	40	10
						
Monthly Transmitted Solar Radiation (Btu/ft²)	203,390 Glass Area = 151 ft²			256,932 Glass Ares = 151 ft²		
Monthly Average Shade Percentage	74			71		
Option (2) (fc)	160	130	70	50	35	10
						
Monthly Transmitted Solar Radiation (Btu/ft²)	27,550 Glass Area = 141 ft²			66,445 Glass Ares = 141 ft²		
Monthly Average Shade Percentage	79			79		

Figure 12: Comparison of daylight levels for three different scenarios (south and south-east orientation) and effects of ceiling geometry and light-shelf on daylight levels (June 21).

Results indicate that the last option would be the best option since uniform distribution of light would be present for summer and winter conditions. Other reasons include:

- It enhances the overall daylight quality within the space. This is visible from the heat-map renderings indicating better light distribution.
- The transmitted solar radiation is dramatically reduced from the original base design option, which allows a reduction in the cooling loads.
- The recommended design option results in using less glass area (141 ft^2) instead of (181 ft^2) from the base design option.

4.0 CASE STUDY (2): GEORGE MASON UNIVERSITY

4.1 Project Overview and Analysis Objectives

George Mason University Science and Technology Complex is located in Fairfax, Virginia. The building complex consists of an addition to an existing academic research center as seen in Figure 13. There is also an existing building bounding the complex on the west. Objectives of this study were to analyze shading strategies, daylight levels and solar exposure for various building orientations and components and methods to improve performance of building envelope. These following objectives were investigated:

- Site context and shadow ranges for winter and summer solstices.
- Addition building: shading devices on east facade; solar exposure, daylight levels and glare for selected laboratories.
- Addition building: shading devices on west facade, daylight levels and solar exposure; daylight levels and glare for corridor area.
- Addition building: solar exposure and daylight for north and south atrium facades.
- Renovation building: shading devices on west facade, solar exposure, daylight levels for selected computer laboratories and glare analysis.
- Properties of building envelope (specifically, glass selection) for improving energy efficiency.

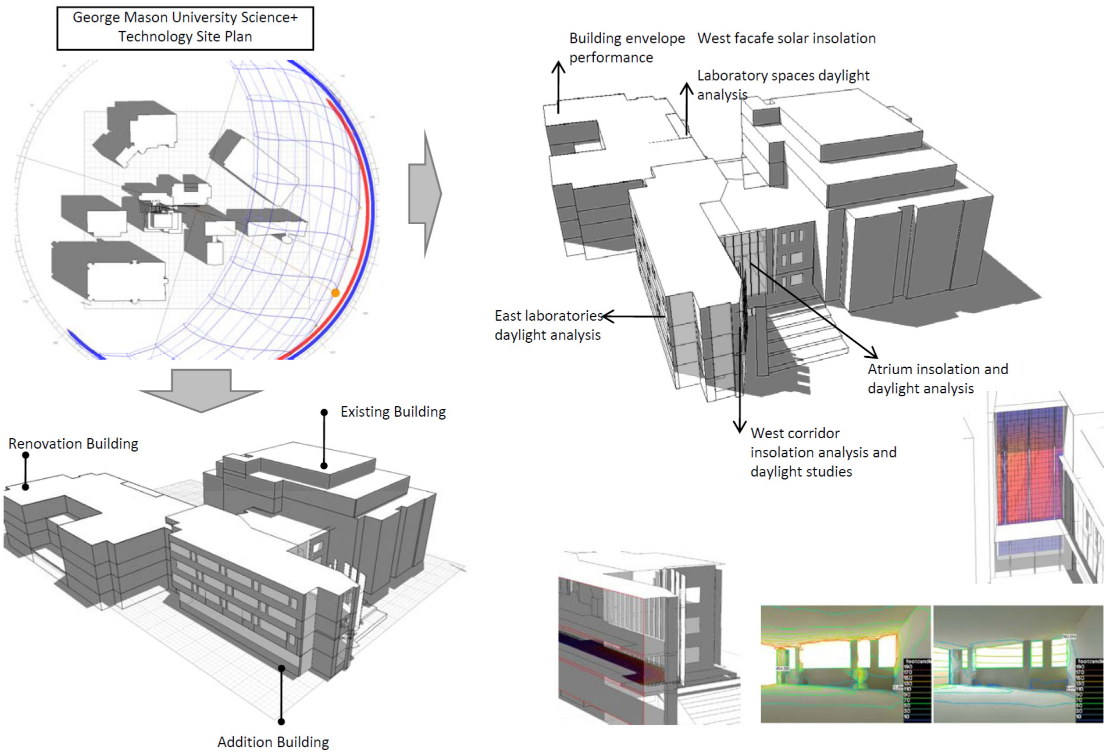


Figure 13: George Mason University Science and Technology complex and analysis objectives.

4.2 Environmental Conditions and Passive Strategies

Fairfax, Virginia is characterized by mild humid climate. Review of average monthly temperatures and humidity conditions revealed that mild conditions are present for the majority of the year (October through April: cool conditions; April through middle of June and middle of September through October: moderate conditions) and only during summer months warm and humid conditions are present (middle of June through middle of September). Passive solar heating is possible for the majority of the winter months for this location, but solar gain should be minimized for summer months, therefore, following sections discuss analysis of site context and orientation, performance of shading devices and relationships between solar exposure and daylight.

4.3 Shading Devices, Daylight and Glare: West Facade

Selection of shading devices depends on building orientation. Generally, horizontal devices should be used for south façades. Vertical devices, such as fins, should be used on east and west facades and be able to rotate depending on the daily sun path. Shading of south facades respond to seasonal changes while east and west façades should respond to daily changes. Since the buildings under consideration are oriented -73° from true north, relative orientation and solar position was taken into account. During the winter months, buildings' east facades do not have direct access to sun and during summer months only receive direct solar radiation for a few hours in the morning. Since there is an existing building directly bounding Addition and Renovation buildings on the west side (as well as other buildings in the near proximity) detailed shadow analysis was performed for the entire site to understand the effects of surrounding buildings. Overall site context, surrounding buildings and daily shadow ranges for selected dates (December 21, March 21, June 21 and September 21) are portrayed in Figure 14. Gradient intensity indicates the amount of time that the selected surfaces spend in shade (in one hour increments). Significant shading is provided by the building that bounds Addition and Renovation Science and Technology buildings on the west (during afternoon hours throughout the whole year, especially Renovation building).

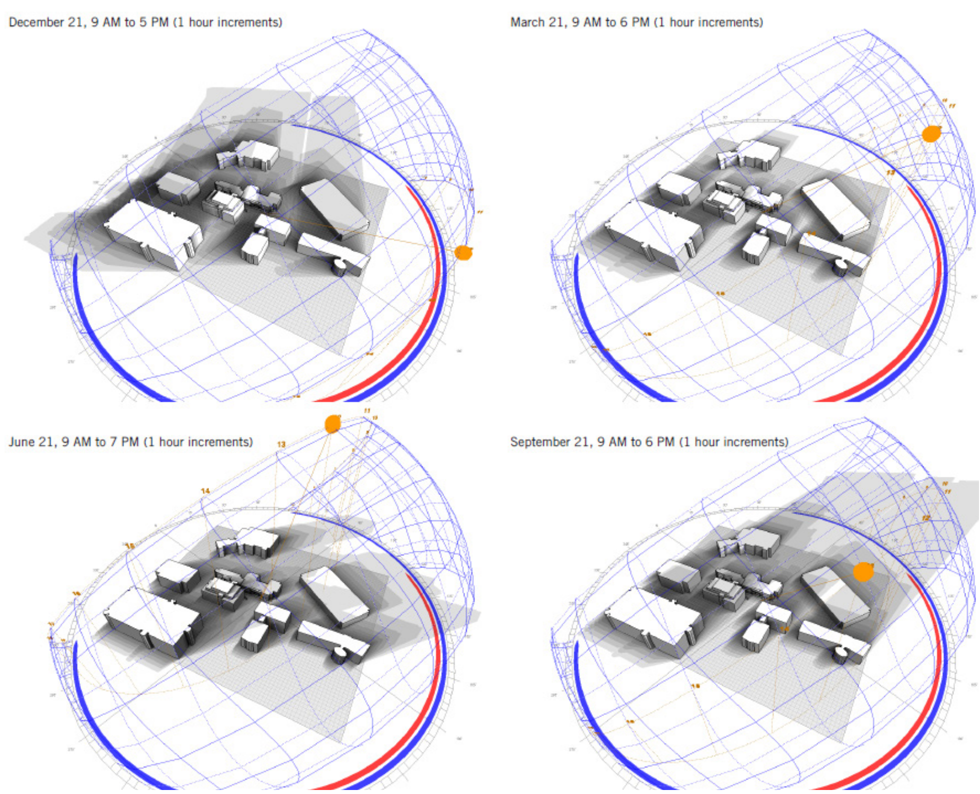


Figure 14: Site context and shadow ranges for selected dates.

Figure 15 shows hourly shadows for June 21. During this time, shading devices are needed during the whole day. Therefore, relative south and west facades are the most critical, especially in the afternoon hours.

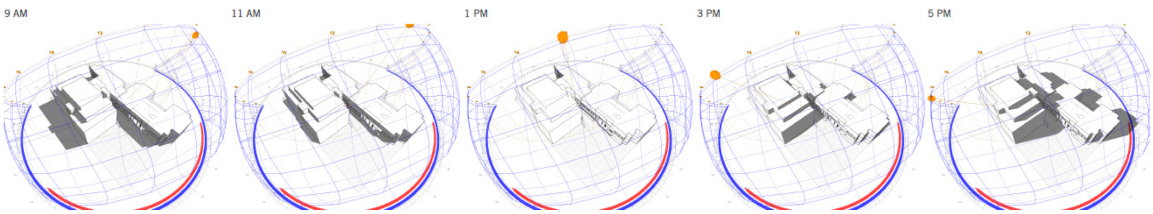


Figure 15: Hourly shadows (June 21).

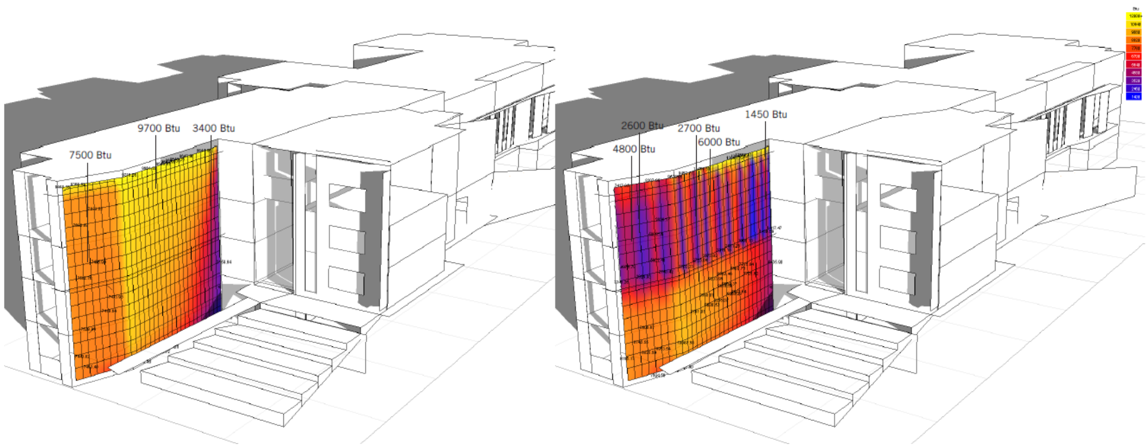


Figure 16: Comparison of average solar exposure for west façade without and with shading devices.

Figure 16 compares average solar exposure for west facade without and with shading devices for summer months. It is evident that shading devices (aluminum screen mesh used as vertical fins) significantly reduce solar heat gains. Moreover, reducing the angle of vertical fins would further reduce solar heat gains. Since shading devices can negatively affect access to natural light, daylight analysis was conducted to investigate the effects. Figure 17 shows daylighting levels in the corridor. It is evident that the vertical fins do not reduce amounts of natural light within the interior space.

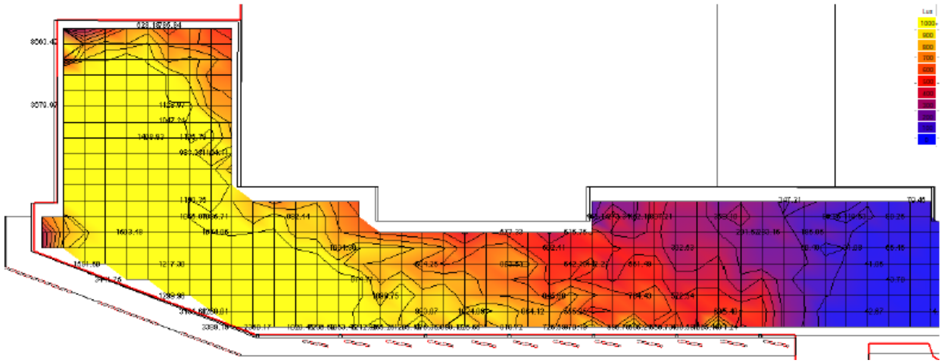


Figure 17: Daylight levels in the corridor and the effects of shading devices.

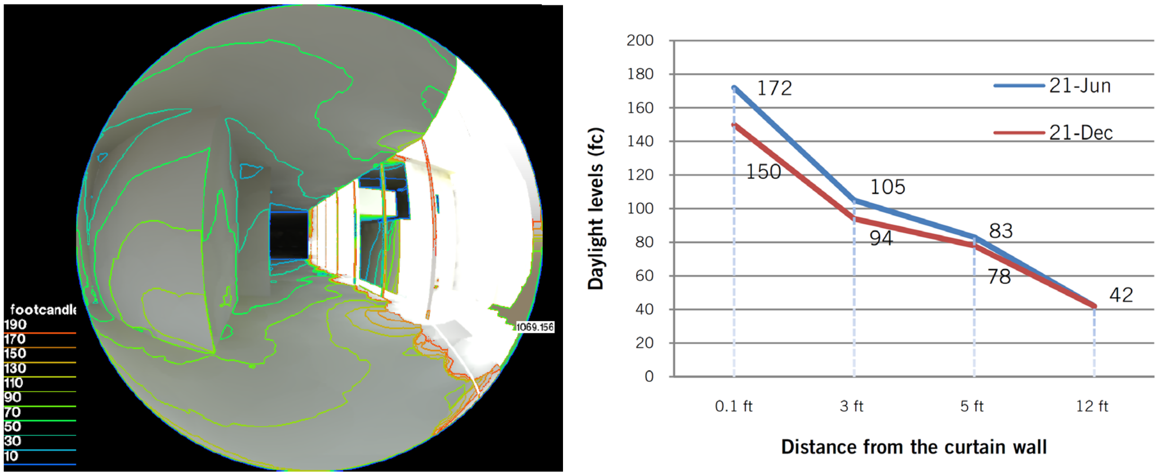


Figure 18: a) Interior view of the corridor and daylight levels; b) Daylight levels at measured distances from the curtain wall (simulated on June 21 and December 21).

Glare analysis has been performed for June 21 and December 21, where two different calculation methods have been used (Unified Glare Rating and Visual Comfort Probability). Figure 18 shows interior view of the corridor used for the analysis (fisheye camera is used to generate the image appropriate for the analysis). Detailed daylight levels at measured distances from the curtain wall are also shown for June 21 and December 21 conditions. Radiance was used to calculate two glare indices Unified Glare Rating (UGR) and Visual Comfort Probability (VCP). UGR indicates visual discomfort and is calculated by a formula that takes into account position and brightness of each potential glare source. Following values for acceptable ranges are recommended[15]:

- Discomfort zone
  - Intolerable: >28
  - Just intolerable: 28
  - Uncomfortable: 25
  - Just uncomfortable: 22
- Comfort zone
  - Acceptable: 19
  - Just acceptable: 16
  - Noticeable: 13
  - Just perceptible: 10

Results for June 21 and December 21 indicate that glare would not be present in this space, since calculated UGR index was 0 for both winter and summer conditions. Visual Comfort Probability index was also calculated. It is an estimate of how many people out of 100 would feel comfortable in the given visual environment, and results showed that VCP index would be 100 for both summer and winter conditions. Therefore, the vertical aluminum screen mesh vertical fins used on the west façade reduce unwanted solar heat gain, but do not negatively affect the amounts of natural light and provide protection against unwanted glare.

4.4 Shading Devices, Daylight and Glare: East Facade and Atrium

East facade of the Addition building is shadowed during most of the year, and receives only small percentage of incident solar radiation, as seen in Table 5. Shading devices on this facade are therefore redundant. Daylight levels for laboratories located on the second level are shown in Figure 19.

Table 5: Average solar radiation, incident solar radiation and average shade percentage for the east façade.

	Available solar radiation (Btu/ft²)	Incident solar radiation (Btu/ft²)	Average shade percentage
Jan	25,744	1,185	91%
Feb	27,208	1,534	88%
Mar	35,784	1,993	87%
Apr	46,550	2,857	86%
May	35,197	2,194	85%
Jun	43,175	2,719	83%
Jul	42,109	2,558	83%
Aug	41,275	2,374	84%
Sep	35,846	2,204	87%
Oct	43,697	2,738	86%
Nov	26,064	1,354	88%
Dec	25,219	1,120	90%
TOTAL	427,868	24,828	

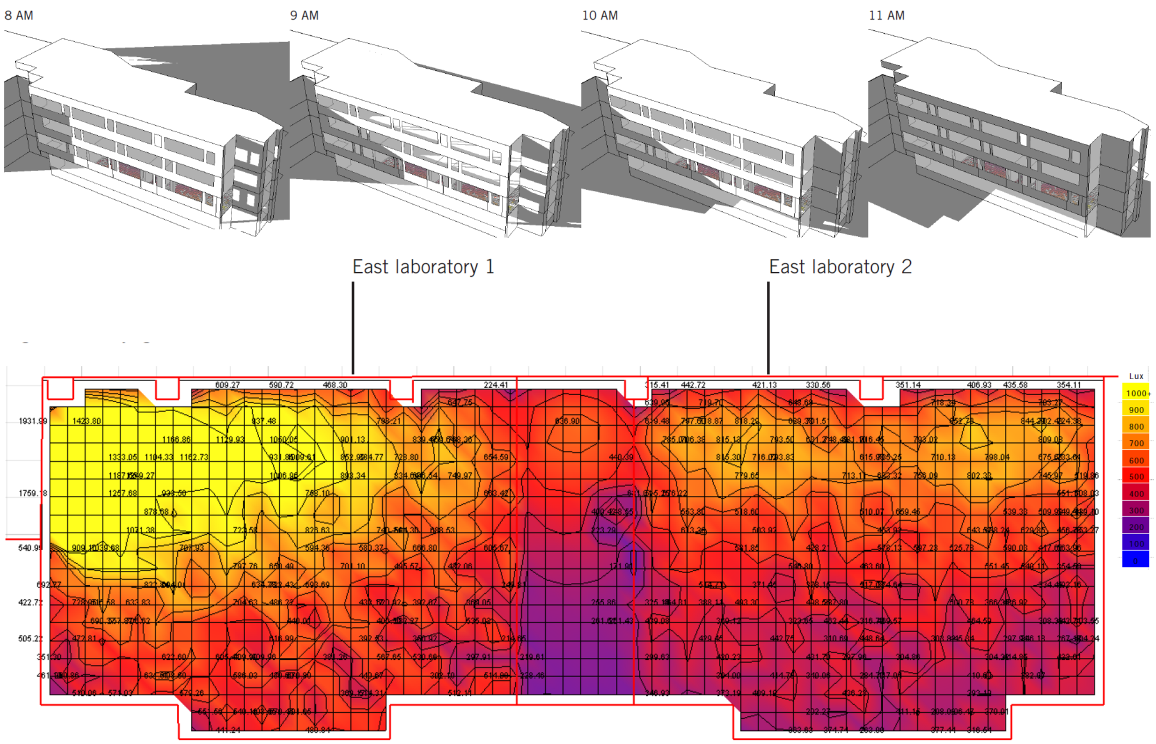


Figure 19: a) East façade and shadows (June 21), b) Daylight levels for laboratory spaces (plan).

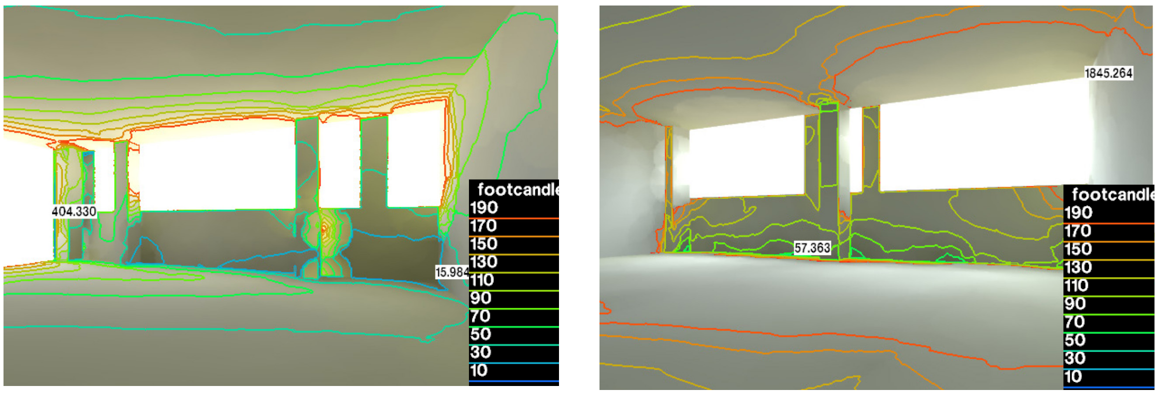


Figure 19c: Distribution of daylight within 3D models of laboratories.

Average incident daily solar radiation for atrium façade is relatively low due to the orientation and shading provided by the existing building. Also, it was found that this facade is shaded for majority of the year, except late afternoon hours during summer months. Therefore, shading devices (or other methods for controlling solar heat gain such as fritted glass) would be redundant. Daylight analysis indicated that sufficient daylight levels would be present in the atrium (Figure 20), where values are shown for measured distances from the curtain wall.

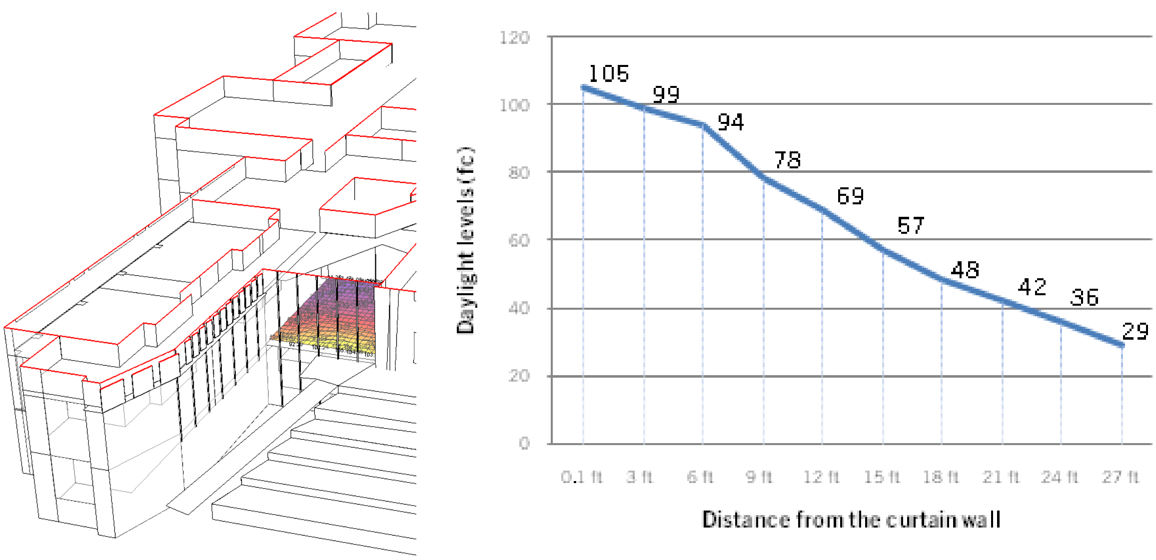


Figure 20: a) Atrium; b) Daylight levels at measured distances from the curtain wall.

4.5 Building Envelope Energy Performance

Solar heat gain plays a major role in determining thermal performance of a building façade. The factors that can influence energy conservation of windows and curtain walls are use of low-emissivity (low-e) coatings, balanced relationships between properties of glass (specifically, solar heat gain coefficient, thermal conductance, and visual transmittance), inert gases and frame materials. Improvements in the thermal performance of windows can be achieved by using spectrally low-e coatings that allow a high proportion of the visible light in the solar spectrum to be transmitted, but block much of the other wavelengths responsible for solar heat gains, thus improving thermal efficiency. Further improvements in thermal resistance can be achieved by replacing air with low conductivity gases such as argon or krypton. In order to investigate building envelope performance and to select glass according to building orientation and energy loads, several representative spaces were selected for areas of low and high solar exposure:

- Low solar exposure:
  - East laboratory (Addition building)
  - East office (Renovation building)
- High solar exposure:
  - Corridor (Addition building)
  - Atrium south entry (Addition building)
  - South office (Renovation building)
  - West computer laboratory (Renovation building)

For low solar exposure, selected glass options that were used in the study have low U-factor, relatively low solar heat gain coefficient (SHGC) and high visual transmission (Tv). For high solar exposure, options with low U-factor, lower SHGC and lower Tv were analyzed. One option with low SHGC and average visual transmittance was analyzed for both areas as well as system with higher visual transmittance (GL 4). Specific properties are listed in Table 6.

Table 6: Properties of glass used for analysis.

	Visual transmittance (Tv)	Solar Heat Gain Coefficient (SHGC)	U-value (Btu/hr-sf-°F)	U-value (W/hr-m²-°C)
Base Case				
Double insulated clear glazing unit (air infill)	0.79	0.70	0.48	2.73
Low solar exposure areas				
GL 1	0.62	0.28	0.30	1.71
GL 1 (argon infill)	0.62	0.28	0.25	1.42
GL 3	0.70	0.38	0.29	1.65
GL 4	0.48	0.28	0.30	1.71
High solar exposure areas				
GL 4	0.48	0.28	0.30	1.71
GL 5	0.36	0.28	0.31	1.76
GL 5 (argon fill)	0.36	0.27	0.26	1.48

Different scenarios were simulated for all cases (base case and options with different glass properties). All of the analyzed spaces were modeled as a single zone. Results showed that for low solar exposure spaces best results are obtained by using glass with low U-value and relatively high visual transmittance (such as GL 1), as seen in Table 7. Heating loads would be reduced by using argon-filled glazing unit, but since heating loads only constitute small percentage of the overall loads, the higher cost of the building façade would not benefit the overall energy/cost savings. For areas with high solar exposure (such as west corridor), results show that glass with low solar heat gain coefficient and visual transmittance (GL 5) would be the best choice (Table 8).

Table 7: Results for low solar exposure options (energy consumption).

LOW SOLAR EXPOSURE (East laboratory)	Base case	GL 1	% (Difference from Base case)	GL 3	% (Difference from Base case)	GL 4	% (Difference from Base case)	GL 1 (argon infill)
Heating (kBTu/sf-yr)	4.2	2.4	-41%	2.4	-42%	2.3	-44%	1.9
Cooling (kBTu/sf-yr)	22.7	18.8	-17%	18.6	-18%	20.3	-11%	19.4
Fan (kBTu/sf-yr)	12.9	8.9	-31%	8.8	-32%	9.6	-25%	8.7
Lighting (kBTu/sf-yr)	21.6	23.3	8%	25.4	17%	22.4	4%	23.3
Total energy (kBTu/sf-yr)	61.4	53.5	-13%	55.2	-10%	54.7	-11%	53.4

Table 8: Results for high solar exposure options (energy consumption).

HIGH SOLAR EXPOSURE (West corridor)	Base case	GL 1	% (Difference from Base case)	GL 4	% (Difference from Base case)	GL 5	% (Difference from Base case)
Heating (kBTu/sf-yr)	8.8	6.9	-22%	5.8	-35%	6.1	-31%
Cooling (kBTu/sf-yr)	134.8	62.4	-54%	69.8	-48%	61.3	-55
Fan (kBTu/sf-yr)	81.6	37.7	-54%	29.6	-51%	35.7	-56%
Lighting (kBTu/sf-yr)	41.9	41.9	0%	41.9	0%	41.9	0%
Total energy (kBTu/sf-yr)	267.2	148.9	-44%	157.1	-41%	145.0	-46%

5.0 FUTURE RECOMMENDATIONS

The authors would like to highlight issues and areas for improvements when it comes to building performance predictions:

- There is a general consensus for the need to develop and derive project designs based on rules-of-thumb in combination with the scientific/analytical approach for performance assessment.
- Coupling BIM-based energy analysis with BIM-based design production tools occurs when all design team members work collaboratively and while they are involved in the iterative process of design decision-making.
- There are both direct (gbXML) and indirect (DXF) routes when it comes to exchanging 3D-BIM models with energy analysis applications. We believe that most of the model-data interoperability is converted properly using gbXML. The challenge becomes the backward process when importing the energy analysis model/features back into BIM, which currently is not a feasible two-way mechanism between Revit and Ecotect.
- It is imperative to understand the underlying concepts and methodologies that a certain tool is applying in the analysis as well as its benefits and drawbacks.
- The final issue is that BIM-production model and the BIM-energy analysis model need to be managed and properly developed. In essence, BIM-production model has too many architectural/construction details and the second is a low level of detail simulation model. Users need not waste time in constructing or exchanging the whole project and details of the building that are not needed for the analysis, but rather focus on the zones under study and dependent on the objectives of the investigation.

6.0 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 assess 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. 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. 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. This article reviewed best practices for data exchange between Revit platform and Ecotect environmental analysis software through gbXML schema. Then, two case studies have been reviewed that illustrate this process in detail, analysis objectives, and results. The first case study reviewed curtain wall energy performance for a healthcare facility located in a mixed-humid climate and daylighting analysis. The second case study reviewed comprehensive analysis for an academic research building, such as site context and shadow analysis, solar exposure studies for different building orientations, daylighting and glare analysis. Finally, recommendations have been identified that suggest future areas of improvement for building performance predictions.

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