A BIM-based workflow concurrently generating quantitative and qualitative output — a focus on energy performance and architectural representation

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A Thesis in the Department of
Building, Civil, and Environmental Engineering

Presented in Partial Fulfillment of the Requirements for the Degree of
Master of Applied Science (Building Engineering) at
Concordia University
Montréal, Québec, Canada

June 2017

CONCORDIA UNIVERSITY

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and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Building Engineering)

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Abstract

The integration of quantitative building energy performance simulation with qualitative architecture representational 3D data can facilitate performance-based decision making in the early phase of building design process. However, there are some problems that delay decision making until the late stages of design.

Many interrelated parameters can affect building energy performance. Unlike design options conventionally created based on offered values of ASHRAE 90.1 or NECB, design alternatives with lower energy consumption can be suggested through the configuration of various parameters. A systematic strategy is needed to support performance-based quantitative evaluation. Due to the complexity of integration of interrelated energy simulation parameters with qualitative architecture representations, this approach is not being adequately accomplished in current architecture/energy-performance practices. There is a lack of an effective integrated workflow between architects and engineers to simultaneously represent visual qualitative 3D data related to quantitative energy performance-based data of each design alternative.

In addition, exchanging data between the architectural model and the energy model in large-scale evaluations is a time-consuming and error-prone process. Collaborative platforms are not sufficiently being used in current practices to facilitate geometric and physical data-sharing through a single environment. In this regard, there is no clear integrated design workflow between architectural needs and engineering needs.

The objective of this research is to propose a workflow to facilitate decision-making at the early design phase by automatically generating the quantitative energy performance data and qualitative visual representations of each design alternative, in order that architects and engineers can collaborate within a common platform of communication. This proposed workflow will be implemented through the utilization of a case study, within the collaborative platform of Building Information Modeling (BIM).

Numbers of 1296 quantitative energy-performance results and their related qualitative 3D designs have been generated automatically through the BIM platform. These results support architects and engineers with a variety of "best performance-based design solutions," while involving them simultaneously in the design process from the early phase without needing to perform the error-prone and time-consuming process of energy model data re-entry.

Acknowledgement

Since I started my journey in Canada, I have been lucky to encounter many kind and compassionate people, some of them strangers, who helped me feel as though I was not so far from home. I consider these individuals to be like angels working on behalf of God, who may not realize how their acts of kindness helped to get me to where I am today.

While studying as a MEng student, I attended a course instructed by Dr. Andreas K. Athienitis. I became excited and interested in the content and it lit a spark within me to explore deeper as a Research Assistant student in the area of energy efficient building design.

I cannot forget the first time I met my supervisor Dr. Bruno Lee. I was immediately impressed by his thorough understanding and sharp insight. He spent considerable hours discussing various terms and concepts with me in order to extract my strength and limitations. I would like to express my gratitude to him for realizing and valorizing my capabilities and granting me the privilege to work with him. Beyond being my supervisor, I learned from him how a professional can incorporate lifestyle considerations and ethics into his objectives.

Despite many situations that could have discouraged me to continue, I did not give up. I am now delighted to be the first student in our research group to graduate.

Without the contribution of the supportive people within the research group, it would have been hard to reach this place. I would like to thank them all, especially Ata Hosseini and Angel Lam for their helpful contribution and comments near my defense time. I also wish to thank Samson Yip for his time, guidance, and constructive comments.

A special thank goes to my parents, Hamid and Monir, who devoted their youth working tirelessly to support our family. Nothing can compensate for their dedication to us during these years. I hope that they feel a sense of satisfaction as they watch their children achieve their goals and that it can warm their hearts.

Last but not least, Mahmoud Ahmadzadeh-Yazdi is my best friend and husband who has been a gift in my life. He is one of the smartest people I have ever known, but he has never been arrogant. I am always learning from him, everything from subjects of science and technology to humanity. Without his intellectual guidance, emotional support, unconditional love, faithfulness and patience it would not have been possible to overcome the difficulties and finalize my thesis, thank you so much indeed.

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Nomenclature

Abbreviations, acronyms:

ACH: Air change per hour

AEC: Architecture, engineering, and construction

AIA: American institute of architects

API: Application programming interface

BEPS: Building energy performance simulation

BESTEST: Building energy simulation test

BIM: Building information modeling

CAD: Computer-aided design

CDD: Cooling degree-days

CRC: Cooperative research center

CSV: Comma-separated value

DOE: Department of energy

DOE: Design of experiment

EUI: Energy use intensity

FORM: First-order reliability method

GBS: Green building studio

gbXML: Green building extended markup language

GUI: Graphical user interface

HSPF: Heat seasonal performance factor

HVAC: Heating, ventilating, & air conditioning

IEA: International energy agency

IFC: Industry foundation classes

LEED: Leadership in energy & environmental design

LPD: Lighting power density

MEP: Mechanical, electrical, & plumbing

NBSLD: National bureau of standards load determination

NECB: National energy code of Canada for buildings

NFRC: National fenestration rating council

NOAA: National oceanic & atmospheric administration

NRCan: Natural Resources Canada

OFAT: One-factor-at-a-time

PCC: Partial correlation coefficient

PF: Projection factor

PNG: Portable network graphics

PRCC: Partial rank correlation coefficient

SBIM: Structural building information modelling

SEER: Seasonal energy efficiency ratio

SHGC: Solar heat gain coefficient

SORM: Second-order reliability method

SRC: Standardized regression coefficient

SRRC: Standardized rank regression coefficient

USGBC: US green building council

WWR: Window to wall ratio

Symbols:

A: Surface area

D: Shading device depth

α: Solar altitude angle

δ: Declination angle

φ: Observer's latitude

Ψ: Building orientation

ω: Hour angle

Chapter 1 Introduction

1.1 Background

1.1.1 High-performance building design in a single-family residential neighborhood

Architectural design decision making in city scale is usually constrained by various conditions. Key factors such as density development levels, land shape/ use, and street layout regularly call for a fixed situation in urban-scale design. For instance, in a neighborhood of attached row houses the design of building geometry is constrained by these conditions. Thus, the equatorial-facing of building units in the northern hemisphere (namely south façade) usually takes priority in an energy efficient design. In this regard, key design parameters such as windows to wall area that have a high impact on solar heat gain and daylighting are mainly considered in designs. It is also an essential task for engineers to evaluate the impact of architectural design components on the energy performance of buildings (Hachem et al., 2012, Grinberg and Rendek., 2013).

Units in single-family attached row house neighborhoods (a common type of residential housing in Montreal, Canada (Charron and Athienitis., 2006)) are usually designed in simple rectangular geometry. Therefore, changes in design parameters of the south façade (like window to wall area and depth of shading devices) can have a significant impact on both architectural features and energy performance of buildings.

It is important to consider the amount of solar radiation gain in the design of energy-efficient buildings. Through an energy-efficient design, the penetration of solar radiation to interior spaces can facilitate the reduction of lighting and heating energy consumption during cold seasons (Hastings, 2007). Though, energy-efficient facades allow interior spaces to exploit more solar radiation, there are additional criteria that contributes to “efficient” design. Avoiding the trap of unwanted solar radiation to prevent too much heat gain during hot seasons is one such criteria. There are other factors such as moisture transportation through building construction, that do not fit within this research scope. In addition to design considerations, other parameters such as weather data, building type and orientation, and internal loads are considered in running energy simulations (Lee et al., 2002).

1.2 Problem statements

1.2.1 Inadequate use of a systematic performance-based quantitative strategy in current practice to support decision making in the early phase of design

Recently, there has been more interest in making performance-based decisions in the early phase of architectural design (Wang et al., 2015). The process of designing a high-performance building is complicated and needs the cooperation of several experts from the schematic stages of design (Wang et al., 2005). The energy efficiency of buildings is highly affected by various parameters such as geometry, thermal properties of materials, building location, weather condition, occupancy pattern and many other factors (Nguyen et al., 2014, Wang et al., 2005). The input values of parameters offered by the ASHRAE standard may not be the best approach to energy performance-based designs. Therefore, the assessment of various ranges for input parameters may explore some design alternatives with less energy consumption than what is suggested by the standard (Lee et al., 2014). The integration of different sets of parameters may cause these levels of complexity (Nguyen et al., 2014).

According to current assessments, the architectural procedure is not able to perform with this level of complexity. This is due to the lack of strategic methodological knowledge to support quantitative performance-based evaluation of many interrelated energy simulation parameters from the early phase of architectural design. Professionals - from architects to engineers- should integratedly be involved in the procedure.

In consideration of all these difficulties, professionals can usually generate and evaluate a narrow set of design configurations, which may not necessarily be the optimal selection of energy performance-based designs (Hensen., 2004). Performing a strategic approach is required to support building design configurations efficiently and to achieve a higher number of simulation runs and design alternatives.

1.2.2 Lack of practical integrated workflow between architects and engineers for qualitative representation of performance-based data

Unfortunately, there is a lack of integrated workflow between architects and engineers to be able to cooperate from the early phase of design through a uniform comprehensive language.

Energy performance assessment of various design configurations by engineers is quantitative (data based). However, providing qualitative data (visual characteristics of each design) is the key parameter in order for architects to make decisions based on the aesthetic features of designs. Through the configuration of different range of design parameters, a broad set of design alternatives can be provided. Engineers can fulfill part of their fundamental goals through the collection of results of energy simulation of design configurations. However, from an architectural point of view, extensive quantitative energy performance data is not sufficient. Architects need to refer to the visual aesthetic features of the building. Therefore, the disconnection between engineers' and architects' workflow is a critical issue in the energy performance-based building design.

Architects are involved with visual characteristics of building rather than how well it will perform. Therefore, the parallel presentation of a three-dimensional (3D) model related to each energy simulation result can aid architects and engineers in synchronizing their developments simultaneously in a common, understandable language.

Moreover, based on surveys, both architects and engineers acknowledge that the 3D spatial representation of designs has more privilege than the selection of a tool with advanced features (Attia et al., 2012).

Through proposing a workflow that makes a connection between a vast number of energy performance data and 3D models of design alternatives, architects and engineers can cooperate more efficiently in the decision-making process, by understanding the full potential of the relationship between energy data and spatial characteristics (LaVine et al., 1982).

1.2.3 Insufficient utilization of collaborative platform to facilitate geometric and physical data sharing

In current assessments, fundamental problems related to designing an energy efficient building are not always being solved (Bazjanac., 2008). Engineers are not able to propose their results in a collaborative way with architects. Although both seek to achieve the same goals (in the process of designing an energy efficient building), the direction of their efforts are independent from each other.

Due to the complexity of exchanging data between architectural models and energy models, very few design configurations can be evaluated during the collaboration between architects and engineers. Consequently, this may cause the designed building to perform at a lower level than expected (Grinberg and Rendek., 2013, Hensen., 2004, Kim et al., 2015). For example, changes in architectural components (like fenestration size) creates a new design option and for each option, engineers must remodel and rerun a time-consuming energy calculation process. (Bazjanac., 2008). Therefore, due to the lack of a centralized collaborative platform performance evaluations of the building are typically accomplished by engineers in the later phase of design (Hensen., 2004).

An error-prone process of regenerating and re-entering the building geometry is one of the difficulties of energy simulation analysis during collaboration of architects and engineers. Regardless of the recent evolution in the building energy performance simulation (BEPS) tools, their capability to automatically share a geometric model with an energy model is still a concern (Bazjanac., 2008).

Building information modeling (BIM) is an object-oriented tool that stores and offers a vast data library related to physical and functional characteristics of building elements (AIA., 2007, Attia et al., 2012). As the building geometry is embedded in the BIM platform, there is no need for the participant to re-enter the geometric model to energy simulation tools, in each phase of the model transformation.

Thus, by utilizing BIM for energy performance-based decision making in the early design phase, the import/export data-driven process among different platforms can be eliminated and ultimately time and effort can be reduced (Asl et al., 2015, Gupta et al., 2014). Such a centralized data management platform that offers both physical and geometric information can facilitate data sharing among different participants and energy simulation tools.

1.3 Objectives

The principle objective of this research is to propose a workflow that can serve the following purposes:

1- Facilitating decision-making at the early phase of design by supporting performance evaluation with both quantitative and qualitative representations
2- Automating the generation of quantitative and qualitative representations for a large number of design solutions
3- Assisting collaboration of design practitioners, namely engineers and architects, in an integrated environment by promoting dynamic selection of design solutions based on quantitative and qualitative representation
4- Ensuring the deployability of the workflow in an integrated design process, by offering generic and non-proprietary solutions

1.4 Structure of the thesis

The problems to be considered in this thesis are represented in three different parts in chapter 1. Chapter 2 will present a literature review, which outlines quantitative and qualitative data, current practices to handle these data, the approaches in which these data can be integratedly handled, and an introduction to platforms and tools in which these approaches can be implemented. In addition, chapter 2 presents sensitivity analysis methods and an explanation of their use.

In chapter 3 the methodology is explained including the identification of design parameters, the establishment of the Design of Experiment (DOE), and the automated approach to generate data. Chapter 4 presents the case study in which the design parameters are identified and the DOE has been established. Chapter 4 also introduces all other input parameters for performing energy simulation.

In chapter 5, the process of the implementation of workflow in the selected case study as well as the usage of BIM platform is presented.

Chapter 6 outlines all the generated qualitative 3D data and quantitative energy performance-based results. In chapter 7, the results are discussed as well as how the proposed workflow can be used in other process of qualitative and quantitative data generation.

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Chapter 2 Literature Review

2.1 Quantitative and qualitative data representations

Quantitative data expresses the numerical mearement of quantities. Quantitative approaches to sustainable building design provide numerical answers to data such as physical variables, simulation results (energy demand/ consumption), luminous intensity, temperature value, CO_2 emissions, embodied energy, the efficiency of operation, and costs.

Qualitative information is illustration or description of non-numerical data. Qualitative results can be provided through visualization in the process of building design. The quality of assessed problems in building design includes aesthetics, space layout, safety, occupant comfort, shadow analyses, rendering, geometry and form visualization.

2.2 Current practices in handling quantitative and qualitative data in the design process

The building design process falls into six phases (AIA, 2013):

i) Schematic design

Usually, architects propose some design options to clients or to another team participants (engineers), in the sketches form. After the selection of the desired option, the design modification and development phase starts.

ii) Design development

During this phase, the design will be refined to finalize the details.

iii) Construction documents

The technical drawings and other specifications will be prepared by the architect or engineer.

iv) Contract bidding and negotiation

Usually architects help clients to find appropriate contractors in this phase.

v) Construction

The image below represents the process of changing the building form (and orientation), by architects in different stages.

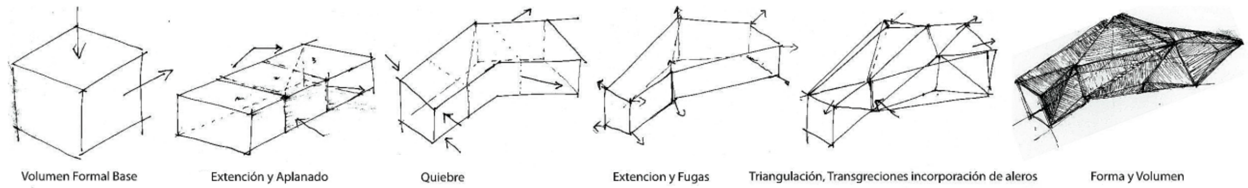


Figure 2.1: Schematic sketch of building form/ mass (Cespedes, 2016)

In the conventional methods of architectural design, a limited number of design options were proposed (usually a single design option was suggested as the best solution). Due to the lack of digital technologies in architectural design process, it was not possible to generate several design options by defining various input values for an architectural component. Consequently, not all design possibilities could be investigated within this limited scope. However as Kelly explains, "the best way to get a good idea, is to get a lot of ideas" (Kelley, 2001).

In recent years, the implementation of Computer-aided Design (CAD) tools in architecture started a revolution in the building design process. By utilizing CAD tools, the manual process of visualizing concepts, drawings, and documentation is replaced by an automated process.

Currently, in advanced levels of architectural design, architects and computational designers are employing programming and scripting skills to create generative forms (Davis, 2015). Through the capabilities of parametric modeling, many design options can be generated.

According to the determination of departments such as Natural Resources Canada (NRCan, 2016) and the U.S. Department of Energy (DOE, 2015), designing energy efficient buildings is becoming essential. Therefore, the interactive evaluation of energy performance with the production of each architectural design option is crucial. In current assessments, energy performance of a building is usually evaluated after the "design development" and "construction document" phases.

Due to the lack of dynamic and interactive workflow between architectural design and energy performance analysis, the geometric information of each design option should manually be exported from architectural drawings in order to run energy simulations.

The image below represents the typical sequences of a building design process.

Figure 2.2: Typical design process of buildings (Autodesk Sustainability, n.d)

Current practices on energy performance assessment and visual representation in the design process (section 2.2) are divided into two approaches that will be further explained in following two sections (2.2.1 & 2.2.2). The first approach explains current workflows to visualize various architectural design options. The next approach presents the most common performance assessment tools currently being utilized.

2.2.1 Visual representational workflows to generate qualitative data

For many years, architects have been limited to drawing what they imagine. As William Mitchell explains, "Architects draw what they can build and build what they can draw." (Mitchell, 2001) Due to the lack of appropriate digital representational platforms, they were not able to illustrate their complex concepts in perceptible documents (Centofanti et al., 2014). As soon as the trend of architectural design transformed to "freeform architecture," the need to utilize Computer-aided Design (CAD) tools increased and the ability to precisely model complex architectural geometry became possible. Frank Gehry is a pioneer architect who utilized digital technology to optimize complex architectural models (like freeform surfaces) and translate them directly into a process of construction. He used CATIA™ 3DEXPERIENCE® to model the Guggenheim Museum Bilbao building. CATIA® is developed by Dassault Systèmes® (CATIA, 2016). It is an advanced tool that was initially utilized in the aerospace industry.

Later, the Gehry Technologies®' company developed the Digital Project Designer CAD tool, which adapted from the CAD system of CATIA™, and was simpler to use in the building industry and now it is being developed by Digital Project, Inc (Pottman et al., 2007).

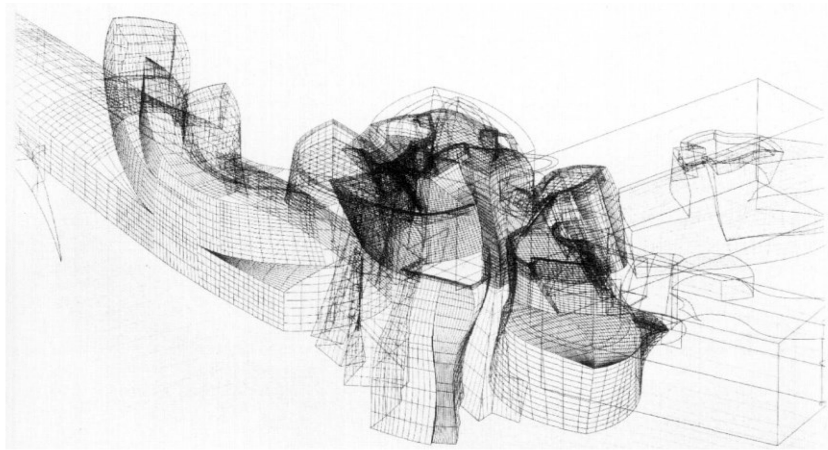


Figure 2.3: Guggenheim Museum Bilbao, computer generated model (LeCuyer, 1997)

In the contemporary process of architectural design, utilizing digital technologies allows the geometry of buildings to be created, represented, and visualized in three-dimensional (3D) forms. 3D modeling platforms help users to visualize design through multi-dimensional and multi-level descriptions (Pottman et al., 2007).

Through the years, the graphic representation and rendering of 3D building models has been developed in many aspects. 3D models can be created manually using CAD tools or existing buildings can be automatically documented through 3D laser scanners (Centofanti et al., 2014, Xiong et al., 2013). Moreover, parametric modeling and scripting skills allow architects and designers to change complex geometry dynamically or to generate many design alternatives instead of producing a single static design. The figure below demonstrates parametric design. As it is shown, various design options can be represented for a single project through the changes of configuration of parameters.

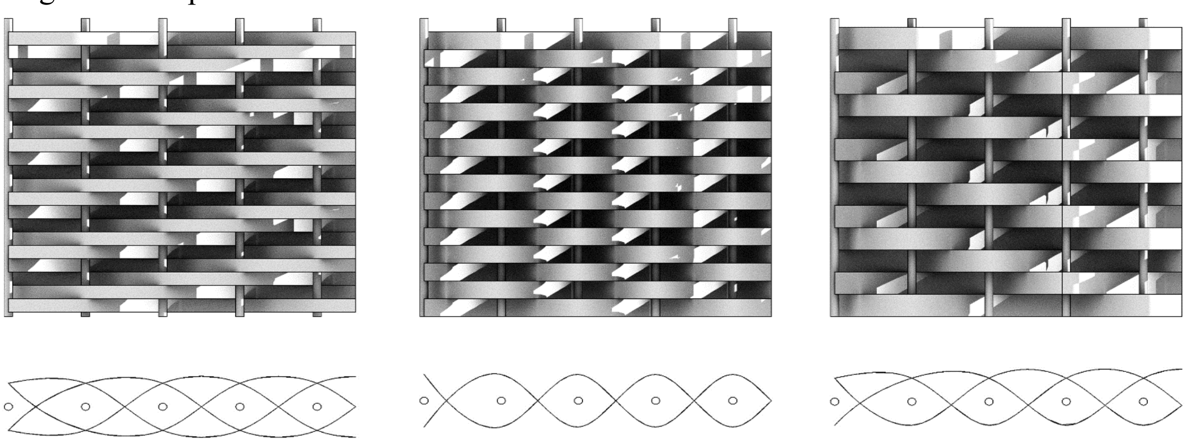


Figure 2.4: Parametric design (Galanou et al., 2013)

Nowadays, there are many platforms that aid architects to precisely deliver drawing documents from the early schematic design phase to the final stages. The comparison of the potential capability of each platform is not the purpose of this research study. However, significant matters related to the selection of tools in this research include:

- the capability of implementation in all phases of design to fulfill the architectural expectations for having precise and detailed drawings (plans, wall sections, etc.).
- the potential to support users with parametric 3D visualization through the automation of the design process by scripting and programming skills.
- the ability to exchange data with other platforms and tools.

2.2.2 Performance assessment tools to generate quantitative data

Traditionally, in order to quantify a building's energy performance, the analytical formulations were manually used to perform calculations through simplified assumptions (Clarke., 2001). Later, the potential of using computers in building energy modeling was recognized, and a computer program named the National Bureau of Standards Load Determination (NBSLD) was developed. Although this program could only model a single zone, this was a big step toward building energy modeling (Walton, 2001).

Over time, virtual building modeling and simulation programs have been developed and used to quantitatively estimate specific output responses such as energy demand and consumption, CO2 emissions, life cycle costs, annual energy cost, and many other options (DOE, n.d). However, other than energy performance evaluations, the quantitative data is beyond the scope of this research.

Energy simulation programs have been adopted by various numerical modeling methods such as the response function method under time and frequency domains, and through statistical methods using finite differences and finite element approaches (Clarke., 2001, Hui., 1996). For example, the response function method under the time domain (known as thermal response factor) has been used in many simulation modeling tools such as DOE-2 and BLAST (Hui., 1996, Kreider., 2000). The descriptions and procedures of the development of building energy modeling techniques can be accessed through the "American Society of Heating, Refrigerating and Air-Conditioning Engineers" (ASHRAE).

Currently, hundreds of simulation and modeling platforms are available for the quantitative evaluation of building performance, or life-cycle cost (Crawley et al., 2001). However, only certified programs can be trusted. ASHRAE Standard 140 (ASHRAE, 2008) which has recently been referenced by ANSI/ASHRAE/IESNA Standard 90.1 (ASHRAE, 2001) was the first codified method to test building energy tools.

There are various techniques to validate building energy simulation programs including empirical, analytical, comparative, or a combination of these techniques. The comparison of these methods and their pros and cons are accessible within the ASHRAE Handbook (ASHRAE, 2005). Accordingly, one of the most commonly used standard methods is the Building Energy Simulation Test (BESTEST) which was developed by the International Energy Agency (IEA), and its code has been published by ASHRAE (ASHRAE, 2008, Judkoff and Neymark., 1995). BESTEST is a "comparative" validation technique in which results from tools are compared to analytical solutions of developed test cases (DOE, n.d, Judkoff and Neymark., 1995).

In addition to the consideration of the certified and validated programs, several factors may lead to the selection of Building Performance Simulation tools (BPS) based on the purpose of use, graphical user interfaces (GUI), and capability of exchanging data with other platforms. Many studies have been done to compare the potentials of various simulation tools (Crawley et al., 2008, Maile et al., 2007).

BPS tools fall into two categories. In the first category, the simulation engine is developed by the US Department of Energy (DOE), such as EnergyPlus®, Autodesk® Green Building Studio® (GBS), eQUEST®, and DesignBuilder®. The second category includes those tools that use their own simulation engines, such as IES VE and Trace 700 (Winkelmann et al., 1993).

Some of the currently used BPS tools have two parts: a GUI and a simulation engine. Information such as building geometry, weather data, HVAC, and internal loads should be fed as an input to simulation engines by users. Data of building geometry can be obtained through the drawing files (Ham and Golparvar-Fard., 2015). However, there is a lack of integrated workflow that can employ all information in a single platform through the implementation of common environment between building modeling visualization and energy performance assessment.

2.3 Integration of qualitative and quantitative approach workflows

In the current process of sustainable building design, the integrated approach of quantitative energy performance-based and qualitative visualization-based platforms has been more attended than the conventional way of design. Based on the U.S. Green Building Council (USGBC) definition, integration is a method that can simultaneously encompass the process of "design" and "operation" of sustainable buildings (USGBC, 2014).

The integrated workflow proposed in this research will be able to contribute to the design in the following ways:

- All experts who are participating in the project will be able to be interactively involved in all phases, from schematic design to construction (USGBC, 2014). The integrated workflow offers the possibility of multidisciplinary team work, and will allow the team to achieve higher levels of energy efficient design.
- The integrated workflow will be able to provide the capability of decision-making in the early phase of schematic design. Decision-making in the schematic phase has a significant impact on energy performance in the operational phase. However, there are few platforms that simplify decision-making in the early stage by proposing qualitative and quantitative data through dynamic interactions (Wakita and Linde., 2003).
- The integrated workflow will offer qualitative and quantitative results by simultaneously performing parametric modeling and energy simulation.
- All the information that are needed for building modeling and energy performance assessment (geometric data, weather data, thermal properties of material, and detailed architectural drawings) will be accessible from the early schematic phase of design through an integrated workflow. Consequently, the back and forth iteration of architectural design manipulation and energy performance simulation will be reduced.
- The energy models' data will be shareable between various tools and platforms through standard formats.

2.3.1 Collaborative data exchange

Recently, several studies have connected architectural models to building energy simulation tools, as most of current BPS tools need geometric data as an input for running simulations (Wang et al., 2015). The common goal of these studies is to automatically translate a building energy model to be used as an input for BPS tools such as EnergyPlus® (Bazjnac., 2008), DOE-2 (Maile et al., 2007), etc. These procedures have some restrictions and disadvantages, but they are an improvement in comparison to the conventional way of building energy simulation. In this regard, the information of energy models can be directly shared with energy simulation tools (Bazjanac., 2008).

Currently, there are two main standards for exchanging building energy models' data among compatible building energy simulation tools (BuildingSMART, 2007, GSA, 2012, Lam et al., 2012):

- The first one named Industry Foundation Classes (IFC), provides object-oriented data and was developed by buildingSMART.
- The second one is called the Green Building XML (gbXML) and was developed by Green Building Studio. It is a text-based (XML) format that contains the information such as building geometry, thermal insulation of building elements, HVAC equipment, etc.

The data can be directly transferred as inputs to be analyzed by compatible energy simulation engines (Ham and Golparvar-Fard., 2015).

2.4 Sensitivity analysis to reduce the dimension of the assessment

When the investigation of a wide variety of parameters is not feasible, sensitivity analysis can help to limit the scope of research. Full factorial design approach (discussed later in section 3.1.2) covers all possible combinations of design parameters. The number of parameters' combinations can be massive due to the defined "levels of investigation"; for example, more than one hundred thousand or a million alternatives can be suggested.

In such situations, too many efforts to evaluate of all the extensive data may result in negligible and unnecessary information. Thus, performing sensitivity analysis can help to limit the domain of assessments to the most influential parameters.

Sensitivity analysis is utilized to recognize key input parameters that have the most impact on output results. In the process of building energy performance evaluation, sensitivity analysis methods can be used to determine the relation of input parameters on energy performance indicators (Heiselberg et al., 2009, Tian, 2013).

Sensitivity analysis methods fall into three types: screening, local and global. Screening methods can be used when parameters are investigated individually (one parameter at each time or one-at-a-time (OAT)). Furthermore, in the local method the response of outputs is being explored under variations of one parameter, while other parameters are fixed. However, in the global method the response of outputs is simultaneously evaluated on the variation of all input parameters. There are several global sensitivity analysis methods such as the Standardized Regression Coefficient (SRC), the Partial Correlation Coefficients (PCC), the First-Order Reliability Method (FORM), the Second-Order Reliability Method (SORM), and variance-based methods (known as ANOVA) (Saltelli et al., 2000).

Though different methods for sensitivity analysis can be chosen, the selection of the appropriate method is a crucial step according to the relationship between values of outputs and inputs.

For correlations which result from linear regression, the Partial Correlation Coefficients (PCC) method is well performed. In addition, the Standardized Regression Coefficient (SRC) method is an appropriate choice when the relationship between input and output are *linear and monotonic* (Saltelli et al, 2008).

In a monotonic relationship, due to the increment of input, the output will decrease or increase. In some cases the relationship between input and outputs values may be monotonic but not necessarily linear. For ranking the sensitivity of parameters in this type of data characteristics (*nonlinear & monotonic*), the Partial Rank Correlation Coefficient (PRCC) and standardized rank regression coefficients (SRRC) are suggested to linearize the relationship (Hamby., 1994, Iman et al., 1985, Reuter and Liebscher., 2008). As an example of monotonic and nonlinear relationships between input and output variables, Lee (Lee, 2014) has investigated the impact of various input parameters (such as U-value of glazing, insulation values of walls and roof, the absorptance of material) on building energy performance. Results indicate that all relationships are monotonic, although some of them are nonlinear. Therefore, to linearize relationships, rank transformation has been suggested to be applied to the output values.

When input parameters are interdependent and it is not simple to precisely encode the relationships into the regression based equations, a method is required in which relationships are not assumed as functional forms. In such cases, ANOVA is a suitable statistical sensitivity analysis approach in *nonlinear and nonmonotonic* relations (Archer et al., 1997). Through the employment of this method in the process of energy performance-based building design, a significant effect of various input parameters on the variance of energy performance indicators can be evaluated. Furthermore, the impact of input parameters' interaction on output variation can be investigated (Mechri et al., 2010).

For instance, Lam (Lam et al., 2016) used the ANOVA method and proposed the sensitivity index of 10 design parameters of a curtain wall façade in an office building in Montreal, Canada. The parameters that were the subject of her investigations were U-value of glazing, solar heat gain coefficient (SHGC), visible transmittance, U-value of the mullion, U-value of the spandrel panel, window to wall ratio (WWR), infiltration rate, depth and inclination of overhang shading devices, and the efficiency of PV. As a result of Lam's assessments, WWR, SHGC, and the depth of the overhang shading device are significant parameters that affect the "annual cooling consumption". In addition, WWR, glazing U-value, and infiltration are important parameters that affect the "annual heating consumption". Moreover, WWR, depth and the inclination of overhang shading device are significant parameters that influence on the "annual lighting consumption".

In this study, the number of investigated design parameters is limited. Only design parameters that are influential on both visual characteristics of the building (architectural aesthetic features) and performance (energy consumption) are selected. Through the full factorial configuration of identified parameters, 1296 alternatives have been produced. Performing sensitivity analysis is not worth the effort on this scale of the dataset. Therefore, the most critical interrelated design parameters are identified based on experience and the results of sensitivity analysis for the large-scale data (specially results driven from the ANOVA method) of other researchers' works (in section 4.2 the identification of design parameters will be further explained).

2.5 BIM as a centralized platform

The idea of Building Information Modeling (BIM) is to connect people with different areas of specializations involved in the building design process. Through utilizing BIM, all design participants are engaged in the process of building problem-solving simultaneously.

BIM is an object-oriented tool that both stores and offers a large number of data related to physical and functional characteristics of building elements (AIA., 2007, Attia et al., 2012, Maile et al., 2007). Every element in BIM corresponds with related information (Wang et al., 2015). The appropriate implementation of this information in the building design process can have a major effect on the time and effort spent (Kumar., 2008, GSA, 2012).

BIM is being used to integrate architecture, engineering, and construction (AEC industry) work procedures (Grinberg and Rendek., 2013). BIM can offer various disciplines of modeling and analysis such as building performance analysis, structural analysis, MEP system modeling, construction management, and cost estimation (Azhar., 2011).

2.5.1 The capabilities of the BIM platform

Building performance analysis:

The data required for building modeling and energy simulation such as the various building components, material thermal properties, weather data, HVAC systems, occupancy schedules, and the spaces/zones, are available in BIM (AIA., 2007, Ham and Golparvar-Fard., 2015, Volk et al., 2014).

Also, some BIM tools have the capability to analyze both qualitative and quantitative lighting data. Quantitative results can be obtained through the analysis of artificial and solar lighting, while qualitative representations are provided through renderings of light distribution and glare.

Structural analysis:

Structural Building Information Modelling (SBIM) contains required data for structural analysis such as the mechanical properties of materials, loads, structural behavior, classes of welds and steel, and the place of the axis in geometry. Furthermore, the elements offered in the BIM tools' library (like walls, curtain walls, mullion windows, columns, beams, slabs, stairs, roof, skylight, truss, foundation, ramp, railing) are helpful in the process of structural modeling and analysis. These elements can be exchanged through IFC file format in forms of IFC-Column, IFC-Wall, IFC-Beam, IFC-Slab (BuildingSMART, 2007).

Cost estimations:

The initial step of cost estimating is quantification. Information embedded in BIM makes quantification effortless through automatic synchronization. For example, any changes in design (changing size or type of window) will be reflected on construction documents and schedules, which helps to save time and cost and reduces human errors.

Construction management:

Construction management helps to efficiently control time, cost, and the quality of the project. Many construction management tools are integrated with BIM models to schedule projects, to check quality assurance and physical safety, and to simulate and visualize the construction process. Construction management helps to reduce delays and to sequence problems by analyzing project activities before construction (Hardin and McCool., 2015, Matthews et al., 2015).

Exchanging data between different parties:

Coordinated multidisciplinary information is offered within the BIM model (Autodesk, 2008). BIM has the capability to impart building information among collaborating organizations or individual construction companies. It can exchange information between various design practitioners who are involved in the modeling and energy analysis of buildings to enhance multidisciplinary and integrated workflows in all phases of design (Attia et al., 2012, AIA., 2007, Grinberg and Rendek., 2013).

Exchanging data between different tools:

BIM tools can communicate with each other through gbXML and IFC standard formats (Wang et al., 2015). Moreover, BIM geometry data can be exported in order to be utilized by other energy simulation tools. Exchanging geometry data through BIM, helps to reduce the time for the creation of models for energy simulations (Bazjanac., 2006, Ham and Golparvar-Fard., 2015).

Manufacture contribution

Currently, many building product manufacturers are sharing details of their products whithin BIM. These manufacturers are making their products available to architects and engineers by creating BIM object (or component) libraries. When products are made available in the BIM libraries as objects, they contain the data of geometry, physical properties, mechanical features, manufacturers information, etc. As an example, an air conditioning unit is associated with data such as flow rates, supplier, operation/ maintenance process, and clearance requirements when it is offered as a BIM object (CRC, 2007).

The image below represents the architectural, structural and MEP model of a single project that has been created through the BIM platform.

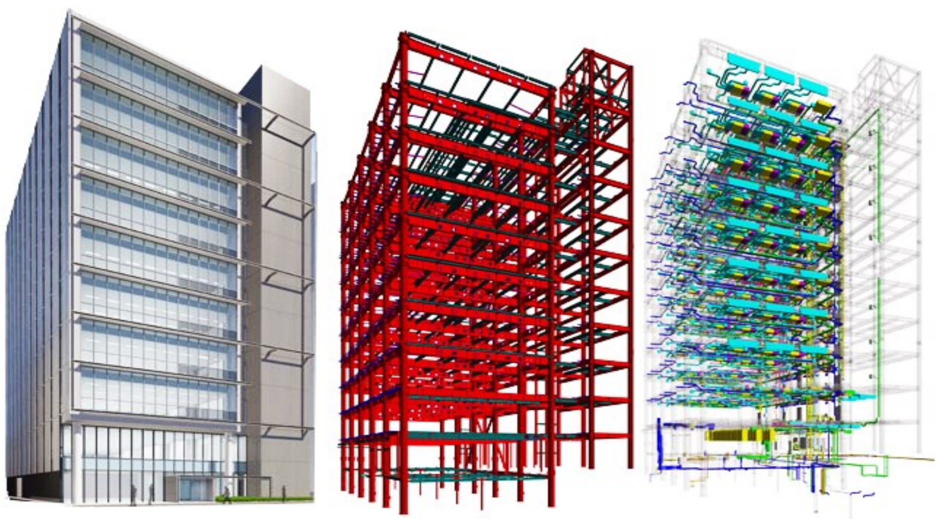


Figure 2.5: i) Architectural ii) Structural iii) MEP models in BIM (AECMAGAZINE, 2011)

2.5.2 BIM platform- Autodesk Revit

Autodesk® Revit® is the most commonly used BIM platform and offers Revit Architecture, Revit Structure and Revit MEP (designs and models mechanical, electrical and plumbing systems). It can be utilized in various areas related to the AEC industry such as energy simulation, daylighting analysis, sustainability analysis, structural analysis, construction management and cost estimation (Asl et al., 2015).

Dynamo is an open-source graphical programming add-in, used in connection with Revit® to provide the capabilities of parametric design/ analysis, that allows architects and designers to generate parametric modeling (Dynamo, n.d). Dynamo can be easily applicable for both programmers and designers who are cooperating in the BIM project with no scripting background.

The Revit® platform has the capability of energy performance analysis through the cloud-based simulation engine called Green Building Studio® (GBS). GBS uses the DOE-2.2 engine for simulations, and it is certified by the U.S. Department of Energy. The results of GBS have been evaluated and have met the criteria under the Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs and ANSI/ASHRAE Standard 140 (ASHRAE, 2008).

Moreover, Autodesk® Revit® can be used for qualitative and quantitative lighting analysis. "Lighting Analysis for Revit" is a plug-in which directly investigates quantitative results of artificial and solar lighting on the Revit model and uses cloud-service (Autodesk 360 Rendering). Analysis types of LEED 2009 IEQc8.1, LEED v4 Eqc7 opt2, or Custom can be selected for performing the simulation. On the other hand, qualitative renders of illuminance simulations can be accessible via the "Rendering as a Service (RaaS)" feature for Revit, which illustrates light distribution and glare.

Revit® can also facilitate the process of cost estimation. There are several approaches existing to obtain material quantities from BIM which are needed for cost estimation such as Application Programming Interface (API), ODBC connection, and Output to Excel.

Through the API approach a direct link is created from Revit® to cost estimators such as U.S. COST or Innovaya. ODBC is a standard programming interface that accesses the information in the building model and exports dimensional data in 2D or 3D CAD files. ODBC integrates BIM with costing solutions such as CostX or ITALSOFT. In the last method (Output to Excel), model is created in Revit and the quantitative data of elements is written on a Microsoft® Excel® spreadsheet, which can then be used as input for cost estimation.

Many companies such as Turner & Townsend Rawlinsons (one of the largest construction and management consultancies in Australia), Parsons Brinckerhoff or PB (one of the oldest consulting engineering firms in the United States), Ryan, and Oculus Inc (Autodesk, 2007) use Revit® to obtain quantitative data for cost estimators.

In order to perform construction management, Autodesk® Navisworks® can be integrated with the Revit® model (as a BIM platform) for project scheduling through simulation and visualization of construction (Hardin and McCool., 2015, Matthews et al., 2015).

2.5.3 BIM platform- Rhinoceros

At the present time, some workflows are being used among architects and engineers for parametric energy analysis and building modeling. For example, Grasshopper™ is being utilized as a visual programming editor for Rhinoceros® (Rhino) that aids designers in creating generative models (McNeel, 2010). In addition, some open-source plugins for Grasshopper™ help for running energy simulations.

One of the widely-used plugins is Ladybug, which imports the EPW standard weather file (EnergyPlus weather file) in Grasshopper™ (Roudsari et al., 2013). Honeybee is another plugin that creates a linkage between Rhino/Grasshopper™ and simulation tools such as EnergyPlus and OpenStudio (Roudsari, 2015).

There are some other open-source plugins as well that provide the capability of parametric energy and daylighting analysis through Rhino/Grasshopper™, such as Gerilla, DIVA, and Archsim.

Recently, a third-party software upgraded Rhinoceros® with some BIM features. VisualARQ supports Rhino with an IFC standard import/ export function. Recently, a plugin for Grasshopper™ called Grizzly Bear was developed, which allows exporting a gbXML format from Rhino/Grasshopper™ (Roudsari, 2014). There has been little research done to investigate the direct linkage of Rhinoceros® with other tools through this plugin, as well as a lack of holistic studies. Moreover, RhinoBIM was developed by Virtual Build Technologies LLC to enhance Rhino v.5 for integration into the AEC industry.

Although the Rhino/Grasshopper™ workflow can offer parametric energy analysis and architectural modeling, it currently being improved by some features of BIM. The third-party software is needed to make Rhino/Grasshopper™ compatible with other BIM tools and it does not primarily have access to the building assemblies' library that BIM tools have (Asl et al., 2015).

2.5.4 Other BIM platforms

Currently, some of the most well-known companies that develop BIM platforms are Autodesk® (Revit), Graphisoft® (ARCHICAD), Bentley® (AECOsim), and Nemetschek Vectorworks® (Vectorworks). In addition, the Digital Project Designer platform was originally developed by Gehry Technologies but is now being developed by Digital Project, Inc.

Some structural BIM tools include Tekla Structural Designer (by Trimble company), RSTAB, and Robot™ Structural Analysis Professional (by Autodesk company).

Also, some of the most well-known construction BIM platforms such as VICO and Solibri Model Checker (SMC), help check for quality assurance, physical safety, and the integrity of building information models and integrate with the ARCHICAD (by Graphisoft company) BIM tool (O'Donnell, 2014).

2.5.5 Summary of some BIM platforms

The table below demonstrates a summary of some of the most used BIM platforms and their capabilities.

Architectural BIM Platform	Generative Modeling	Architecture	MEP	Structure	Building Energy Modeling	2D detail technical drawings	3D modeling	IFC export	gbXML export	Cost estimator integration	Construction management
Archicad	–	✓	GRAPHISOFT MEP Modeler™ plugin	TEKLA Structures tool	EcoDesigner	✓	✓	✓	–	✓	VICO
AECOsim	–	✓	✓	✓	AECOsim Energy Simulator	✓	✓	✓	–	✓	–
Digital Project Designer	–	✓	✓	✓	–	✓	✓	✓	–	–	✓
Revit	Dynamo	✓	✓	✓	Green Building Studio (GBS)	✓	✓	✓	✓	✓	Navisworks
Rhinoceros	Grasshopper	✓	–	RhinoBIM	✓	✓	✓	VisualARQ plugin	Grizzly Bear	–	–
Vectorworks	Marionette	✓	✓	Scia	IESVE	✓	✓	✓	✓	✓	Synchro

Table 2.1: Summary & comparison of architectural BIM platforms

2.6 Scope of the study and tool selection

Since energy efficiency is a critical economic issue and since buildings have too much impact on this issue (because of their high energy consumption), designing energy efficient buildings will help to save money while reducing the amount of greenhouse gas emissions (USGBC, 2014). On the other hand, early decision making can contribute to reduced time and effort. In this regard, making the connection between several experts who are participating in the process of designing an energy efficient building is a crucial step.

There are some studies tried to integrate qualitative architectural representations with quantitative energy performance assessment from the early phase of design (Ochoa et al., 2012, Nembrini et al., 2014). However, there are some lacks in these studies. For example, many parameters can affect both visual features and energy performance of the building, but only the effect of windows to wall area is assessed in these studies. In addition, various window size distributions can be defined for each window to wall area but has not been considered in these researches. Moreover, a clear systematic method has not been proposed in these studies in order to generate and evaluate all the possible design alternatives.

The main goal of this research is to propose an integrated workflow that generates quantitative energy performance data and qualitative visual 3D representational data through a systematic full-factorial and an automated process within the BIM platform.

The choosing of the right Building Performance Simulation (BPS) tool based on goals of studies is a challengeable step for professional users because there are many BPS tools (Attia et al., 2012). Among different BIM platforms, Autodesk® Revit® is usually selected as it is the most widely used. However, there are many gaps in research regarding a feasibly integrated workflow through BIM between architects and building engineers. The use of a third-party software for exchanging data between architectural models and energy models can be eliminated by proposing an integrated workflow. Accordingly, by offering an integrated workflow the contribution between the various experts can be accessible through a single platform, and the data can be exchanged between architects, engineers and construction managers (AEC industry) (Lam et al., 2012).

Currently, several researchers have concentrated on the automation of applying geometry created through BIM in the building energy simulation tools (EnergyPlus, DOE-2, or TRNSYS). Unfortunately, this focus loses some ability to exploit BIM (a model-oriented platform) to connect the spatial characteristics with corresponding building energy performance data.

However, a few studies have integrated the computational modeling with energy simulation under the assessment of a wide range of input parameters through the BIM-based platform. For example, Rahmani Asl has worked on the development of a “BIM-based performance optimization" (BPOpt) tool. His study is focused mostly on the creation and introduction of a multiple-objective optimization tool/ framework (named Optimo) through the BIM platform. This desired framework provides an opportunity for designers to assess multiple-objective optimization through supplying a set of Pareto Optimal Solutions (Asl., 2014, Asl et al., 2015).

However, ***in this research, the workflow is proposed to connect architectural and engineering workflows by simultaneously generating 3D architectural models and energy simulation data through the automatic process, while proposing all design possibilities by full-factorial configuration.*** Revit® (as a BIM platform) is utilized in this study to integrate parametric architectural modeling and building energy performance analysis, in order to facilitate decision making from the early design phase.

Since Revit® can provide the accurate virtual geometry of a building as well as a high-level of static and dynamic information (such as a physical characteristic of materials and location specifications) (Eastman et al., 2011, CRC, 2007), the computational energy analysis and model visualization can be more straightforward.

Chapter 3 Methodology

3.1 Identification of design parameters

The proposed workflow in this research allows architects and engineers to make decisions through integrated contributions starting in the early phase of design. Since both architects and engineers need to simultaneously communicate in order to make decisions, selection of parameters is based on their common domain of interference. This means that parameters that have an impact on both architectural design and energy performance have to be identified for evaluations. For example, a parameter such as R-value, which does not have any effect on visual characteristics of architectural design, is not the target of this study. On the other hand, utilizing various colors or decorative components in architecture may improve the aesthetic features of the design, while they may have only an insignificant impact on the energy performance of the building. By changing the colors of materials, their reflectance value may change, which will usually not have a significant impact on energy performance. Parameters such as depth of shading devices and windows to wall areas can influence both architectural features and energy performance evaluations.

In this regard, numbers of common interrelated parameters are limited, and their combinations will not suggest massive design alternatives. Therefore, sensitivity analysis for the identification of sensitive parameters on the output variable (energy performance) is not part of the assessment of this study. Parameters will be identified in section 4.2 according to experience and the derived outcomes from relevant research studies.

3.1.1 Establishment of design of experiment (DOE)

The “design of experiment (DOE)” approach that is used in this research is briefly explained in this section. The term “experiment” refers to one type of systematic statistical exploration being used to comprehend the design. The experiment in this investigation will be systematically structured by classifying controlled input variables.

DOE exploration introduces the sets of conditions in which input variables may directly have an impact on the output results. In fact, by utilizing the DOE method, the effect of various input parameters (experimental factors) within defined settings (levels of factors) to the output results (response variable) will be assessed. One of the main purposes of using DOE is to compare the constructed design alternatives. All results and solutions can be investigated to reply to any “what if ” inquiries of design decision makers. This method is very practical, and its application helps improve the design process (Freeman., 2004, Winer et al., 1971).

In this study, in order to pick the most significant parameters and to subsequently establish the most effective experiment, a good knowledge of building energy performance is needed. The DOE technique permits the arrangement of all energy simulations and the exportations of three-dimensional models in a systematic way. This will significantly help save time and reduce the complexity of the combined processes of design and performance assessment in controlled conditions.

The levels of investigations in this methodology are based on the following hierarchy:

First, the system is designed with various components, where each component can convey a specific function. Then, the parameters that may have a recognizable impact on the desired objective will be selected, and the levels of the investigation will be defined for these parameters. Next, according to the establishment of the DOE and the type of chosen appropriate experimental method, the configuration of input parameters will be determined. Ultimately, the results for each alternative will be computed, and the data will be analyzed to select the best configuration.

After identifying the desired parameters in this study, the full factorial experimental approach has been applied to investigate all possible combinations. In the next section, the full factorial approach is explained in detail.

3.1.1.1 Full-factorial experiment

The conventional parametric experimental design is known as one-factor-at-a-time (OFAT) and is the valid approach for testing only one factor while others remain fixed. The OFAT experiment is more appropriate for design alternatives that are restricted under certain technologies or conditions. In contrast, the multi-factor experiment (called the full factorial experiment) is a suitable comprehensive design approach to investigate multiple variables simultaneously. Through full factorial design, all possible configurations of input parameters within the defined levels can be proposed. Hundreds or thousands of runs may be generated to ensure the coverage of all settings. This feature allows designers to have more flexibility in selection of design alternatives by proposing a broad set of options.

The full factorial experiment is practical when the numbers of the investigated parameters are few and can be determined in the finite ranges. By adding any further parameters, the number of combinations will increase exponentially. As an example, the shading device depth is considered as one parameter, and for a certain design range, the level of investigation is assumed to be 6. If it is assumed that there are three other parameters with the same level of investigation, the result of all possible combinations through full factorial method will be 1296. However, if only one other parameter with the same level of investigation will be added, results will rapidly increase to 7776. The table below shows the effect of adding parameters in a quantity of runs.

Number of input parameters	Number of investigation level	Number of full factorial run
2	6	36
3	6	216
4	6	1296
5	6	7776

Table 3.1: Effect of adding parameters in number of full factorial run

In this study, 1296 design configurations have been assessed through applying the full factorial approach. Details of parameters' selections and design ranges will be explained more in the case study (chapter 4).

3.2 Automated generation of qualitative representational data in parallel with energy simulation

To obtain more energy efficient buildings with the least amount of energy consumption, engineers tend to explore more design alternatives at the early phase of design. It can happen by deploying a large number of energy simulation runs, which is in contrast to the conventional deterministic approaches (input values extracted from building standard codes or similar practice guidelines). On the other hand, proposing the qualitative data of each design configuration facilitates decision making for architects who are collaborating in the design of energy efficient buildings. As described, through the full factorial combination of input parameters, a vast number of design alternatives will be available. However, the parametric energy performance analysis and architectural modeling of vast design alternatives requires an appropriate platform, that can integrate 3D modeling with energy simulation through an automated workflow.

The manual creation of numerous energy models in order to run multiple energy simulations requires inputs from several disciplines, which is time-consuming (Asl et al., 2015). Therefore, automating both sides of the process (3D modeling and energy simulation) and generating them together is significantly important in order to decrease the human interference and effort, and to avoid probable input errors. The presented design workflow in this research, is more efficient because the building geometry can be directly exported as energy model while the energy simulations are being run automatically.

Although many studies have been done, there are still some challenges to automate parametric performance-based design and make it feasible from the early stages (Lin and Gerber., 2014). To facilitate the procedure of automating the generation of many 3D models and energy simulations, it is important to organize the required input parameters into the appropriate groups and to structure the building simulation in a suitable hierarchy.

Subsequently, the proposed workflow can be developed in the design of buildings which consider qualitative representations (architectural aesthetic appeal) and quantitative data (energy performance) simultaneously through the automated parametric evaluations.

3.3 Proposing performance based design trend to support decision making

By continuing the methodology steps, simplifying the analysis within the comprehensive systematic approach and automating the whole process, the proposal of design alternatives is the final step.

The suggested workflow will provide engineers and architects with the design trend to synthesize large quantities of visual qualitative and energy performance quantitative data. Thus, the ability of designers or clients to make better choices will increase dramatically. In addition, by application of a holistic design approach, there would be more than one ideal performative-architectural design solution and users would be served with more than one “best performance-based” design.

Chapter 4 Case Study

4.1 Introduction of case study

The case study selected in this research is the designed residential unit in Montreal, Canada. The low-rise and single-family row house stocks are the typical typologies of residential houses in the central neighborhood of Montreal (Charron and Athienitis., 2006). The forms are designed as long rectangular shapes with a narrow façade.

Figure 4.1: Traditional row houses in Montreal, Canada (Hargrove, 2010)

Since new constructions tend to be adaptive in the modern urban setting of Montreal, while at the same time respecting the traditional type of living spaces, the interest in contemporary architectural design is rapidly growing. Moreover, the need for designing energy efficient single-family houses is increasing. Therefore, the residential row house case study has been selected for this research in order to represent the feasibility of the proposed workflow in the design process of energy efficient modular façades.

The image below demonstrates the contemporary architecture of attached row houses that have been designed by some architects from the School of Architecture at McGill University. The target of design is "International Solar Decathlon in China 2018," and at the same time feasibility of constructing this building in attached row houses' urban setting in Montreal. The preparation for this competition is through the collaborative team work of McGill and Concordia University (TeamMTL).

Figure 4.2: Design of two-story and single-family row residential stocks (TeamMTL)

In this study, the architectural design has been used for further façade assessment through a proposed integrated workflow between architects and engineers that can automatically generate various south façade design alternatives while running the energy simulation for each configuration through the BIM-based platform. The orientation of façades is considered to be south-facing.

Although the initial design has been inspired by works of architects in TeamMTL, all the descriptions, statements, hypothesis, and process levels are independently done and are only exclusive to this study's workflow. The building has been remodeled in Autodesk®Revit®, and all the parametric families (Revit components) like windows and the shading device have been created within this platform. In addition, the thermal properties and input factors needed for energy simulation have been set based on the standards and requirements that will be represented later in the following sections.

The key design parameters of the south façade related to this particular case study are introduced in the next section, while characteristics and design principles for each of them are also investigated and explained. In chapter 6, combinations of those design parameters are quantified by pursuing their effect on the energy consumption of the whole building.

4.2 Identification of design parameters for establishment of the DOE

One of the main objectives of the proposed workflow is the integration of architectural design with energy performance assessment, which in practice typically takes the form of a collaboration between architects and engineers from the early phase of design. Therefore, the identification of parameters is based on the common area of expertise of both groups. Many parameters have an effect on the whole building energy performance. On the other hand, many design factors influence the characteristics of architecture. In the proposed workflow only interrelated parameters that affect both architectural design and energy performance are the target of assessment. Interrelated parameters are identified according to experience, and prior researches. In the table below, some parameters are identified, while interdependent parameters are highlighted.

Parameters	Architecture aesthetics	Energy demand/consumption	Note
WWR	✓	✓	
Building shape & orientation	✓	✓	Changes in aspect ratio of south's width to length (W/L) influences on energy demand
Shading device Depth	✓	✓	
Colors/ materials/ textures of exterior surfaces	✓	✓	Such as various color coatings, textured façade panels
Decorative components	✓		Such as non-structural columns
Thermal insulation		✓	RSI value of constructions such as walls & roof
Roof shape, orientation & tilt angle	✓	✓	
U-value of glazing	✓	✓	Such as mullion, skylights, etc.
SHGC of glazing	✓	✓	
Infiltration rate		✓	

Table 4.1: Identification of design parameters (highlights show the interdependence parameters on both aesthetic and energy performance)

The parameters that are interest of this research are WWR and the depth of shading device. WWR is evaluated through the variation of separate parameters such as the width and height of windows. In total, four parameters are parametrically combined to produce various design alternatives that respectively are: the width of the first-floor window, the width of the ground-floor window, the height of the ground-floor window, and the depth of the shading device. Through the establishment of DOE and the full factorial combination of all these parameters with the level of investigation of 6, 1296 design alternatives have been proposed in total. (See section 6.1 for result of full factorial combinations.)

The numbers of design parameters in this study are few and through the configuration of them limited design alternatives are suggested. Therefore, performing sensitivity analysis is not worth the effort in this study. As mentioned in the literature review (of section 2.4), the amount of sensitivity index for WWR and the depth of shading device are high for the south orientation façades in Montreal, Canada.

The information provided in table 4.1, shows other categories of parameters (building shape/ orientation, colors/ materials/ textures, roof shape/ orientation/ tilt angle, U-value of glazing, and SHGC of glazing) which are influential on both architectural aesthetic and energy consumption but are not of interest to this research. The following points outline why these parameters are not investigated in this study:

- Since the building geometry is restricted in attached row houses due to the site constraints, *building shape and orientation* have to be maintained as constant parameters. Therefore, in this particular case study, various building shapes are not being considered. However, different shapes can be explored by applying their dimensions as input parameters through the proposed workflow (width of the south facade and the length of building in non-complex forms).
- Changes of *colors, exterior textures, and exterior finished materials* have an impact on reflectance value. However, due to the results of sensitivity analysis that have been done by some researchers the reflectance of exterior walls is not an influential parameter on energy consumption (Lee, 2014).
- *Roof orientation* may have an impact on architectural features, but it does not have a significant impact on the energy performance of the building (roof orientation is assumed to be a separate parameter from building orientation). However, *roof tilt angle and shape* (in unvented attics designs) can improve the energy performance, especially in hot climates. More cooling energy consumption in hot seasons and more heating energy consumption in cold seasons is being saved through an unvented attic design (Rudd and Lstiburek., 1998).

Because of the building height restrictions defined by “zoning by-law Ville de Montréal” (Règlement, 2010), flat roof designs are common typologies in Montreal. Therefore, the assessment of various roof tilt angles and shapes are not of interest to this study. Although, the proposed workflow has the potential to generate qualitative and quantitative data by the dynamic changing of roof tilt angles and shapes (as long as the geometry is not too complex, like in free-form designs).

- Window framing is an architectural component which can affect the overall *U-value of glazing.* Window’s U-value presented in the National Fenestration Rating Council (NFRC) database is an overall value that considers window parts such as frames, glazings, and spacers (Carmody and Haglund., 2012). In simulations done within Autodesk® Green Building Studio, the effect of the U-value of a window’s frame on energy performance is not considered separately because the total area of framing to glazing is negligible in this designed case study.
- *SHGC of glazing* is an effective parameter on energy performance. Through various SHGCs, visible transmittance will be changed, which is effective on the clearness of windows and the architectural appearance of façades. In residential building design, it is important to connect occupants to outdoors views. Therefore, using low transmittance glazing is not an efficient design because this makes interior spaces dark when solar intensity level is lower (Bell., n.d). Therefore, the offered values by the National Energy Code of Canada for Buildings (NECB, 2015) have been used in this study for the selection of glazing’s SHGC.

In the following sections, details of design principles and ranges for identified parameters will be described in more detail.

4.2.1 Windows: design principles and ranges

Designing the size of the window in the south oriented façade is an essential factor because it is a key design parameter that will have an impact on the architectural characteristic of the building in this study. Furthermore, it directly influences the amount of solar radiation gain and energy load. Therefore, the general common sets of design rules should be established between architects and engineers from the early phase of the design process in order to reduce the time-consuming iterative process of changing the window's geometry in later phases of the process.

In this proposed case study, only the effect of south façade fenestration is investigated, hence the design range for the south façade windows is suggested. Later, in the result section, the effect of different design configurations on the energy performance of the building will be evaluated, and the most energy efficient design alternatives will be reported accordingly.

The windows in this specific design are categorized into three different types that are specified in the figure.

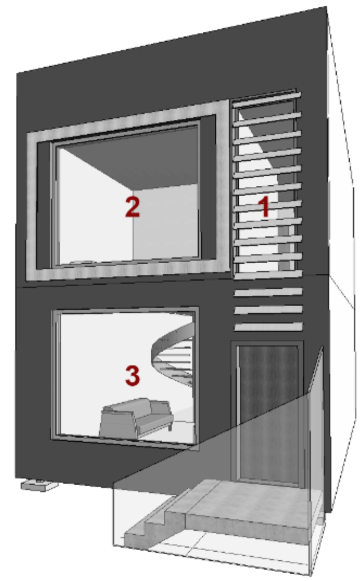


Figure 4.3: Three different types of windows investigated in this study (1, 2, & 3 specified in the image respectively imply; Type 1, Type 2, & Type 3)

4.2.1.1 Type 1: narrow vertical window on the side of the façade

This window is considered a static component due to certain restrictions in architectural design. Restrictions that constrain the design are:

- no more space for the manipulation of the geometry of this window in the designed façade.
- any changes in the orientation or size of the window where, the aesthetic harmony of design will be affected.

Therefore, the window's design is a vertical narrow rectangle shape with exterior louvers. The purpose of use is having a type of architectural aesthetic component in the design of a modern façade. Moreover, some assumptions and simplifications are considered for window type 1:

- The louvers attached to the south-facing vertical window are assumed to be static parameters.
- The exterior louver control blind has been assumed to block all direct solar radiation into the interior space.

4.2.1.2 Type 2: first floor's south façade window

The first-floor window is in the master bedroom. Some assumptions to be considered for the sizing of this window would be:

- The maximum height of the window is assumed to be 2200 mm. This is a fixed parameter.
- The minimum width is assumed to be 700 mm, and the maximum is 3050 mm.
- The reason for choosing the range with the minimum value of 700 mm for assessment of this window is related to the anticipation of its functionality. Interaction of parameters may suggest some designs with a balcony (if the depth of the shading device will be adaptable with an amount defined by "zoning by-law Ville de Montréal" (Règlement, 2010) for the design of a balcony in Montreal). Therefore, it can be utilized as a window or, can be used as a door to the balcony (in such cases where 700 mm is the minimum acceptable value).

4.2.1.3 Type 3: ground floor's south façade window

The ground floor window is for the living room. Both the height and width of this window are parametrically changed in the configurations with other parameters. These changes are symmetric since parameters vary from center to edges.

- The minimum height is chosen to be 300 mm, and the maximum is 2200 mm.
- The minimum width is chosen to be 300 mm, and the maximum is 3050.
- The minimum height and width have not been assumed to be zero. Due to the function of the space (living room), the psychological effect of the window on occupants (Veitch, J.A. and Galasiu., 2012) can not be disregarded. Thus, a small window is required to be designed in the worst case design configuration. It helps residents to be exposed to visual experiences while letting narrow sunbeams pass through it.

The table below demonstrates the summary of ranges considered for parameters of south façade windows in this case study. In addition, the level of investigation for each of them is displayed.

Window's Parameters	Design Range (mm)	Step (mm)	Level of Investigation
Width_ first floor Win	700 – 3050	470	6
Width_ ground floor Win	300 – 3050	550	6
Height_ ground floor Win	300 – 2200	380	6

Table 4.2: Ranges considered for parameters of south façade window

4.2.2 Shading device: assessment of ranges for depth of the shading device

Shading devices control the intensity of solar radiation gain to interior spaces to guarantee occupants' comfort levels. In fact, they have an essential impact on thermal comfort and daylighting. These comfort levels could be improved when glare is reduced by the intercepting of unwanted radiation through the application of exterior shading devices.

The most efficient shading devices are the ones that help the improvement of the thermal performance of buildings in different seasons. For example, direct solar radiation gain in the interior spaces of buildings can reduce the heating energy demand during the cold months of the year, while the same condition during warm months may increase the cooling energy demand due to the overheating. Consequently, the designing of the façade must be at a high level of excellence and requires decisive assessments.

The impact of different depths of the exterior shading device on the solar radiation incident passing through the south façade windows have been evaluated (see Appendix B).

The design principles for the shading device and selection of design day will be investigated in the next subsections.

4.2.2.1 Design principles of shading devices

Principles that represent the design of different types of shading devices in this study are based on prior investigations by prominent architects. Le Corbusier was the first architect who invented the Brise-soleils, and the principles of his architecture were mostly based on a passive solar design with respect to shading strategies (Sobin, 1980, Solla, 2012).

In figure 4.4, Le Corbusier's sketch presents the use of Brise-soleil and how this helps to avoid overheating during summers while controlling the natural light passing through the interior spaces.

In general, external shading devices can be categorized into different types such as louvers, overhangs, fins, blinds, or perforated screens (Baker., 2009). See figure 4.5.

Despite many studies done to test different Brise-soleils, there is still a lack of assessment to control the east/west solar radiation that passes through the south façade (Urbanalyse, 2012). Since the sun elevation in the east and west during the morning and afternoon are too low, some more considerations are needed in the design of exterior shading devices to control these radiations.

The mere design of an overhang shading device can not help to break the east/west solar radiation. Therefore, a particular Brise-soleil can be designed to ensure all solar radiation is being controlled (see Appendix A for more details about various exterior shading devices).

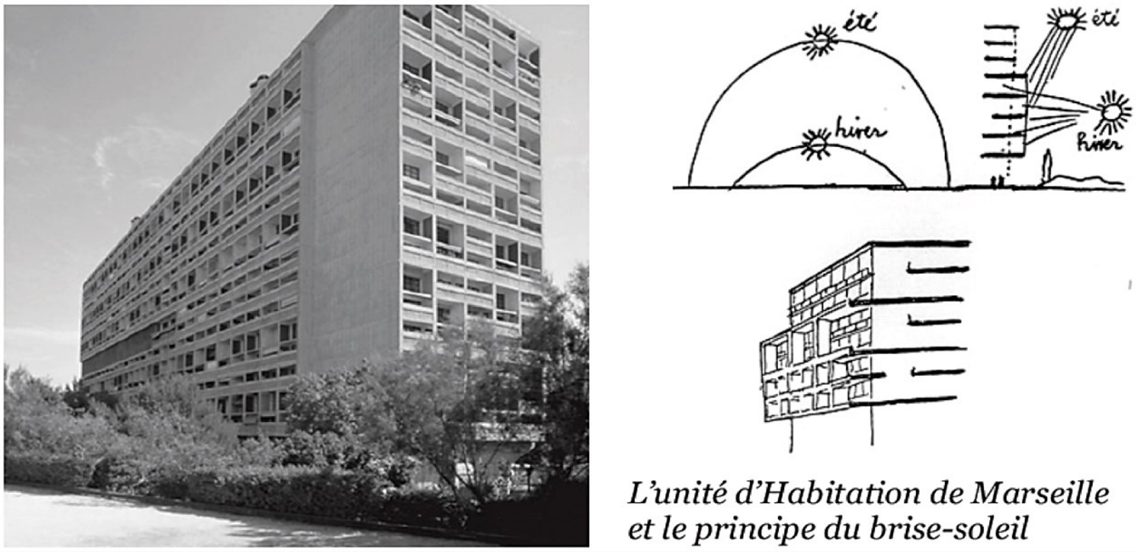


Figure 4.4: The Brise-soleil, sketches by Le Corbusier (Solla, 2012)

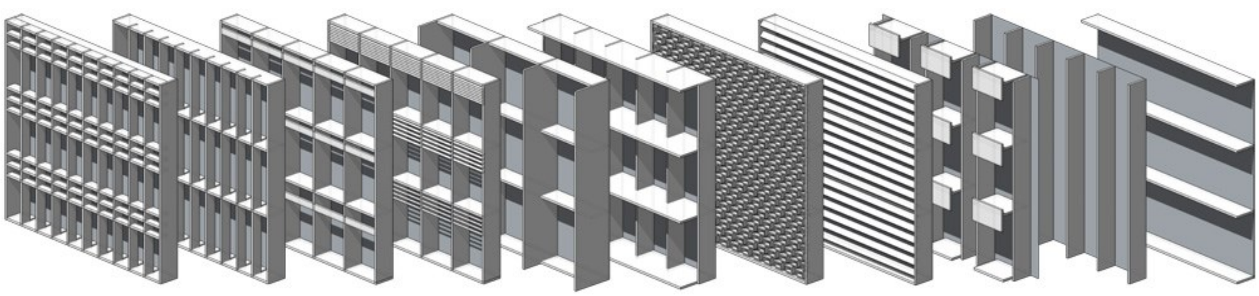


Figure 4.5: Various types of Brise-soleil (Urbanalyse, 2012)

According to the above explanations, a combination of “fixed overhangs” with “vertical fins” are studied as a shading device in this research. The image shows the final design of the shading device that is simply created by the combination of vertical fins and horizontal overhangs.

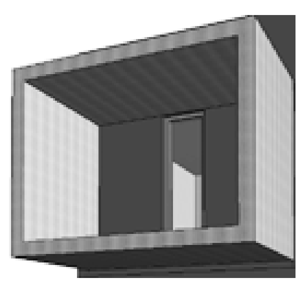


Figure 4.6: Shading device in this case study

An important parameter for the analysis of the shading device in this research is the dimension of depth that is kept equal for both types of elements (fixed overhangs & vertical fins) during the whole process of parametric assessment. ***Different depths of the shading device have been evaluated in this study in order to observe the impact of each design on the total energy consumption of the building.*** Besides, the architectural aesthetic of each design option is an important feature that can be considered by architects for final decision making as well as for energy performance.

4.2.2.2 Design day selection for assessment of maximum efficient depth of a shading device

The methodology for finding the maximum depth of the shading device in the proposed study is based on a calculation of the area of shadow that is generated by the shading device on the surface of the maximum size of the first-floor window.

By changes in the sun's position in the sky during the day, the generated shadow area will be different at various solar angles. Based on the variation of the solar elevation angles during the winter and summer, and according to the criteria for finding maximum depth of shading device in this study, summer solar radiation should be totally blocked to aid in reducing the cooling energy demand. First, solar altitude angles for summer months are found, then calculations for assessment of the maximum shading device depth will be done for the summer day with lowest altitude angle (see Appendix B for automated quantitative and qualitative evaluation of maximum depth of shading device).

The monthly cooling degree-days (CDD) for Montreal, Canada (45º N Latitude) is shown in figure 4.7, which is according to data derived from the Weather Network (The Weather Network., n.d). According to the definition, "cooling degree-days for a given day are the number of degrees Celsius that the mean temperature is above 18 °C. If the temperature is equal to or less than 18 °C, then the number will be zero" (The Weather Network., n.d). The cooling degree-days for Montreal start from mid-May and continue untill mid-September.

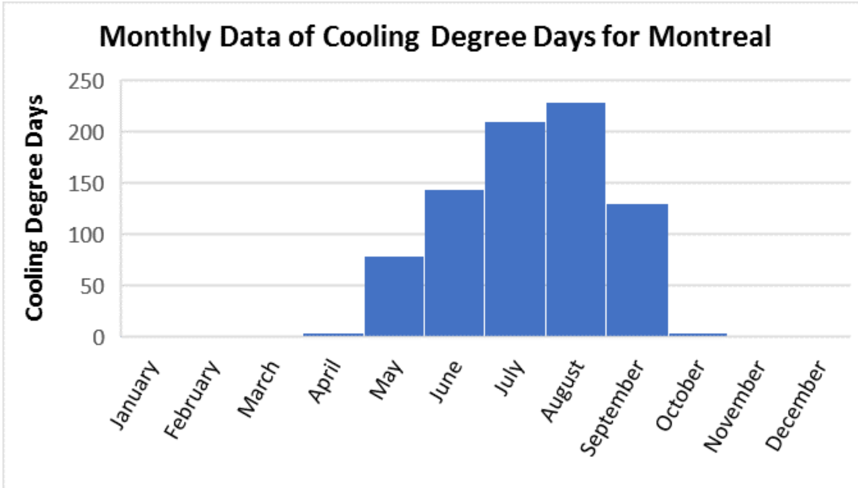


Figure 4.7: Cooling degree-days in Montreal (The Weather Network., n.d)

The most important dates for analyzing the solar positions in the sky are during equinoxes and solstices. The table below shows these days for the whole year in the northern hemisphere. Accordingly, one day at each month of summer has been selected for calculation of solar altitude angles.

NAME	NORTHERN HEM.	DESCRIPTION
Summer Solstice	21 Jun	Sun at its highest noon altitude
Autumn Equinox	22 September	Sun rises due east, sets due west
Winter Solstice	22 December	Sun at its lowest noon altitude
Spring Equinox	21 March	Sun rises due east, sets due west

Table 4.3: Important dates for solar position assessments (NOAA, n.d)

In order to calculate the solar altitude angle (α) for the dates listed above, declination angle (δ) and hour angle (ω) should be calculated. In the following equation, the altitude angle can be calculated, in which the observer's latitude is shown as φ:

$$\sin\alpha = \sin\delta\sin\varphi + \cos\delta\cos\omega\cos\varphi$$

Declination angles are calculated for the given days (n) through the following equation:

$$\delta = 23.45\, sin[360^{o}\left(\frac{284+n}{365}\right)]$$

Hour angles are calculated through these equations, where *Az* stands for the solar azimuth angle. The results for ω would be positive in mornings, negative in afternoons, and zero at solar noon.

$$sin\,\omega = -\frac{cos\,\alpha\, sin\, Az}{cos\,\delta}$$

$$sin\,\omega = \frac{sin\,\alpha - sin\,\delta\,sin\,\varphi}{cos\,\delta\,cos\,\varphi}$$

Sunrise and sunset hour angles (ωs) would be calculated based on the following equation:

$$\cos \omega s = -\tan \varphi \tan \delta$$

These equations derived from Athienitis's and Santamouris's study (Athienitis and Santamouris., 2013).

Ultimately, solar altitude angles (α) for specific days of summer months are calculated for Montreal, to compare the sun's elevations at solar noons (when the sun is at its highest altitude) and are represented in Table 4.4.

The day that has the lowest altitude angle (among CDDs of Montreal) is a target for selection of the design day in this study (which is 21^{st} of September).

The following figure displays the solar altitude angles calculated for specific days during cooling degree days in Montreal. The sun altitude angle in the sky from sunrise to sunset for days of May 21, June 21, July 21, August 21, and September 21 are demonstrated in the figure 4.8. The time step considered for this analysis is fifteen minutes.

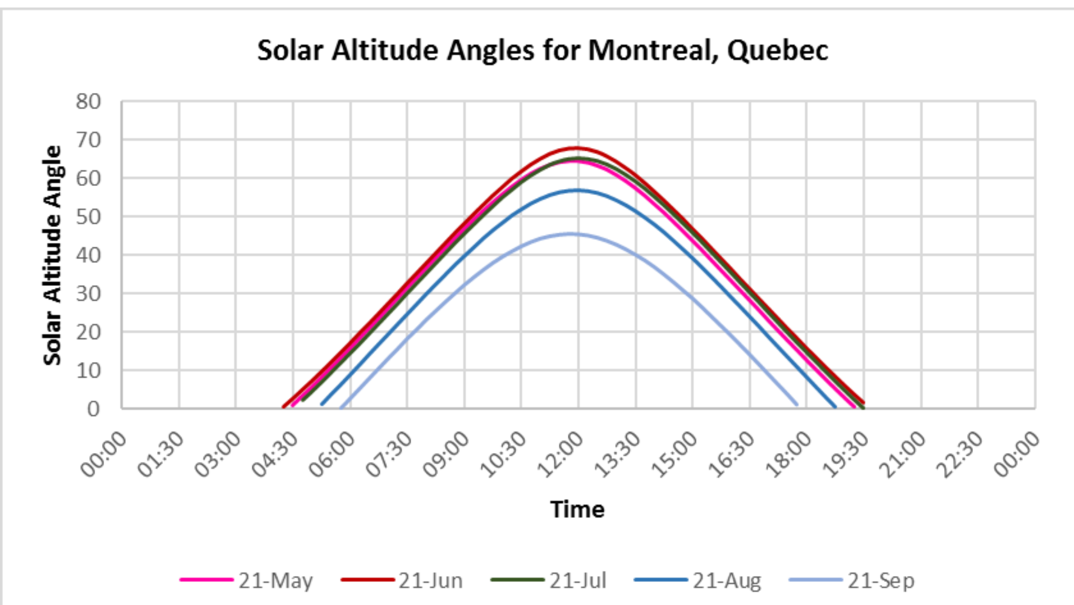


Figure 4.8: Solar altitude angles for specific days of summer in Montreal

Based on calculations, the solar noon time and altitude angles for each of the selected days in summer in Montreal have been represented in the table below.

Date	21 May	21 June	21 July	21 Aug	21 Sep
Solar Noon	11:45-12:00	12:00	12:00	12:00	11:45
Highest Altitude	64.4	67.9	65.1	56.8	45.4

Table 4.4: Solar noon and altitude angles for specific days in summer, Montreal

According to all the above assessments, the maximum depth of a shading device will be determined (see Appendix B) when the shadow created by the shading device can fully cover the surface of the designed window (when the ranges are considered at their maximum amount) during the whole day of 21st September. The analysis will be done in the hourly time step during the period between 9 am to 3 pm, when solar radiation has the most energy intensity in the south orientation (Robertson and Athienitis., 2009).

Finding the maximum amount for depth of the shading device on September 21 can ensure that the window will be fully covered by the shadow in other months of the summer, while the solar radiation can penetrate to interior spaces in the winter months when the solar altitude angle is lower.

By finding the amount of maximum depth, the design range for the shading device will be specified. Later in the result chapter, depth parameter will be configured with other parameters through the full factorial approach to evaluate the impact of each design alternative on the energy performance of the building. These evaluations will be done automatically through the BIM-based workflow.

4.2.2.3 Initial range assumed for design of depth of shading device

According to the goals of this study, the maximum depth needed in the design of the shading device will be calculated and visually observed through the automated workflow within the BIM platform. The details will be explained more in the Appendix B.

In this section, the question is raised: ***What would be the maximum value of depth for designing a shading device?***

In order to solve the problem, the maximum depth can be found when the shadow created by the shading device fully covers the surface of a first-floor window on September 21.

On September 21 the sun has the lowest altitude angle during solar noon in comparison to the other selected summer days in Montreal. Therefore, according to the assumptions of this study, the maximum depth of the shading device can be evaluated when the area of projected shadow (caused by the shading device) on the surface of the window is equal to the area of that window (during this evaluations the maximum ranges of height and width are considered for this window. See the previous section, 4.2.1, for designed ranges of windows).

The table below demonstrates the information and ranges considered for the designing of the shading device. The shading device in this study can be utilized as a balcony (when the depth is more than the minimum defined standard for the balcony design in Montreal, according to the "zoning by-law Ville de Montréal" (Règlement, 2010)) or only as a console in front of the window for breaking part of the solar radiation.

The minimum depth considered for the shading device is 25 mm. It is not assumed to be zero since there is a limitation for the minimum value of dimension in the software used. Since the shadow created by the depth of 25 mm is negligible, it can be assumed to be zero.

Parameters	**Range**	**Notes**
Time of the day in Sep 21	9 Am – 3 Pm	time steps of 1 Hour
Depth of shading device	25 mm – 2400 mm*	*check appendix B to find out how maximum amount evaluated
Outcome	**Range**	**Notes**
Area (area of projected shadow on the window to the area of window)	0 % - 100 %	maximum depth evaluated when shadow coverage on the window is 100%

Table 4.5: Information and ranges considered for designing of the shading device

4.3 Other simulation inputs and design parameters criteria

All values of input simulation factors in this study are maintained as static, except the dynamic parameters mentioned earlier. Values of input simulation factors are chosen based on standards. This study is only evaluating the parameters that have an impact on both architectural features and energy performance (see sections 3.1 & 4.2), such as windows to wall area and the depth of shading device.

- All the simulations have been run for Montreal, Quebec in Canada with the latitude of 45 °N. Based on the ASHRAE climate zone definitions, it is located in zone 6 with cold climates.
- It is assumed that the building is not obstructed by other buildings or environmental elements, and solar radiation is gained as presumed.

- The daylighting performance analysis is not the target of the proposed workflow in this study.
- The building type in this study is a two-story single-family house with the total floor area of 90 m^2 (only one zone (south zone) of the designed building for Solar Decathlon 2018's competition has been selected as a case study). The average occupancy density has been considered to be three people for the entire dwelling through the Revit® schedules properties.
- The building has a wooden structure, and the structure of walls are made from wood stud framing. The thermal resistance assigned to the building is based on the minimum requirement suggested by National Energy Code of Canada for Buildings (NECB, 2015) for walls, roof, and floor that are respectively 4.04 RSI, 5.46 RSI, and 5.46 RSI (for ASHRAE climate zone 6).
- The east and west walls that are attached to the neighbour houses' walls are assumed to be highly insulated (little amount of heat exchange through them).
- The window characteristic is selected from the lists provided through the Analytical Properties section in Revit®. The Low-E triple glazing with SHGC of 0.5 and visual light transmittance of 0.64 is chosen for all south facing windows in this case study.
- According to the ASHRAE standard 62.2 (ASHRAE, 2003), the suggested ventilation rate based on the dwelling size and occupancy density has been assumed as 0.35 air change per hour (ACH).
- According to the recommendation of Natural Resources Canada (NRCan, 2004), the Seasonal Energy Efficiency Ratio (SEER) of the air-source heat pump is required to be greater than 12 for a single package unit or greater than 13 for split systems. Also, the Heat Seasonal Performance Factor (HSPF) can be selected as high as commercial availability. The selection of a higher amount can operate efficiently in most of the zones in Canada (NRCan, 2004). Consequently, based on the suggestions and the default HVAC systems offered by Autodesk® Green Building Studio® (GBS), the 17 SEER residential air-source heat pump with HSPF of 9.6 has been selected.
- The default input value of average lighting power density (LPD), which is defined by Green Building Studio®, is 4.84 w/m^2 for single-family residential buildings.

- All the other input factors for energy simulation analysis are default assumptions by GBS, which is defined based on the building type and location. All the GBS default values are according to the minimum efficiency requirements suggested by ASHRAE Standards. The ASHRAE 62.1, ASHRAE 90.1, ASHRAE 90.2, and CBECS data are used as baseline sources (Autodesk, n.d).

Chapter 5 Details of Implementation of Workflow in the Case Study

5.1 Utilizing BIM platform to generate qualitative 3D models and quantitative energy performance data automatically

The proposed workflow is a novel approach that allows the integration of qualitative representations and quantitative data generations. In this study, the proposed workflow supports the engineer and architect's decision-making by suggesting numerous building energy simulation results and architectural 3D models in the early phase of design. The BIM platform has been used to automatically generate quantitative energy performance data and qualitative 3D design alternatives.

The image below represents the flowchart of the proposed workflow. In the next section, the details of the implementation of each step will be explained.

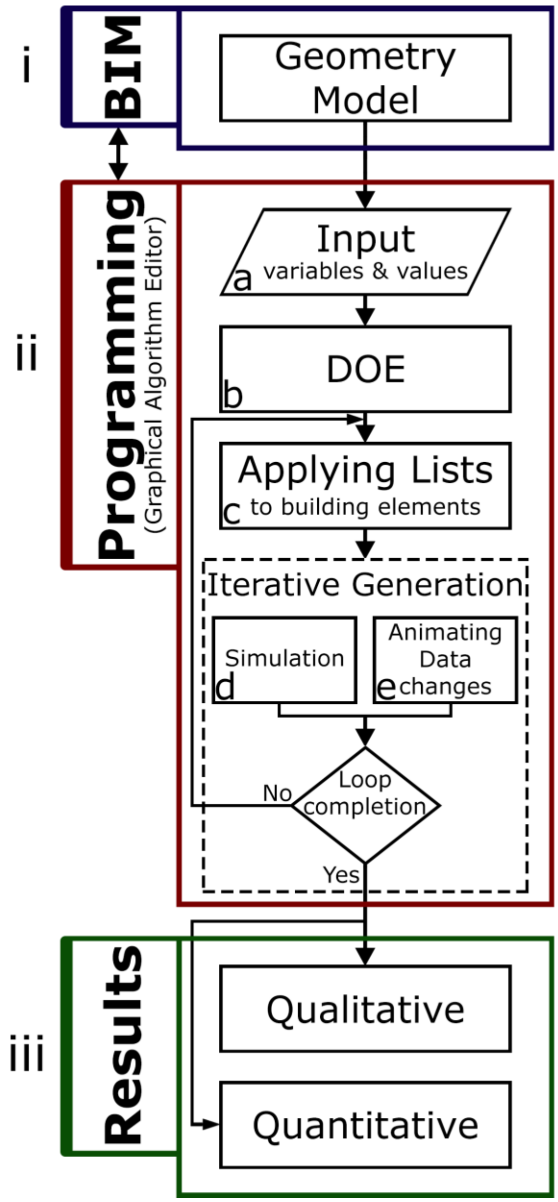


Figure 5.1: Flowchart of the proposed workflow

5.1.1 Using BIM, the graphical algorithm editor, and the simulation engine in the automating process of qualitative and quantitative data generations

In this study, the BIM platform has been utilized in connection with the graphical algorithm editor to perform the parametric architectural modeling and energy simulation of various design configurations through an automated process. In this section, step-by-step recommendations to operate the workflow are introduced.

The proposed workflow embraces three main platforms/ tools:

- Usage of a BIM platform
- Programming (to perform the automated parametric study)
- A utilization of performance simulation engine

Through the correct application and collaboration of these platforms and tools, the desired qualitative and quantitative assessments from the early stages of design can be achieved. Subsequently, the qualitative and quantitative results will be generated.

Details of the implementation of each step of the workflow and generation of results (shown with i, ii, and iii in figure 5.1) are explained below:

i. Creation and preparation of the geometry of the model in BIM platform

In this stage, the overall process of the model creation is explained. The desired quantitative result in this study is energy perfrormance of the whole building. In this regards, the first step is creating the geometry of building in BIM (Autodesk® Revit® in this study) and setting up the factors needed for energy simulation such as weather data, building type, material thermal properties, and operation schedules, which are embedded in the BIM platform (some of these factors can also be arranged through the visual programming add-ins which are not within the scope of explanation in this study). All the details of values for thermal properties of building elements and other simulation factors have been explained before (see section 4.3).

ii. Utilizing the graphical algorithm editor

In this study, the programming used in connection with Revit® is an open-source graphical algorithm editor called Dynamo. The following parts explain the process of proposed workflow which are done through Dynamo.

ii.a. The input values of parameters which are the target of this study have been fed as lists into the Dynamo.

ii.b. Lists have been combined through the full factorial approach within Dynamo (each list contains design ranges for input parameters). In this regard, the scripts for combining the lists (based on chosen full factorial DOE method) are written through the use of CodeBlock node within Dynamo.

ii.c. The combined lists, which contain the values of inputs for each design alternative, have been applied to the relevant building elements.
ii.d. By the integration of the Application Programming Interface (API) of Revit® with Dynamo, and through writing custom Python (programming language) scripts in Dynamo, the connection will be created to the Revit® libraries (The Dynamo Primer, n.d). Accordingly, the energy simulations of each design alternative will be automatically run through a cloud-based simulation engine called Autodesk® Green Building Studio® (GBS). The GBS is a cloud-based web service that performs building energy simulation using the DOE-2.2 engine. The results of GBS are validated under the ANSI/ASHRAE 140 standard test method and certified by the U.S. Department of Energy (ASHRAE, 2008).
The Green Building XML schema (gbXML) is a common format that can be shared between various building energy analysis software. The essential data needed for energy simulation which is embedded in BIM or defined by the user can be transferred through the gbXML for energy analysis assessment (gbXML, 2014). The "gbXMLExport" node in Dynamo has been used to automatically export energy model data (needed for energy simulation) from each loop in the gbXML format through Revit API. The Python scripts for this node have been updated by the author of this research in order to ensure compatiblility with the newest version of Dynamo (version 1.0 at the time of the study).

The "EnergyAnalysisforDynamo" package is developed by Thornton Tomasetti CORE Studio (CORE, 2015). This package is utilized in combination with the updated Python scripts of the "GBSSingleRun" node which is part of "Optimo" workflow that was developed in BIM-SIM Lab in the College of Architecture at Texas A&M University (Asl et al., 2015). Accordingly, all the design configurations were managed in loops to perform the automated process for energy simulations. Subsequently, the generated gbXML files in the desired directory path have been automatically uploaded to Autodesk® Green Building Studio® (GBS) to run energy simulations. The energy performance of each design alternative has been assessed parametrically. Consequently, the simulation results were automatically returned into Dynamo and written into the excel sheet.

ii.e. Within the application of the full factorial combined list to desired model elements, changes of parameters can be previewed within the Revit® viewport workspace, and any transformations can be immediately visually updated. In addition to instantaneously seeing visual changing of parameters, the ability to create nodes in Dynamo to export 3D viewport as an image file exists. Thus, by customizing the desired loop, the Portable Network Graphics (PNG) file have been written in the determined directory path from each loop iteration. In this regard "Dynanimator" (an animation package for Dynamo) has been used. It is developed at Autodesk University 2014 and released by Håvard Vasshaug (BadMonkeysTeam, 2014).

iii. Results of investigations

The key design parameters of interest in this research study (the shading device depth and window to wall area of south façade) can be systematically changed through the full factorial approach, while the effect of changes of these design parameters on both energy performance and visual characteristic of the building can be assessed via the proposed workflow. The quantitative results (energy performance) and qualitative representations (3D models) will be automatically written as an Excel file and exported in PNG image format through the connection between BIM platform (Autodesk®Revit®), programming (Dynamo), and simulation (Autodesk® Green Building Studio®). The production of simultaneous visual outputs with text-based data will significantly facilitate decision making based on architectural features during the process of design. Therefore, architects and engineers can efficiently collaborate from the early phases.

Chapter 6 Design Trend to Support Decision Making

In this chapter, the results will be explained into two different parts:

- The first part demonstrates the summary of results of the full factorial combination of design parameters.
- In the second part, the results of qualitative representational design alternatives and quantitative energy performance data are presented.

As a consequence of assessments and results generations, the best design options introduced (based on lowest energy use intensity). The results that have been automatically generated by the configuration of various design parameters through the full factorial experimental design approach.

6.1 Summary of parametric full-factorial combinations of design parameters

In order to evaluate the energy performance of various design options through the automated BIM-based platform, the systematic approach is utilized. The full factorial design of experiment approach covers all possible design alternatives. This approach is used to propose the feasibility of early energy performance-based decision making.

In section 3.1.1, this experimental approach was explained and in this section, the implementation of this experimental approach in the process of design and assessment is described in more detail.

Through the investigation of the maximum depth of shading device (see Appendix B), the minimum and maximum values of design ranges are determined. Subsequently, all the considered parameters in this investigation approach and their design ranges are configured with the full factorial method and fed as input parameters in the Dynamo- Revit® workflow.

All the values of parameters considered for the design of the shading device depth, ground-floor window, and first-floor window, are summarized in the table below.

Different design options (1296 in total) have been achieved as well as the effect of each design parameter on the energy performance of the building evaluated.

Factors	Name	Levels	Level Values					
A	Width 1st-floor Win	6	700	1170	1640	2110	2580	3050
B	Width G-floor Win	6	300	850	1400	1950	2500	3050
C	Height G-floor Win	6	300	680	1060	1440	1820	2200
D	Depth Shading device	6	25	500	975	1450	1925	2400

Table 6.1: Values of investigated design parameters

In order to demonstrate the full factorial coverage of all possible design alternatives, the parallel coordination plot that shown below visualizes the configuration of all parameters.

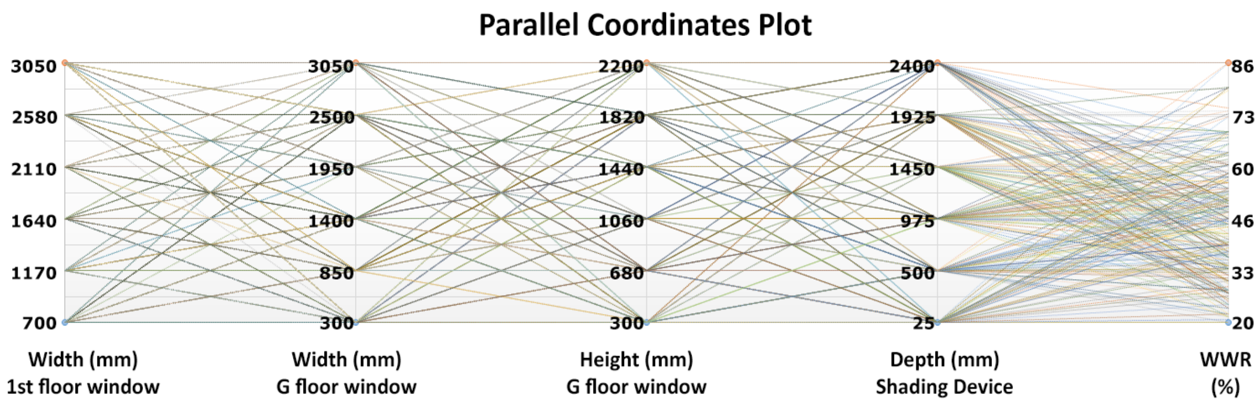


Figure 6.1: Parallel plot represents configuration of parameters

6.2 Qualitative representational design alternatives and quantitative energy performance data

In this section, the effect of each design parameter on the total energy performance indicator of the building is studied. Ultimately, the most energy efficient design alternatives are introduced. As previously stated, by employing a full factorial experiment to combine design parameters for investigating various design options of south façade, a set of data will be accessible. This design trend offers the aggregation of thousands of data sets related to all possible design configurations extracted automatically from proposed BIM-based workflow. Accordingly, based on the level of investigation defined for ranges of desired façade components (section 6.1), all possible combinations of parameters are offered to be 1296 design options.

For each design alternative, the energy performance indicator is estimated within the range specified for each of the designed parameters. The assessment indicator is based on measurement of the energy performance of total heating and cooling consumption accomplished by the effects of each design variable. The evaluation workflow is applied to the case study for attached row-housing units in Montreal, Canada. Consequently, the qualitative design configurations are illustrated to express the architectural means of parameter changes. All the visual 3D models that have been extracted as design alternatives through the proposed workflow will be presented at a later point. Quantitative energy simulation data is generated automatically by using Dynamo for Revit® to analyze the impact of suggested design parameters on total energy consumption.

Figure 6.2 is a heat map graph that demonstrates the Annual Energy Use Intensity (EUI) with respect to changes in the level of windows to wall ratio and the shading device's projection factor. The annual EUI is the extractable text-based results through the Revit® and Dynamo platform. In addition, figure 6.2 shows the relationship between changes of windows sizes and the shading device depth with total energy consumption.

The EUI represents the total fuel and electricity consumed by the building per floor area in a year, that is expressed in the unit of kWh/m^2 -yr. In this study, windows to wall ratio (WWR) represent the total WWR for both the ground-floor and first-floor window area to the wall of the designed south façade (range of WWR is from 20 percent to 86 percent for all windows).

Also, the shading device projection factor (PF) is one of the principle considerations in this study. According to the definition from ASHRAE 90.1 (ASHRAE, 2001), the projection factor is a horizontal measurement of the overhang projection depth that is divided by the distance between the lowest part of the window (sill) to the lowest part of the overhang. In the design of this shading device, vertical fins are attached to the horizontal overhangs so that the overhangs and fins depth are equal through each step of changes. Windows frames are assumed to be very thin and negligible in this assessment. In the table below, projection factors related to each shading device depth are displayed.

Projection factor coeficient	0.01	0.22	0.44	0.66	0.88	1.09
Shading Device Depth (mm)	25	500	975	1450	1925	2400

Table 6.2: Projection factors related to depth of the shading device

Each dot on the surface of the heat map graph (figure 6.2) illustrates each design alternative that has been generated by a full factorial combination of various design parameters. As the results reveal, the impact of changes in only two components of the south façade (windows and shading device) on the total energy consumption of the building is considerable, while other energy simulation factors maintain static. The difference between the highest and lowest amount of energy consumption among all design options is 815.4 kWh per year for a 90 m^2 middle size single-family building (the minimum annual EUI is 77 kWh/m^2 & the maximum is 86.06 kWh/m^2). When the shading device projection factor (PF) is between the amount of 0.4 to 0.6 and the windows to wall ratio (WWR) is between 50 to 75 percent, the zone of minimum EUI is reachable. As the WWR and PF go above or below the mentioned ranges, increases of the amount of energy consumption can be seen.

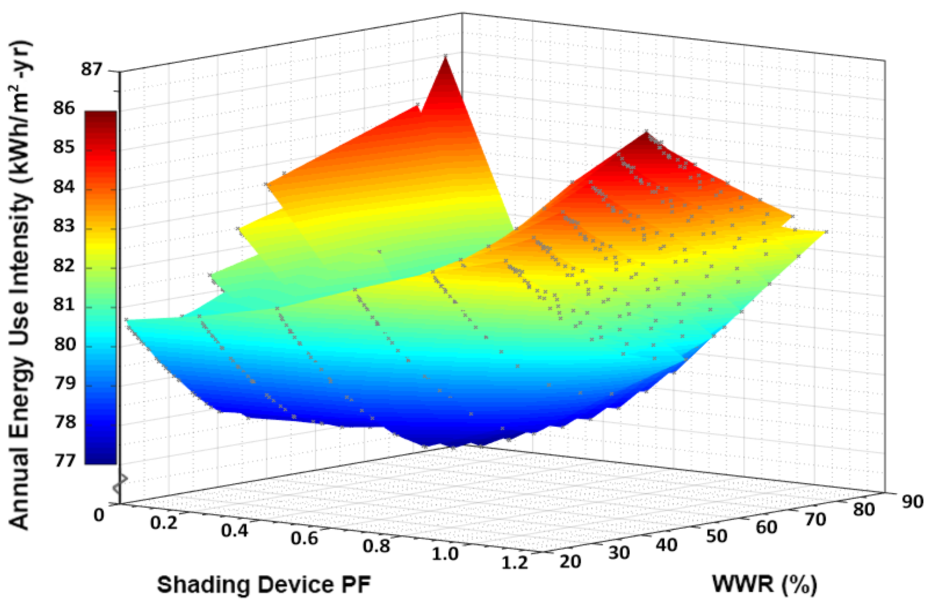


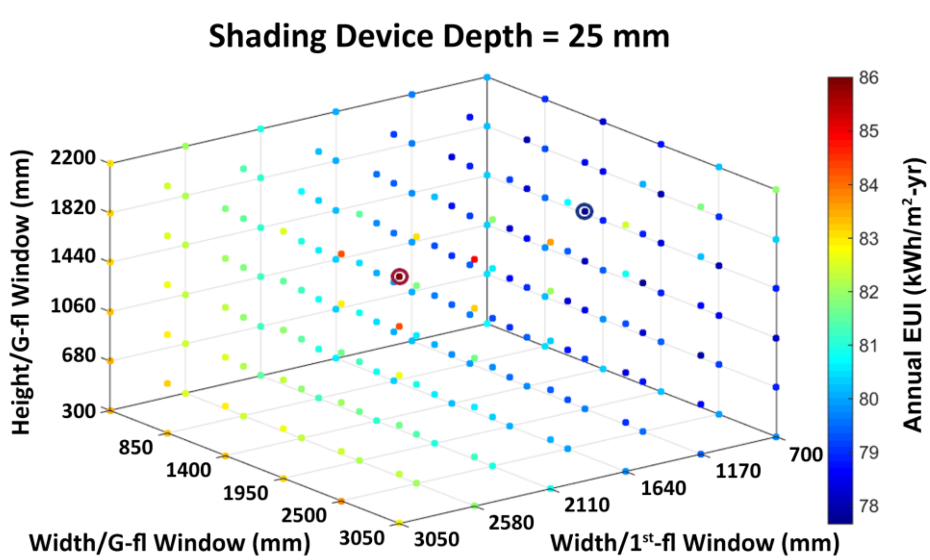
Figure 6.2: Annual Energy Use Intensity (EUI) with respect to WWR & PF

In the scatter plots below (figure 6.3), the effects of desired design parameters on the energy performance of building are compared for different design options. There are six plots available. Each of them impart a combination of parameters of the ground floor window and first floor window in various levels of depth investigation for the shading device. Figure 6.3 shows a comparison between the energy performance of design alternatives when shading depths are 25 mm, 500 mm, 975 mm, 1450 mm, 1925 mm, and 2400 mm.

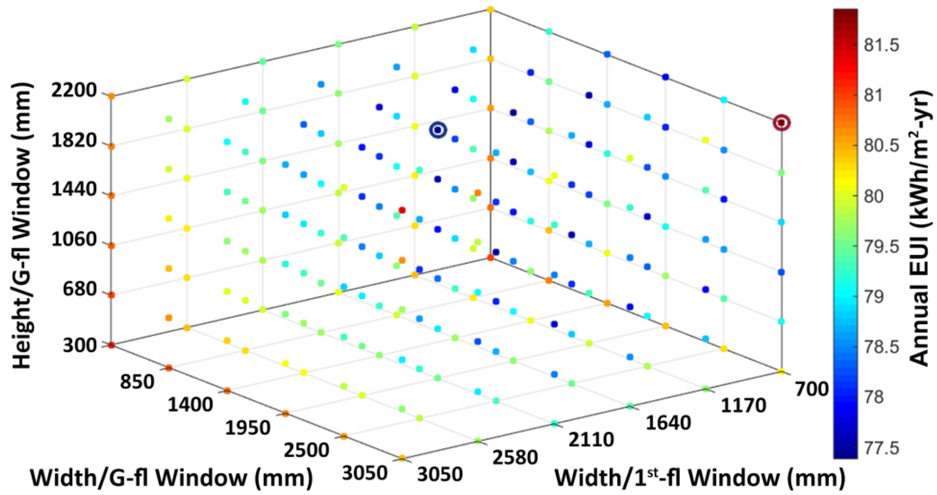
The XYZ coordinates represent the exact amounts for the width and height of the ground and first-floor window that have been assessed through the design configuration process. Moreover, the height of the first-floor window remains static as 2200 mm because of the functional purpose explained in section 4.2.1. The heat map color range illustrates the annual energy use intensity for each design alternative. Each particle in each plot, demonstrates one design option associated with different window sizes.

Table 6.3 is related to each scatter plot. The details of the design parameters related to the most and least energy efficient design alternatives (with minimum and maximum energy consumption) are organized in table 6.3 (for each level of the shading device depth) while are coded with blue and red circles in figure 6.3. Also, WWR in table 6.3 represent the total area of both windows to the south façade's wall area for most energy efficient, as well as the least energy efficient design alternatives.

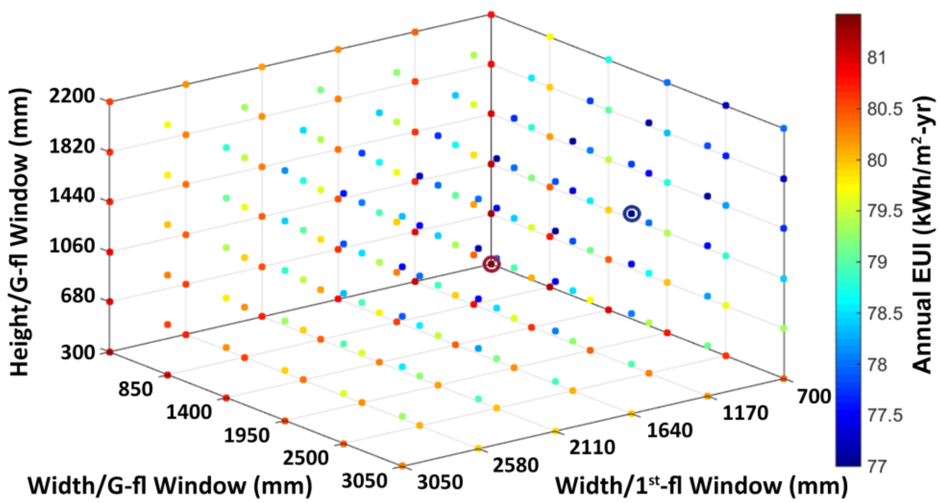
Ultimately, the design alternatives with minimum and maximum energy consumption within whole design configurations are determined in table 6.3 with blue and red rectangle boxes around them. According to the outcomes, the optimum performance based façade design can be reached when the shading device depth is nearly 1 m, height and width of the ground floor window, and width of the first-floor window are respectively, 1.82 m, 3.05 m, and 1.64 m (with WWR of 62).



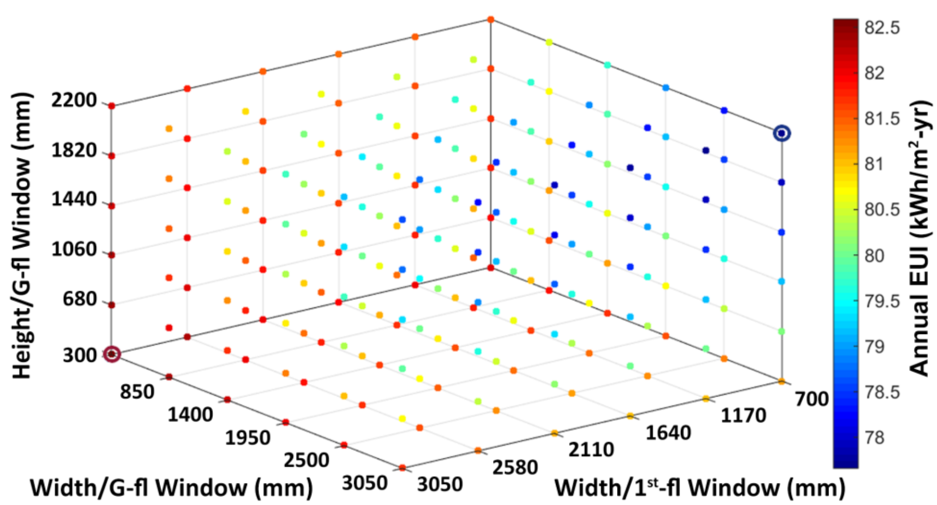
Shading Device Depth = 500 mm



Shading Device Depth = 975 mm



Shading Device Depth = 1450 mm



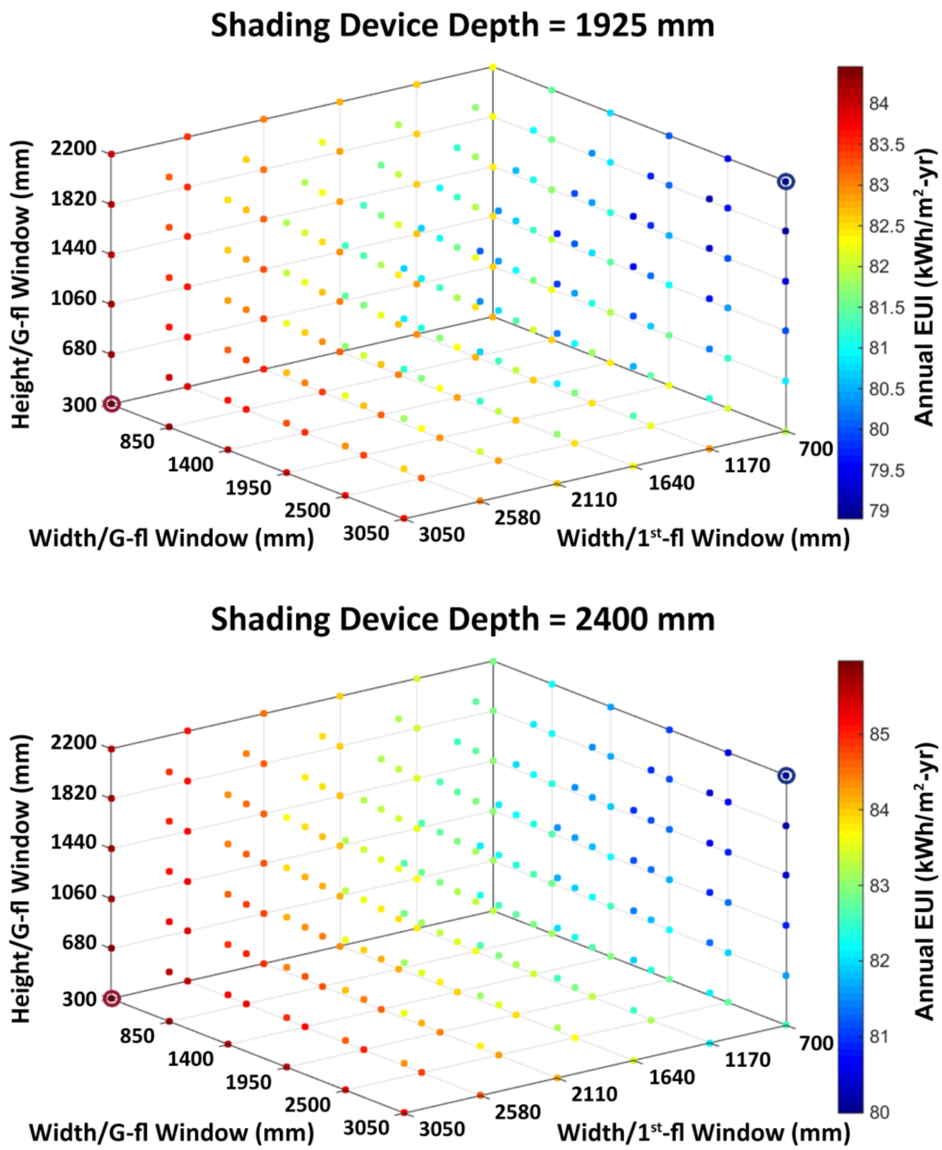


Figure 6.3: Comparison between energy performance of design alternatives due to different depths of the shading device

	Design Scenarios	Width (mm) 1st-fl Window	Width (mm) G-fl Window	Height (mm) G-fl Window	WWR (%)	EUI (kWh/m²-yr)
Shading Depth (mm): 25	Most Energy Efficient	1170	1950	1820	45	77.66
	Least Energy Efficient	3050	3050	2200	86	86.06
Shading Depth (mm): 500	Most Energy Efficient	2110	1950	2200	61	77.38
	Least Energy Efficient	700	3050	2200	57	81.85
Shading Depth (mm): 975	Most Energy Efficient	1640	3050	1820	62	77
	Least Energy Efficient	700	300	300	20	81.42
Shading Depth (mm): 1450	Most Energy Efficient	700	3050	2200	57	77.65
	Least Energy Efficient	3050	300	300	49	82.59
Shading Depth (mm): 1925	Most Energy Efficient	700	3050	2200	57	78.90
	Least Energy Efficient	3050	300	300	49	84.45
Shading Depth (mm): 2400	Most Energy Efficient	700	3050	2200	57	79.99
	Least Energy Efficient	3050	300	300	49	85.96

Table 6.3: Design alternatives with lowest & highest energy consumptions due to various depths of the shading device

In following tables (6.4 and 6.5), the results of 3D images of five "most energy efficient" and five "least energy efficient" design solutions are presented, and specifications of parameters are compared in the relevant table. As mentioned, all image results related to 1296 design alternatives are accessible in this research. The most energy efficient and the least energy efficient designs specified in previous table are highlighted among qualitative data in table 6.4 and table 6.5.

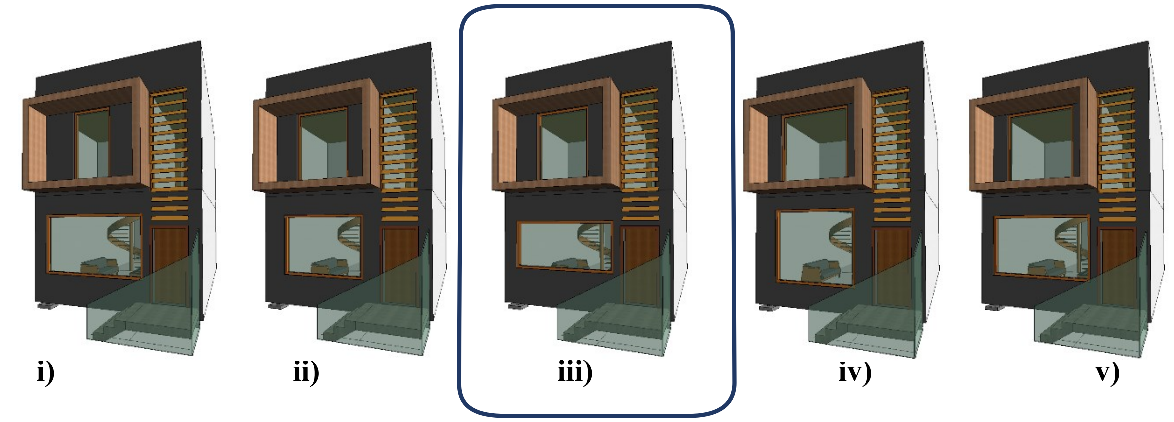
As a result, it can be seen that through such full factorial combination of parameters, reaching the design alternatives with lower energy consumption and better aesthetic features is feasible. A final design solution can be selected based on architectural criteria or concern among the proposed visual representational images.

Table 6.4 shows the five most energy efficient design options. As demonstrated from the results, the shading device depth has the same value of 975 mm for all energy efficient design alternatives. This indicates that through this design for the shading device, unwanted solar radiation is blocked during the summer when the solar altitude angle is high and as a result, cooling energy demand will be decreased. On the other hand, there is much solar heat gain in winter when the sun altitude angle is lower. Therefore, designing the shading device depth with the amount of 975 mm helps to reduce the heating energy demand during the cold season in this case study (see figure 6.4).

Table 6.5 shows the five least energy efficient design options. This table presents two types of the least energy efficient design cases.

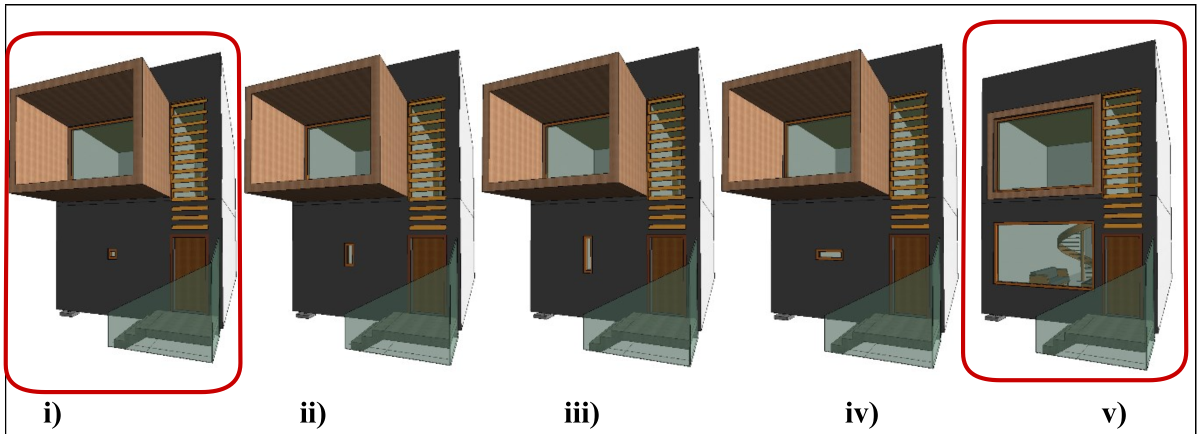
The first type of “least energy efficient” design alternative (cases no. i) is related to the design with maximum depth for a shading device, the maximum width for a first-floor window and minimum width and height for a ground floor window. In such design options with a maximum depth of shading device, the penetration of solar radiation in interior spaces is minimized. Furthermore, the insulation value of the wall is decreased by the design with a large window on the first floor. Therefore, there is minimum solar heat gain during winter while there is more heat loss through the large designed windows of the first floor. On the other hand, in this design configuration, the ground floor window is not large enough, which means there is little amount of solar heat gain to the interior space (similar to condition when the larger shading device is designed). Therefore, the heating energy demand in winter will be increased, while the cooling energy demand in summer will be decreased. The discrepancy between heating and cooling loads in this design is considerable (see figure 6.5).

The second type of “least energy efficient” design alternative (case no. v) is related to the design option when the shading device depth is minimum (near zero), and width of a first-floor window, as well as the width and height of a ground floor window are at their maximum amount. In this type of design, the solar heat gain is too much and there is no shading device to block part of the radiation. Thus, due to the design of large windows, heat loss through windows during cold seasons is high which increases the heating energy demand. In addition, overheating during summer causes an increase in cooling energy demand (see figure 6.6).



	Shading Depth (mm)	WWR (%)	Width_1st floor Window (mm)	Width_ G floor Window (mm)	Height_G floor Window (mm)	EUI (kWh/m²-yr)
i)	975	56	1170	3050	1820	77.07
ii)	975	61	1640	2500	2200	77.03
iii)	975	62	1640	3050	1820	77
iv)	975	68	2110	2500	2200	77.07
v)	975	68	2110	3050	1820	77.03

Table 6.4: Five design options with lowest amount of EUI



	Shading Depth (mm)	WWR (%)	Width_1st floor Window (mm)	Width_ G floor Window (mm)	Height_G floor Window (mm)	EUI (kWh/m²-yr)
i)	2400	49	3050	300	300	85.97
ii)	2400	50	3050	300	680	85.81
iii)	2400	50	3050	300	1060	85.73
iv)	2400	50	3050	850	300	85.77
v)	25 (~0)	86	3050	3050	2200	86.06

Table 6.5: Five design options with highest amount of EUI

According to the results presented in the table 6.4 (related to most energy efficient design alternatives), windows can be designed in various sizes and orientations while still holding the same or very close values of the window to wall ratio (WWR). For example, both the dimensions of the first-floor window and the ground floor window can be oriented and designed in wider or thinner ranges. In terms of the energy efficient design, the important parameter is the total WWR, while the specification of designs may not be of concern. However, from an architectural point of view, each design configuration may have a major impact on the design or construction process.

The charts below (figure 6.4, figure 6.5, and figure 6.6) display the monthly cooling and heating loads related to the best energy performance-based design (case no.iii) and the worst energy performance-based designs (cases no.i & no.v) which have been derived from the charts generated by Autodesk® Green Building Studio®.

In the charts related to heating loads, the amounts above the zero axes represent heat energy gain. In addition, the amounts below the zero axes represent heat energy loss, which means that heat needs to be added to compensate for this loss and to maintain thermal comfort. However, cooling load charts can be explained in the same way; amounts that are above the zero axes represent heat energy being gained. This means that the amount of heat must be removed from the building to compensate for the extra heat being added and to maintain thermal comfort (Autodesk Sustainability, n.d).

In the color bar, internal loads and externals loads are displayed in different colors. Internal loads that present the amount of heat generated within the building are categorized as miscellaneous equipment (includes plug loads), lighting, and occupants. Other loads such as window solar, window conduction, infiltration, etc, are external loads that represent the amount of heat gain or loss due to conduction, convection, and radiation through the building envelope. The charts below show heating/cooling loads related to one "most energy efficient" design and two "least energy efficient" designs.

The simulation results are validated through the inter-model comparison approach (check Appendix C).

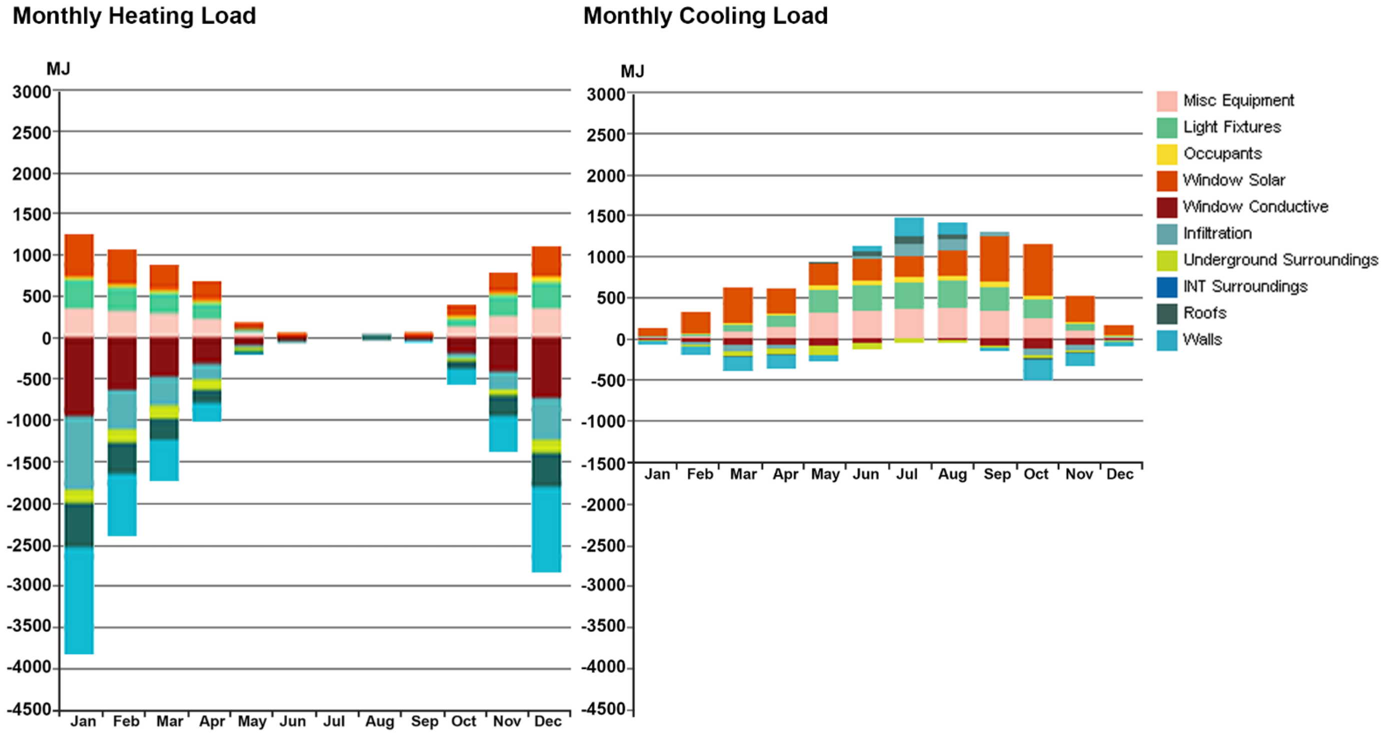


Figure 6.4: Most energy efficient design (no. iii), monthly heating & cooling load

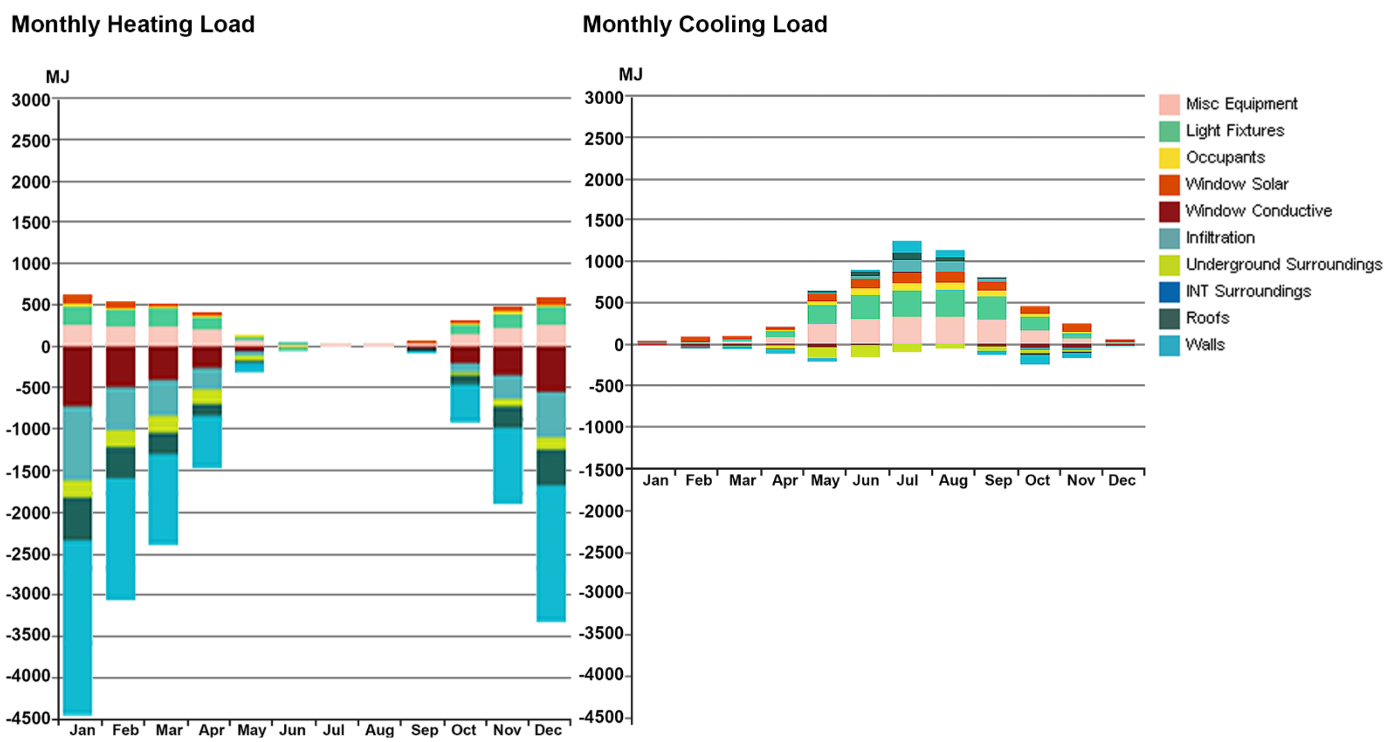


Figure 6.5: Least energy efficient design (no. i), monthly heating & cooling load

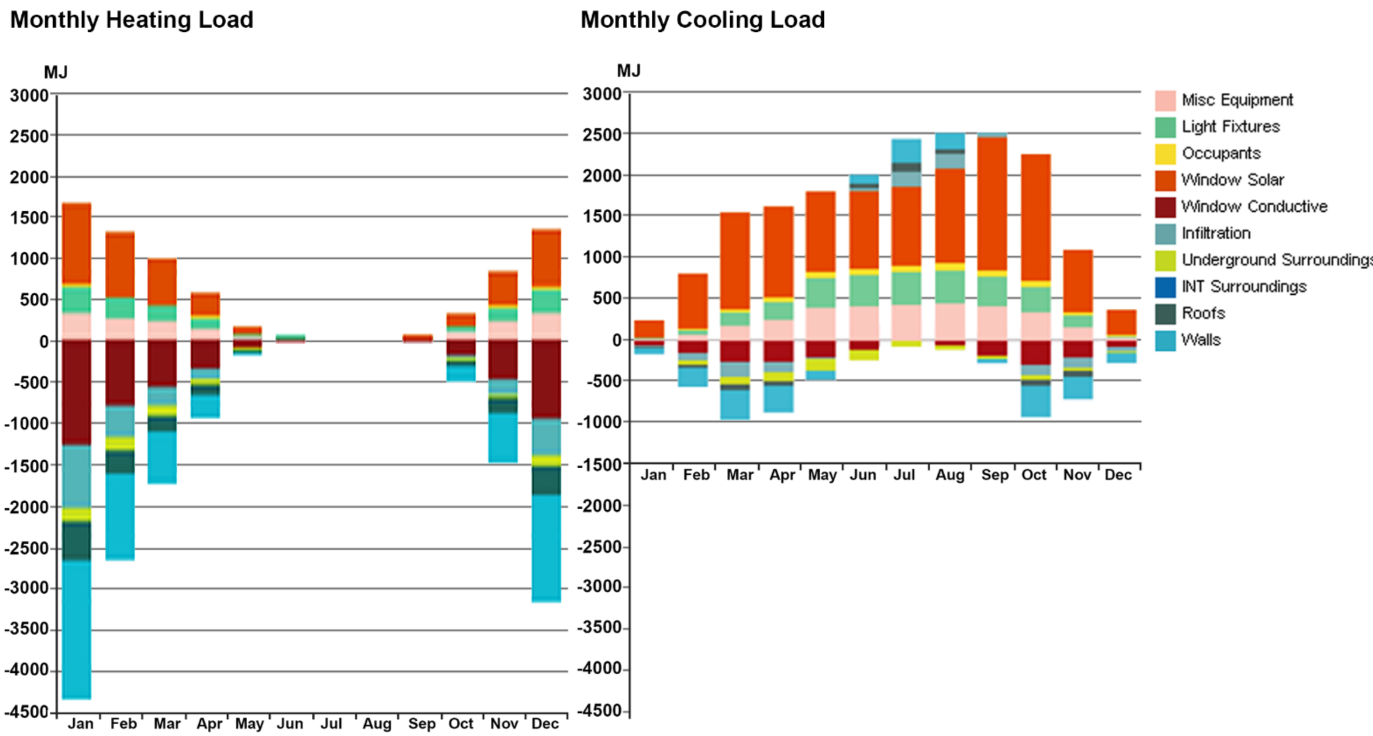


Figure 6.6: Least energy efficient design (no. v), monthly heating & cooling load

The images below (figure 6.7) represent qualitative 3D forms of 1296 design alternatives. Images are arranged according to the most energy efficient designs with the lowest amount of EUI to the least energy efficient designs with the highest amount of EUI. The designs are being illustrated through the usage of Design Explorer which is an open-source interface that suggests interactive visualization of sets of design options and was developed by CORE Studio (CORE, 2016).

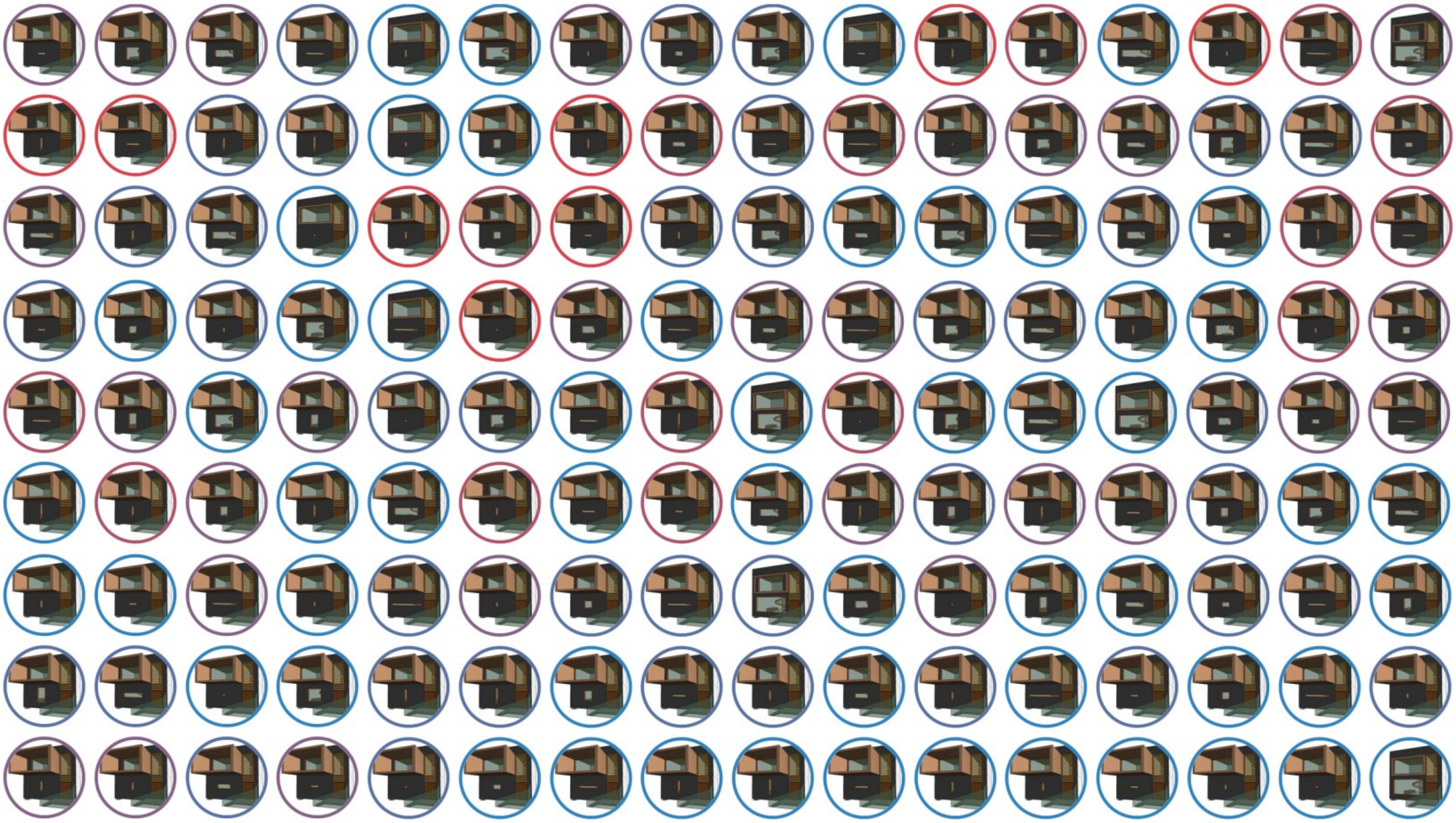


Figure 6.7: Qualitative results arranged based on lowest EUI to highest EUI

Drawing from the above explanations, five possible best design options according to energy performance results have been introduced. However, the decision making based on architectural features and energy performance is not the target of this research. The generation of interactive qualitative and quantitative results is difficult to obtain without using the proposed workflow.

Chapter 7 Conclusion and Discussion

7.1 Summary of qualitative & quantitative investigations through proposed workflow

This research presents a workflow in which:

- quantitative data (in this research, energy consumption) and qualitative representations (a 3D form of architectural design) are being generated simultaneously,
- with consideration of all possible design configurations of various input parameters (via a full factorial experimental approach), and
- in an automated process within BIM (a centralized data management platform).

The proposed workflow suggests a common language for communication between architects and engineers. The cooperation between architects and engineers in such an environment fulfills each group's need from the early phase of design. Through the elimination of error-prone data exchange between the architectural model and the energy model more time is being saved.

Design parameters can be selected by performing sensitivity analysis on large scale data (In this research sensitivity analysis is not worth the effort since only 1296 design alternatives are produced by a full factorial combinations of 4 parameters with the level of investigation of 6, see sections 2.4 & 4.2 for more explanations). Consequently, the full factorial combined list is fed as input parameters in the workflow's environment, and related qualitative and quantitative data are being produced through the automated process. As a result of this research, the effect of each design parameter on energy performance is observed visually (through qualitative 3D renders and quantitative data in tables). Contrary to conventional energy performance-based design, more than a single design with best energy performance results (and also with worst energy performance results) is being suggested, which helps both architects and engineers make early performance-based decisions in an integrated environment.

In the study of the selected case study, the modules of façade design in attached row unit houses are being repeated with minor changes (usually all façades are alike in each row of buildings). Thus, the results that indicate the best energy performance-based design alternatives can be propagated in each row of units.

7.2 Usefulness of the proposed workflow

When the impact of windows on the energy performance of a building is studied, usually the parameters being evaluated include total window to wall ratio (WWR), window orientation (due to different directions of south, north, east & west), U-value of glazing. However, ***the impact of a window's size distributions on energy performance is not being considered.***

According to the investigation done on the selected case study, a variety of design options are offered. ***For some designs with an equal amount of depth of shading and total WWR of the south façade, the EUI is not the same.***

Figure 7.1 presents various design options, which possess the same amount of shading depth and the same value of total WWR, though their energy performance is not equal.

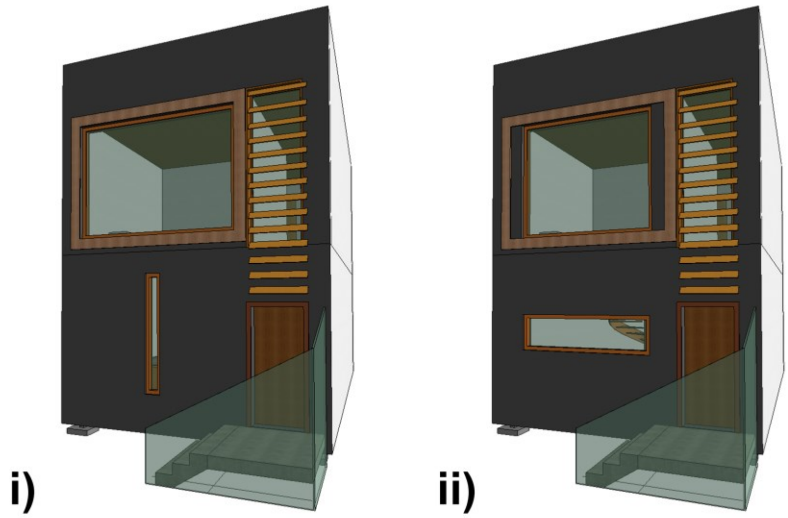
Designs number i and ii have a very near value of the entire south façade's WWR (with only a 0.04 percent discrepancy) and have equal value of shading depth. However, these two designs do not have the same "annual energy consumption per area" (or EUI). The difference in their amount of EUI is 1.7 kWh/m^2-yr (or 153 kWh/year).

In addition, designs number iii and iv, with only a 0.04 percent difference in the entire south façade's WWR and having the same amount of shading depth, have 0.7 kWh/m^2-yr of discrepancy in the annual EUI (or 63 kWh/year).

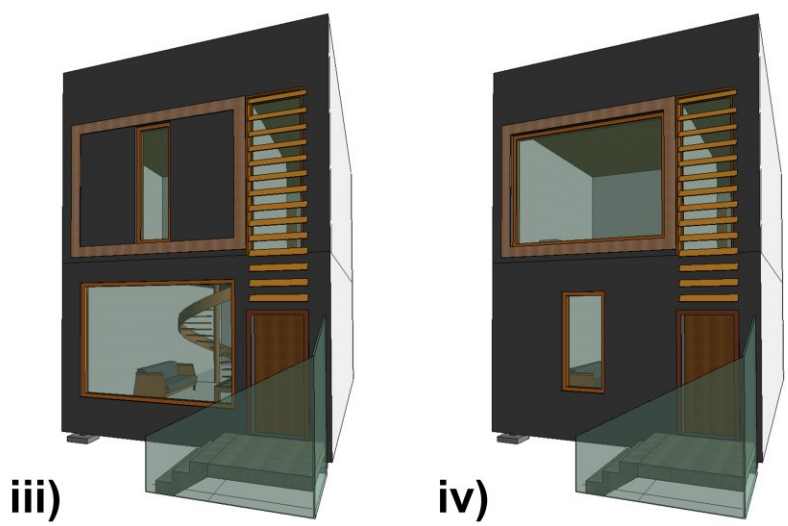
Although the amount of discrepancies of EUI results (for designs number i & ii and iii & iv) are not very significant in this study, a consideration of window's size distribution may help the improvement of energy performance in designs with a larger WWR in the south façade or multi-levels building.

In addition to the consideration of various parameters in the design of the south façade, the energy performance of the building is not only dependent on WWR but also influenced by the distribution of each window size and geometry. In this regard, performing daylighting analysis can help to understand the light distribution pattern and identify why some discrepancies occurred in the energy performance results. Future studies that apply some analysis such as daylighting are required in order to investigate the reasons for such discrepancies.

By utilizing the proposed workflow, the impact of distribution of windows on energy performance can be quantitatively and qualitatively distinguished.



Width (mm) 1st floor window	Width (mm) G floor window	Height (mm) G floor window	Shading Depth (mm)	WWR (%)	EUI (kWh/m^2-yr)
i) 3050	300	2200	25	52	83.13
ii) 2580	2500	680	25	52	81.43



Width (mm) 1st floor window	Width (mm) G floor window	Height (mm) G floor window	Shading Depth (mm)	WWR (%)	EUI (kWh/m^2-yr)
iii) 700	3050	2200	25	57	81.85
iv) 3050	850	1820	25	57	82.55

Figure 7.1: Qualitative representation of designs with the same WWR but different EUI

7.3 Applicability of workflow to investigate quantitative data & qualitative representations

The flowchart below displays the algorithm for implementation of the proposed workflow. Response variables in this study are manifested as qualitative 3D forms as well as quantitative building energy performance data. In future studies, the applicability of applying the workflow in other building projects with needs of generating the qualitative and the quantitative data can be further investigated.

In order to produce more design options and increase the possibility of choices, the interaction of parameters can be assessed via the proposed workflow. Through the application of full factorial experimental design, all possible combinations of parameters can be suggested. However, the scale of these investigations may be too large. In such cases, only the most critical parameters can be selected. In this regard, the recommended method is to perform the sensitivity analysis in order to omit non-significant parameters. In some cases by reducing the level of investigations, the scale of data can be decreased (by increasing the level of investigations in the full factorial approach, numbers of alternatives will exponentially increase). By achieving few number of datasets, performing the sensitivity analysis is not worth the effort.

After a final identification of parameters and defining ranges, lists of ranges of parameters will be fed to the proposed BIM-based workflow for an automatic generation of qualitative data in image format and quantitative data in CSV format. In this study, each set of energy simulation data is associated with its 3D architectural form. Finally, architects and engineers can make decisions based on requirements.

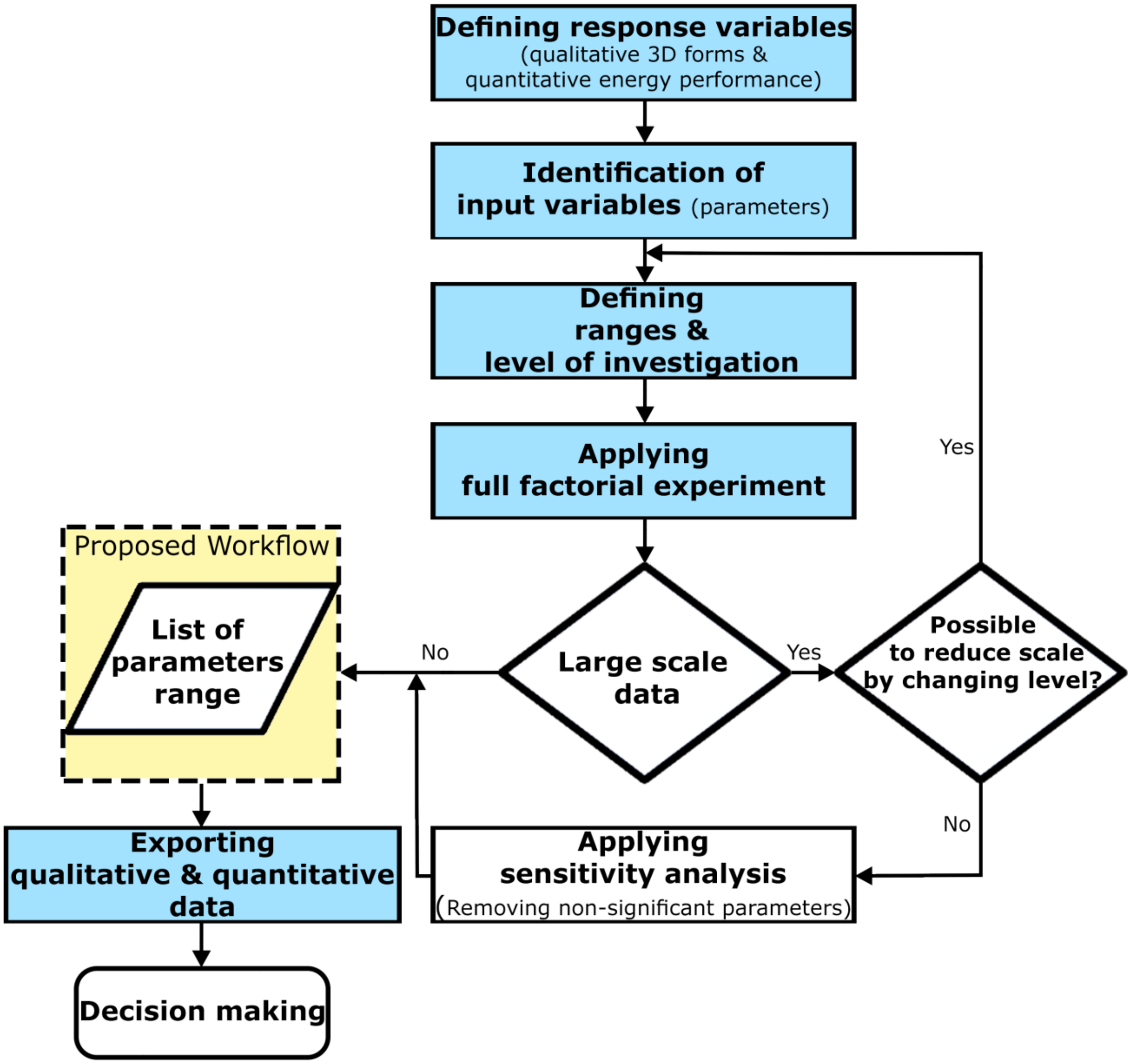


Figure 7.2: Algorithm of Applicability of workflow to investigate quantitative data & qualitative representations

The highlighted areas in figure 7.2 identify the steps performed in this research study. In addition, details of the proposed workflow which is highlighted in yellow, can be accessed in chapter 5.

7.4 Contribution of this study

The proposed workflow in this study helps to:

- utilize a ready-to- employ workflow in a similar integrated design process.
- make connection between architectural and engineering design requirements, through the representation of qualitative and quantitative energy performance-based data to support decision making in the early phase of design.
- provide architects and engineers with a wide variety of design solutions, which offers a large variation of choices.
- eliminate the error-prone process of import/ export building geometry among various quantitative energy performance assessment tools.
- reduce the time for the generation of many design solutions with various energy performance and aesthetic features in the early phase by automating the procedure.
- facilitate the sharing of building models among different simulation tools by adhering to standard file formats.

7.5 Future works

The same methodology through a "BIM-based workflow" can be modified to be adapted in other aspects such as:

- Representation of qualitative and quantitative daylighting analysis
- Automatic integration of a BIM-based workflow with cost estimation approaches
- Qualitative and quantitative assessment of multi-family or multi-zone energy efficient buildings
- Environmental analysis and practices like CO_2 emissions, embodied energy, lifecycle costs.
- Qualitative & quantitative assessment of shading of buildings in urban scale neighborhoods

Moreover, the workflow can be integrated with the architectural process to feasible the possibility of more complex geometry designs.

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Appendix A

Types of exterior shading devices

This section studies the shading devices with emphasis on the different types of exterior shadings. Shading devices are essential building elements to control the solar radiation intensity and the amount of daylighting gain in interior spaces.

Shading devices can directly have an impact on the thermal comfort and energy demand by allowing solar gain during winter and blocking unwanted radiations during summer. By passing the direct solar radiation to interior spaces during winter, the heating energy load can be decreased, while by providing the same condition during summer, due to overheating the cooling energy load will increase. Therefore, having proper shading devices is crucial in the design of energy-efficient buildings. Shading devices are cost-effective and an efficient way to save a significant amount of annual energy consumption, as well as providing thermal comfort and reducing glare (Khoroshiltseva et al., 2016).

External sun shading devices can be categorized into different types such as louvers and fins (they can be fixed or adjustable), overhangs (can be fixed or extendable), exterior roller blinds, or any type of perforated façade panels (Baker., 2009).

The term Brise-soleil (sun breaker) refers to any kind of permanent architectural feature that can act as shading structures to deflect direct solar radiation. Le Corbusier was the architect who popularized the use of Brise-soleil as modular pattern components in modern architectural design for the first time (Sobin, 1980, Solla, 2012).

The image below demonstrates the variety of Brise-soleils. In investigations that have been done done so far by many researchers, some type of Brise-soleil have failed to create shades on south-oriented façades when the sun altitude is lower in the east and west. Furthermore, additional specifications should be considered for designing a Brise-soleil in south- oriented façades because of the sun path variation during the day (Urbanalyse, 2012).

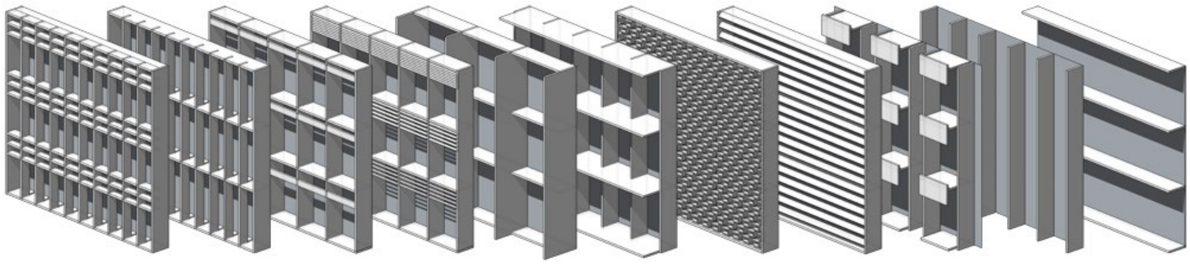


Figure A.1: Various kinds of Brise-soleil (Urbanalyse, 2012)

The type of exterior shading devices utilized in this research are louver, overhangs, and vertical fins, which are explained in two different parts below (the design specification is explained more in chapter 4).

Fixed louvers shading devices

The advantages of appropriately applying fixed louvers are their low-maintenance necessity and simplicity in design, as well as their functionality for providing summer shading while offering passive heating gain during winter.

Exterior fixed louver shadings can be proposed in a type of light shelf (can be installed horizontally or vertically) in order to distribute more daylighting to interior spaces and at the same time block some unwanted radiation. This type of louver is more beneficial when used in south façades during summer, when solar elevation is higher (Bellia et al., 2014). See the figures below.

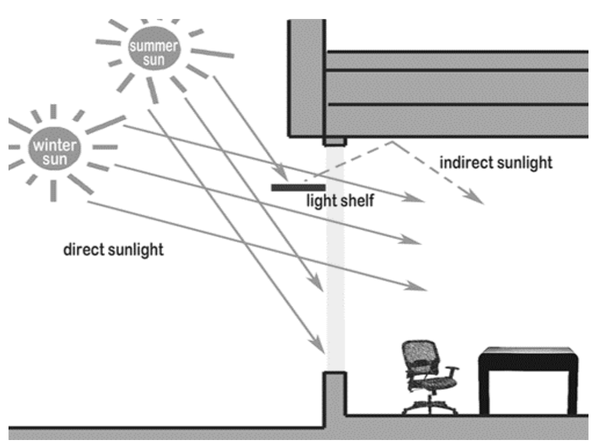


Figure A.2: Light shelf (https://www.pinterest.com)

Also, louver shading devices can be offered in commonly used types. The images below represent various types of exterior louver shading devices in horizontal or vertical positions.

Figure A.3: vertical and horizontal exterior louvers (Bellia et al., 2014)

The louver shading device assessed in this research is a fixed horizontal exterior louver.

Fixed overhangs & vertical fins shading devices

The figure below represents the commonly used exterior overhangs (can be solid or louvered overhangs) and vertical fins.

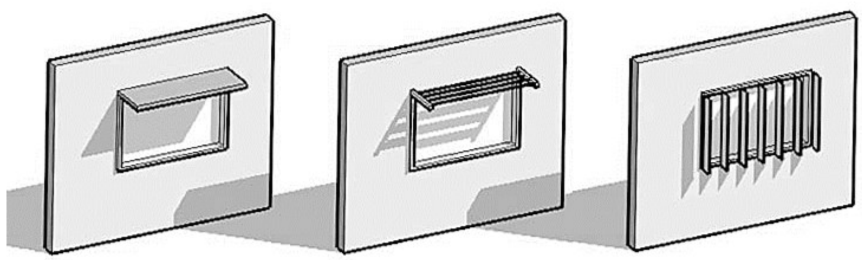


Figure A.4: Common types of exterior overhang and vertical fins, from left to right; overhang, louvered overhang, vertical fins (Robertson and Athienitis., 2009)

According to the investigation done by Center for Sustainable Building Research at University of Minnesota (Carmody and Haglund., 2006), various types of fixed overhang and vertical fins have been analyzed in order to assess the impact of exterior shading devices of south- oriented façades on the energy consumption, peak energy demand, and glare conditions in commercial buildings. The purpose of the study was to offer some general guidelines for evaluation of shading devices in the early phase of design.

According to the figure below, different types of overhang and vertical fins are designed for this assessment. The type of shading devices and values of their depth from left in the image to the right are respectively: vertical fins (1524 mm), shallow overhang (1024 mm), deep overhang (1536 mm), integrated deep overhang and vertical fins (1536 mm & 1524 mm). The values are converted to SI units.

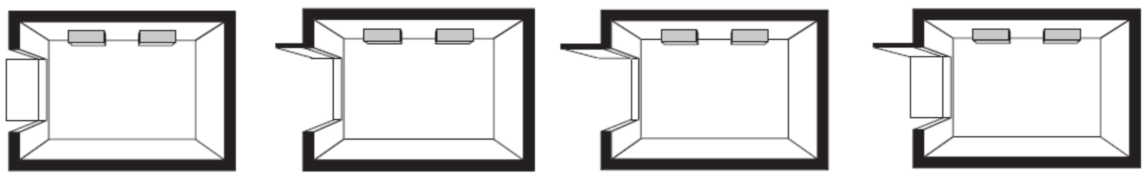


Figure A.5: From left to right; vertical fins, shallow overhang, deep overhang, integrated deep overhang & vertical fins (Carmody and Haglund., 2006)

The evaluations have been done for various input parameters. For example, the results have been presented for six different U.S cities with different climates. Also, various input parameters are considered for windows to wall ratios (0.3 for moderate window and 0.6 for larger window). One series of results are reported here as an example of analysis done for designing of shading devices in a south façade.

Energy simulations were done for a large window (with a constant amount of WWR of 0.6), while various initial assumptions were made for glazing properties such as U-value, SHGC, and glazing types. The results were assessed while each parameter was combined with different types of shading devices (explained in figure A.5). According to the outcomes, the lowest amount of energy consumption happened when the integrated deep overhang and vertical fins were used in design, while the window property was Low-E clear glazing with U-value of 0.2 and SHGC of 0.22 (Carmody and Haglund., 2006).

Based on results, it is concluded that vertical elements like fins integrated with overhang can suggest the best design configuration for a shading device in the south oriented façades.

Therefore, vertical shading fins are the best design option for the east and west orientations when the sun elevation is lower in the sky. As the solar intensity of east orientation during the morning does not have too much effect on internal heat gain, only the west and south shading devices can be invested if the budget is limited (Köster, 2004).

Consequently, there are many studies to investigate the impact of external shading devices on the energy consumption of a building. Through the proposed automated workflow in this research, a large number of design options can be evaluated to identify different dimentions in the design of shading devices. The shading pattern produced on window surface by each design alternative can be visually tracked in order to provide a better perception of designs. On the other hand, at the same time the impact of each design option on total energy consumption can be assessed.
In chapter 4, more details about the criteria for the design of a shading device were explained.

Appendix B

Quantitative and qualitative evaluation of maximum depth of shading device through automated BIM-based workflow

The investigation of the effect of south façade parameters such as a window to wall ratios on the energy performance of the building is not sufficient for comprehensive assessment of various design alternatives (see sections 3.1 & 4.2 for details about the identification of design parameters). Accordingly, additional parameters such as the various depths of shading devices are the object of study as well.

Through the evaluation of maximum depth of a shading device the question should be answered: How deep can the shading device be to fully shade the surface of the window (when it is designed at its maximum size, section 4.2)?

The maximum depth of a shading device is evaluated through the automated BIM- based workflow. Both qualitative (visual) and quantitative (numerical) data are generated through the proposed workflow.

In this appendix, the results (both numerical and visual data) and the details about the process of production of them are described. Before, in section 4.2.2, the statements about design criteria of a shading device and selection of specific day for analysis was described. In this part, through the implementation of these hypotheses in the Revit®-Dynamo platform, the desired results have been generated.

Various nodes have been utilized through Dynamo to run this analysis. One of the main nodes used in this study is the "SolarAnalysis" node from the "SolarAnalysisforDynamo" package. It is used to calculate the shadow area on the surface of the window. The input variables for the "SolarAnalysis" node are the weather location, analysis surfaces, shading surfaces, time of the study, building orientation (Ψ) and spacing that are explained below:

- Weather location input is set for Montreal, Canada.
- The geometry of analysis surfaces and shading surfaces have been set respectively to the surface of the window (The geometry of the first-floor window is assumed to be in its maximum size driven from the section 4.2.1.) and the shading device element.
- The time of study is considered for September 21 (the desired design day, as explained in section 4.2.2). The input hours are from 9 am to 3 pm when the solar radiation has the most

energy intensity in south orientation (Robertson and Athienitis., 2009). Also, the time step for this calculation is assumed to be 1 hour.

- The building orientation (Ψ) has been set as zero, which means the façade is facing due south.
- The output derived from this node is representing the shadow area by points. Points are projected on analytical surfaces, and XYZ coordinates define each point. By setting an appropriate value for input parameter of "spacing," the spaces between calculated points can be indicated and ultimately the area of shadow can be evaluated. The value assumed for the "spacing" variable in this investigation is 10 mm, which means the quantities of output points demonstrate the shadow area in cm^2. The shadow area unit in this study is finally converted to m^2.

The depth of the shading device is the variable that will be changed. In each loop, the area of shadow (caused by various depth of the shading device) on the desired window is calculated. In each interaction, the model is updated with new value of depth within the Revit® 3D workspace (the shadow option is turned on through settings). Then, images of the 3D workspace are parametrically written in the defined directory path through the usage of "Dynanimator" node (BadMonkeysTeam, 2014). The shading depth parameter is assumed to be increased by 200 mm in each step.

The "loopWhile" has been used to automate the iterations of calculations. Through this analysis, the accuracy of calculation of shadow area by the assumption made is 99 percent. The maximum calculated shadow area that fully covers the desired window is 6.70 m^2, while the surface area of the window is 6.71 m^2. In each time step the loop is continuing when the calculated shadow area is less than 6.70 m^2. As an outcome, the area of calculated shadows in each loop is written in CSV format by using the "CSV.WriteToFile" node and the related image data are being saved in PNG format through "Dynanimator".

The qualitative visual data and quantitative numerical data are represented in following sections.

Qualitative visual results

As a result, 91 images have been generated through the automated BIM-based workflow.

In the table below, all the exported images for each time step from 9 am to 3 pm are presented.

In image B.1, the shading device depth is displayed as D and the shadow area on the surface of the window as A. The gray region demonstrates the surface of the first-floor window when it is designed to its maximum size. The black region is showing the shadow pattern that is created by a shading device on the surface of the window on September 21.

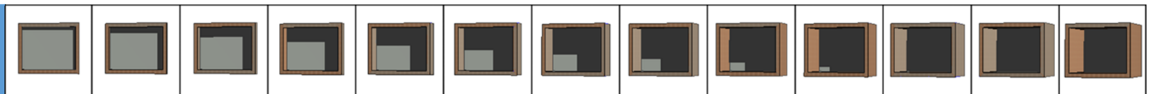
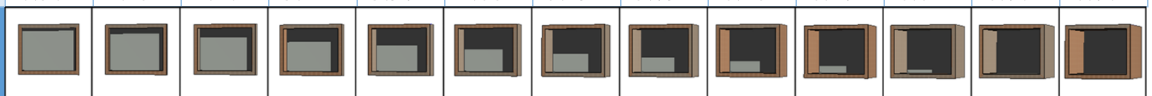
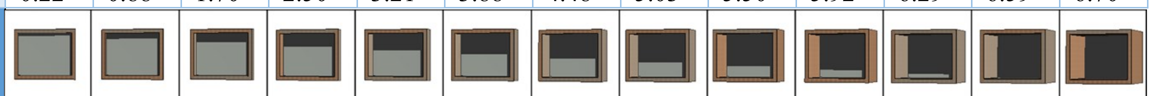
9 am													
D (m)	0.025	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4
A (m^2)	0.30	1.15	2.20	3.14	3.97	4.68	5.29	5.79	6.18	6.47	6.64	6.70	6.70
10 am													
D (m)	0.025	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4
A (m^2)	0.22	0.88	1.70	2.50	3.21	3.88	4.48	5.03	5.50	5.92	6.29	6.59	6.70
11 am													
D (m)	0.025	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4
A (m^2)	0.17	0.70	1.37	2.02	2.69	3.30	3.88	4.47	5.01	5.52	6.01	6.50	6.70
12 pm													
D (m)	0.025	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4
A (m^2)	0.13	0.54	1.11	1.70	2.26	2.84	3.39	3.94	4.51	5.05	5.62	6.15	6.70
1 pm													
D (m)	0.025	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4
A (m^2)	0.10	0.38	1.47	2.18	2.86	3.50	4.11	4.68	5.23	5.74	6.22	6.66	6.70
2 pm													
D (m)	0.025	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4
A (m^2)	0.24	0.96	1.89	2.73	3.52	4.21	4.83	5.38	5.85	6.24	6.55	6.70	6.70
3 pm													
D (m)	0.025	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4
A (m^2)	0.30	1.20	2.28	3.28	4.12	4.86	5.48	5.97	6.34	6.60	6.70	6.70	6.70

Table B.1: Qualitative results for evaluation of maximum depth of the shading device

This study can be developed to do further analysis in various aspects such as the investigation of the percentage of self-shading components in façades while tracking the shadow pattern created by movement of the sun in different hours of the day.

The quantitative numerical results related to this study is presented in next section.

Quantitative results

In this section, the numerical results driven through the BIM-based workflow is shown in the 3D graph. These outcomes are related to the assessment of maximum shading device depth on September 21 (when the solar radiation has the lowest altitude angle during summer in Montreal, canada).

According to the results, when the shading device depth is 2.4 m the shadow area that is projected on the surface of the window is equal to the area of that specific window. It means that through this design option, the first-floor window is 100 percent covered by shadow. Subsequently there will be no solar heat gain in interior spaces during the whole summer in Montreal (the detail is explained more in section 4.2.2).

Therefore, the maximum shading device depth that can be designed in front of the desired window in order to fully block the solar radiation is 2.4 m. This design helps to reduce the amount of cooling demand during the summer season, but as explained before, it may not cause reduction of total energy demand. Through parametric configuration of shading device depth with other parameters such as windows to wall area, another designs with less amount of energy consumption will be identified.

In the figure below the amount of shadow coverage on the surface of the analyzed window is normalized between 0 to 100 percent, which is demonstrated in the color bar.

Due to the investigation, the range of depths of a shading device in the specified case study is between 25 mm (assumed to be zero) to 2400 mm. As it can be seen in the figure, when the shading device depth is 2.4 m the shadow coverage on the analytical surface is 100% for all hours from 9 am to 3 pm.

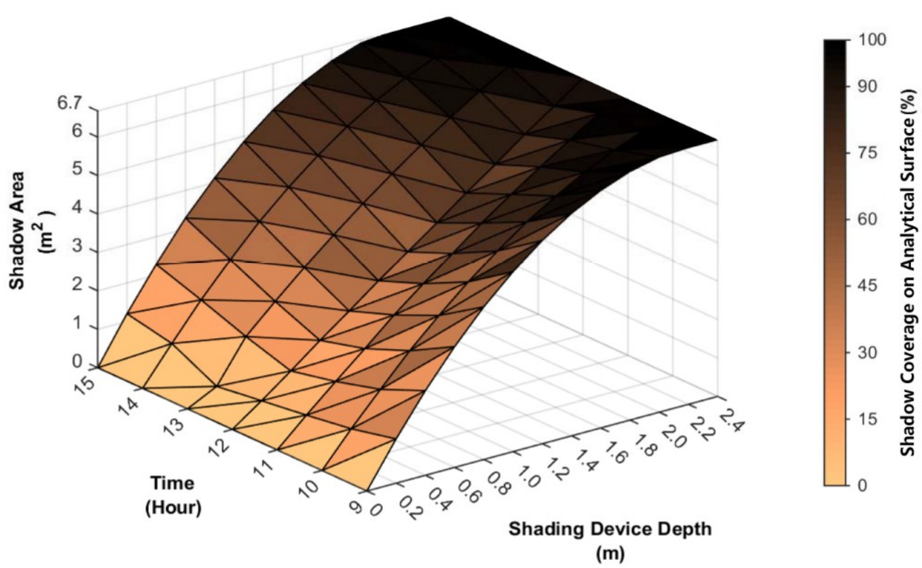


Figure B.1: Quantitative data presents maximum depth of shading device

Appendix C

Comparing energy performance results with EnergyPlus

Green Building Studio® (GBS), the chosen building energy performance simulation tool in this study, is BESTEST certified. In order to confirm if the models created in GBS perform similarly with different energy performance simulation tools, a comparison is made with EnergyPlus by concentrating on the predicted energy performance.

The comparison is made for 20 different design alternatives, where 18 of those are randomly selected among all 1296 design alternatives together with the “most energy efficient” and the “least energy efficient” designs (design alternatives were introduced in chapter 6). The results of the annual energy consumption of selected design alternatives is compared with the results of the same set of design alternatives which are predicted by EnergyPlus. All of the input parameters and building specifications are defined in the same values proposed in chapter 4. Table C.1 presents the simulation results of GBS and EnergyPlus for 20 design alternatives.

	WWR (%)	Projection Factor	Energy Consumption (kWh/m^2), GBS	Energy Consumption (kWh/m^2), EnergyPlus
Most energy efficient design	62	0.44	77.00	71.18
Random design selection 1	44	0.88	80.07	78.46
Random design selection 2	37	0.01	78.55	73.44
Random design selection 3	48	1.09	83.52	81.02
Random design selection 4	44	0.44	80.57	75.73
Random design selection 5	79	0.44	77.54	72.88
Random design selection 6	33	1.09	84.10	80.73
Random design selection 7	54	0.88	81.54	79.90
Random design selection 8	52	0.22	78.05	74.92
Random design selection 9	47	0.01	82.09	80.03
Random design selection 10	63	1.09	84.45	82.16
Random design selection 11	64	0.22	79.17	73.62
Random design selection 12	74	0.44	77.89	75.55
Random design selection 13	52	0.88	83.95	78.08
Random design selection 14	63	0.66	80.34	77.92
Random design selection 15	50	0.66	78.28	72.80
Random design selection 16	31	0.88	82.90	80.83
Random design selection 17	51	0.66	80.92	77.68
Random design selection 18	31	0.44	79.37	73.81
Least energy efficient design	86	0.01	86.06	83.04

Table C.1: Comparing predicted energy consumption results of GBS and EnergyPlus for 20 design alternatives

The difference between the two sets of results is quantified by CVRMSE (Coefficient of Variation Root Mean Squared Error) with the following formula:

$$\mathrm{CVRMSE} = 100 \times \left[\sum (y_i - \hat{y}_i)^2/(n-p)\right]^{1/2} / \bar{y}$$

The error is found to be less than 5% based on the 20 studied cases.