Univerza *v Ljubljani*
Fakulteta *za gradbeništvo in geodezijo*

**RAZAN RASHID**

# BIM AUTOMATION: DESIGN OPTIONEERING TOWARDS ENERGY PERFORMANCE OPTIMIZATION

# AVTOMATIZACIJA BIM: PROJEKTNE MOŽNOSTI ZA OPTIMIZACIJO ENERGETSKE UČINKOVITOSTI

BIM A+ European Master in Building Information Modelling

Master thesis No.:

Supervisor:
Assist. Prof. Tomo Cerovšek, Ph.D.

Ljubljana, 2023

Co-funded by the Erasmus+ Programme of the European Union

Does not print (tittle page)

**ERRATA**

| Page | Line | Error | Correction |
|---|---|---|---|

*»This page is intentionally blank«*

## BIBLIOGRAFSKO – DOKUMENTACIJSKA STRAN IN IZVLEČEK

**UDK:** **004.946:620.9-044.963(043.3)**

**Avtor:** **Razan Mohammad Mustafa Rashid, mag. inž. grad.**

**Mentor:** **doc. dr. Tomo Cerovšek**

**Somentor:** **Andraž Starc, mag. inž. grad.**

**Naslov:** **Avtomatizacija BIM: Projektne možnosti za optimizacijo energetske učinkovitosti**

**Tip dokumenta:** **magistrsko delo**

**Obseg in oprema:** **91 str., 84 sl., 7 pregl.**

**Ključne besede:** **Avtomatizacija BIM, optimizacija načrtovanja, energetska učinkovitost, izbiranje možnosti oblikovanja, analiza podatkov, poteki dela avtomatizacije, Revit, Dynamo, API, Python.**

**Izvleček:**

Gradbeni sektor je odgovoren za velik delež porabe energije in ima posledično znaten vpliv na okolje, zato je ena izmed prioritet načrtovalcev tudi izboljšava in optimizacija energijske učinkovitosti stavb. Vendar pa je načrtovanje energijsko učinkovitih stavb kompleksen proces, kar pogosto pomeni, da projektanti ta vidik pri načrtovanju spregledajo. Številka razpoložljiva orodja se v glavnem osredotočajo na analizo energijske porabe v zaključnih fazah načrtovanja, ne v zgodnjih, konceptualne fazah, ko se sprejemajo ključne odločitve, ki vplivajo na energijsko učinkovitost stavbe. Posledično je bistveno poenostaviti začetne faze načrtovanja. Tu se izkaže BIM (angl. Building Information Modelling) kot močno orodje, ki preoblikuje celotno gradbeno industrijo, saj lahko s pomočjo orodij BIM za avtomatizacijo načrtovalci lažje ustvarijo energetsko učinkovite in optimizirane stavbe. Namen te naloge je raziskati raznolike uporabe različnih tehnik avtomatizacije BIM za potrebe optimizacije projektnih rešitev in energijske učinkovitosti. Naloga si prizadeva ugotoviti in oceniti potencialne prednosti integracije avtomatizacije BIM tekom faze načrtovanja z namenom povečati energijske učinkovitosti stavb. Raziskava je uporabila več kvantitativnih in kvalitativnih metodologij. Metodologija je strjena v tri ključne faze: analiza metodologij iz prejšnjih študij, izbira osnovnega primera za študijo in pregled predlaganih delovnih tokov avtomatizacije. Osnovni primer, izbran za študijo primera, je enostavna stavba, ki jo je avtor naloge zasnoval z namenom testiranja različnih delovnih tokov. Raziskava zajema tri metodološke ravni avtomatizacije. Prva raven vključuje uporabo ročnega dela, ki poleg časovne potratnosti in nagnjenosti k nastopu človeških napak omejuje možnost proučevanja različnih variant projektnih rešitev. Druga raven se osredotoča na uporabo delovnih tokov, ki vključujejo vizualno programiranje. Izkaže se, da se zgolj zanašanje na vizualno programiranje morda ne zadošča za celovito avtomatizacijo. Kot dobra rešitev za povečanje učinkovitosti in pospešitev delovnega procesa se pojavi integracija tekstovnega programiranja znotraj vizualnega programiranja. Zadnja, tretja raven vključuje kombinacijo vizualnega in tekstualnega programiranja, konkretneje uporabo programskega jezika Python. Ta delovni tok se osredotoča na v celoti avtomatizirano generiranje različnih variant projektnih rešitev, izvoz v datotečni format gbXML, optimizacijo in analizo podatkov. Programski jezik Python se izkaže za zelo zmogljivega z vidika avtomatizacije in analize podatkov, saj omogoča hitro in natančno generiranje velikega števila variantnih rešitev. Rezultati opravljene študije tvorijo predlagani delovni tok za avtomatizacijo optimizacije projektnih rešitev v zgodnjih fazah načrtovanja. Čeprav so omejitve zaradi uporabe zaprto kodnih programskih orodij še vedno prisotne, postaja vloga programiranja v procesu načrtovanja vse pomembnejša, saj omogoča neoviran dostop do informacij za potrebe sprejemanja informiranih odločitev.

*»This page is intentionally blank«*

## BIBLIOGRAPHIC– DOKUMENTALISTIC INFORMATION AND ABSTRACT

**UDC:** **004.946:620.9-044.963(043.3)**

**Author:** **Razan Mohammad Mustafa Rashid, M. Sc. Architectural Engineering**

**Supervisor:** **Assist. Prof. Tomo Cerovšek, Ph.D.**

**Cosupervisor:** **Andraž Starc, M. Sc. Structural Engineering**

**Title:** **BIM Automation: Design Optioneering towards Energy Performance Optimization**

**Document type:** **Master Thesis**

**Scope and tools:** **91 p., 84 fig., 7 tab.**

**Keywords:** **BIM Automation, Design Optimization, Energy-Efficiency, Design Optioneering, Data Analysis, Automation Workflows, Revit, Dynamo, API, Python**

**Abstract:**

The building sector accounts for a significant amount of energy consumption, exerting a substantial environmental impact. Hence, prioritizing the enhancement and optimization of building energy performance is imperative for designers. However, designing such efficient buildings is a complex process, often leading designers to overlook this aspect. Many available tools primarily target energy prediction in final design stages rather than the conceptual phases, where critical decisions are made. Consequently, streamlining the initial design stage is essential. This is where Building Information Modeling (BIM) emerges as a potent force, reshaping the Architecture, Engineering, and Construction (AEC) industry. By harnessing BIM tools for automation, designers and architects can readily create energy-efficient, optimized buildings.

This research aims to delve into the diverse applications of BIM automation techniques in design optimization and energy efficiency practices. The study seeks to ascertain and evaluate the potential advantages of integrating BIM automation during the design phase to bolster energy efficiency in buildings. The investigation employed several qualitative and quantitative methodologies. The methodology is concluded into three key phases: analysis of methodologies from prior studies, selecting the base-case for the study, and examining the proposed automation workflows.

The study-case is a simple building designed by the author, serving as a base to assess the different workflows. The exploration encompasses three levels of methodological automation. The first level involves manual workflow application, which, while time consuming and prone to human errors, limits the design options exploration. The second level focused on visual programming workflows but struggled due to limitations and inflexibility of tools like Dynamo for automation. It's evident that sole reliance on visual programming might not suffice for comprehensive automation. Integrating textual programming scripts emerges to augment and expedite the process more effectively.

The final level merges both visual and textual programming, particularly Python. This workflow focused on fully automating design options generation, exporting to gbXML, optimization, and data analysis. The use of Python demonstrates its prowess in automation and data analysis, allowing for rapid, accurate creation of numerous design options. Through these investigations, the study gauges the efficacy and best practices of BIM automation in design optimization. The outcomes of the study culminate in proposed workflows for automating design optimization during early stages. Though limitations persist due to closed-source design tools, the role of programming in the design process is increasingly pivotal, offering unencumbered access to data for informed decisions.

*»This page is intentionally blank«*

## ACKNOWLEDGEMENTS

I am profoundly grateful to Allah, my creator, for His unwavering guidance and blessings that have illuminated my journey throughout this work and all my life's endeavors.

I extend my heartfelt gratitude to my supervisor, Tomo Cerovšek, and my co-supervisor, Andraž Starc, for their invaluable guidance, unyielding support, and expert insights. Their mentorship has been pivotal in shaping the course of this thesis. Their wisdom and experience have been instrumental in overcoming challenges and achieving milestones.

My gratitude extends to my beloved family members: Mohammed (Baba), Fadwa (Mama), Rasheed, Ahmad, Aseel, and Rashed. Your unwavering encouragement and support have been my constant motivation. To my friends across Jordan, KSA, and around the world, your love, support, and heartfelt prayers have accompanied me throughout this arduous journey.

I extend my appreciation to my colleagues in the BIM A+ program, whose camaraderie has made this experience enriching, fulfilling, and unforgettable.

I extend my sincere acknowledgment to the University of Ljubljana and the University of Minho, along with the coordinators of the BIM A+ program, for providing the platform and resources that have facilitated the completion of this thesis.

In closing, I recognize that this achievement is the culmination of collective efforts, and I am deeply thankful to all who have played a role, whether big or small, in making this endeavor possible.

And as I often say, this is not an end but rather a new beginning. It is my sincere hope that the insights and findings from this work may serve as an inspiration for others to embark on their own research journeys and continue the pursuit of knowledge and innovation.

°• وَمَا تَوْفِيقِي إِلَّا بِاللَّهِ عَلَيْهِ تَوَكَّلْتُ وَإِلَيْهِ أُنِيبُ •°

*»This page is intentionally blank«*

**TABLE OF CONTENTS**

**INDEX OF FIGURES**

**INDEX OF TABLES**

## LIST OF ABBREVIATIONS

| | |
|---|---|
| AEC | Architecture, Engineering and Construction |
| AI | Artificial Intelligence |
| API | Application Programming Interface |
| BEM | Building Energy Modeling |
| BIM | Building Information Modelling |
| BPS | Building Performance Simulation |
| EUI | Energy Use Intensity |
| GD | Generative Design |
| WWR | Window to Wall Ratio |

# 1 INTRODUCTION

## 1.1 Background

Building sector is accountable of a considerable amount of energy consumption as it has a huge impact on the environment [1]. Therefore, it is crucial for architects, engineers and designers to consider the importance of improving the building energy performance in the early design stage [2]. Achieving an energy performance design is a highly complicated process, it deals with a complex Multi-Optimization problem to minimize the costs, and keep the occupants' comfort [3]. The complexity in the process usually comes from the huge amount of data and the large number of parameters involved in the design. such as building envelope materials, geometry, weather data, Occupancy schedules and MEP systems. The simulation tools in general developed in a way to be used in the later design stages. On the other hand, there are far fewer tools for decision-making in the early design stages. However, research indicate that, building performance decisions are always taken in the preliminary design stages [4]. As a result, architects and designers often decide to neglect the energy performance and rely on general recommendations leading to inefficient building designs, or they may opt to engage building energy experts to simulate different design alternatives and optimize energy performance. Due to the time-consuming and error-prone process of transferring the architectural model to the energy simulation tool, designers and energy experts are often constrained to select only a limited set of design alternatives for energy analysis. As a result, this approach frequently leads to suboptimal design solutions that are not fully optimized for energy efficiency [5]. Therefore, there is a necessity for an innovative design workflow and integrated process that integrates parametric modeling and Building Information Modelling (BIM) automation. The integration of these techniques holds significant potential to enhance the building design process.

The Architecture, Engineering, and Construction (AEC) industry is undergoing a transformative shift due to the evolution of BIM [6]. BIM enables users to analyze different design alternatives and make important energy-related decisions during the early stages of a project. By utilizing BIM tools, designers can select appropriate materials and make choices that have a significant impact on the entire lifecycle of the building [5]. In fact, BIM automation encompasses the utilization of automated tools and techniques within the BIM framework to streamline processes, increase efficiency, and optimize design outcomes.

The study aims to investigate and explore the various applications of BIM automation techniques in the AEC industry, with a specific focus on optimizing architectural design for energy efficiency practices. It aims to identify and analyze the potential benefits of implementing BIM automation in the design phase to enhance energy efficacy in buildings. In order to achieve this aim, a number of objectives were set; to review previous studies on BIM based design optioneering and energy optimization and analyze the current practices and challenges in architectural design related to energy efficiency within the AEC industry. Furthermore, to explore the potential of BIM automation techniques in optimizing energy efficiency during the architectural design phase, and to evaluate the impact of BIM automation on design decision-making processes in the earlier stages. To explore and develop automation workflows that can support efficient design optioneering and energy optimization processes, and to apply different workflows on a base case and examine the effectiveness of BIM automation for energy-efficient architectural design. Moreover, to contribute to the existing knowledge by enhancing our understanding of the role of BIM automation in promoting energy-efficient design practices. Investigate the integration of energy simulation tools and data-driven approaches within BIM workflows to enhance energy efficiency practices. Additionally, to assess the benefits and limitations of BIM automation techniques in terms of energy optimization and overall design quality. The study will provide recommendations for implementing BIM automation techniques effectively in architectural design to achieve energy efficiency goals and identify areas for future research and improvement in the field of BIM automation and energy optimization in architectural design.

The study will investigate three methodological levels; the first level is the manual workflow application. In this level the traditional approach for energy simulation using Revit and Green Building Studio (GBS). The second level will examine the automation workflow using visual programming (Dynamo), this workflow will focus on creating design options based on the provided variables. The last level will be applied using both visual and textual programming (Python), this workflow will focus on automating the whole process of creating options, exporting to gbXML and the optimization process. The three workflows will be examined to investigate the best practices and the efficiency of BIM automation in the design optimization. The selected base-case is a simple gallery administrative building designed by the author to examine the different workflows. The selection of the base case was made to get the flexibility to have many design options.

The anticipated outcomes of the study comprise suggested workflows for automating the design optimization process during the initial stages. It is evident that relying solely on the visual programming tool may not be adequate for complete automation. Therefore, incorporating textual programming scripts is expected to enhance and streamline the process more effectively.

## 1.2 Aim and Objectives

### 1.2.1 Problem Statement and Research Aim

The Architectural Engineering and Construction (AEC) industry faces many challenges in optimizing designs for energy efficiency, and there is a need to explore the potential benefits of implementing Building Information Modeling (BIM) automation techniques during the design process. Despite the growing application of BIM in the AEC industry, there is a gap in understanding how BIM automation can enhance energy efficacy in buildings and promote sustainable design practices.

While BIM tools have proven effective in facilitating design coordination, data integration, and visualization, their specific application in optimizing architectural design for energy efficiency requires further investigation. The industry lacks comprehensive knowledge on the practical implementation of BIM automation techniques and their impact on energy optimization and design optioneering.

Moreover, understanding the potential benefits of implementing BIM automation in the design process is crucial for stakeholders in the AEC industry. Architects and engineers need evidence-based insights into the advantages and limitations of BIM automation for energy-efficient design decision-making. Without a thorough exploration of the various application workflows and benefits of BIM automation in design optimization practices, the industry may miss the effective use of this technology.

Therefore, there is a need for a systematic investigation and exploration of the applications of BIM automation techniques in the AEC industry, with a specific focus on optimizing architectural design for energy efficiency. This research aims to investigate the potential benefits of implementing BIM automation in the design phase to enhance energy efficacy in buildings. By addressing this gap, the study will contribute to the advancement of sustainable architectural practices and provide valuable insights for industry professionals seeking to optimize energy performance in their designs.

The aim of this study is to investigate and explore the various applications of BIM automation techniques in the Architectural Engineering and Construction (AEC) industry, with a specific focus on optimizing architectural design for energy efficiency practices. The study aims to identify and analyze the potential benefits of implementing BIM automation in the design phase to enhance energy efficacy in buildings.

### 1.2.2 Research Objectives

The research objectives are summarized as the following:

- To review previous studies on BIM based design optioneering and energy optimization and analyze the current practices and challenges in architectural design related to energy efficiency within the AEC industry.
- To explore the potential of BIM automation techniques in optimizing energy efficiency during the architectural design phase, and to evaluate the impact of BIM automation on design decision-making processes for energy-efficient architectural design.
- To explore and develop automation workflows that can support efficient design optioneering and energy optimization processes. To apply different workflows on a base case and examine the effectiveness of BIM automation for energy-efficient architectural design.

- To contribute to the existing knowledge by enhancing our understanding of the role of BIM automation in promoting energy-efficient design practices. Investigate the integration of energy simulation tools and data-driven approaches within BIM workflows to enhance energy efficiency practices.
- Assess the benefits and limitations of BIM automation techniques in terms of energy optimization and overall design quality.
- To Propose recommendations for implementing BIM automation techniques effectively in architectural design to achieve energy efficiency goals.
- To identify areas for future research and improvement in the field of BIM automation and energy optimization in architectural design.

## 1.3 Research Methodology

This research aims to investigate the potential benefits of implementing BIM automation in the design phase to enhance energy efficacy in buildings, with a specific focus on optimizing architectural design for energy efficiency practices. The study aims to identify and analyze the potential benefits of implementing BIM automation in the design phase to enhance energy efficacy in buildings. Therefore, several qualitative and quantitative methods will be applied, as shown in the graph below. These methods can be summarized into; analysis of previous studies methodologies, selection of the base case, and then examine the proposed automation workflows.

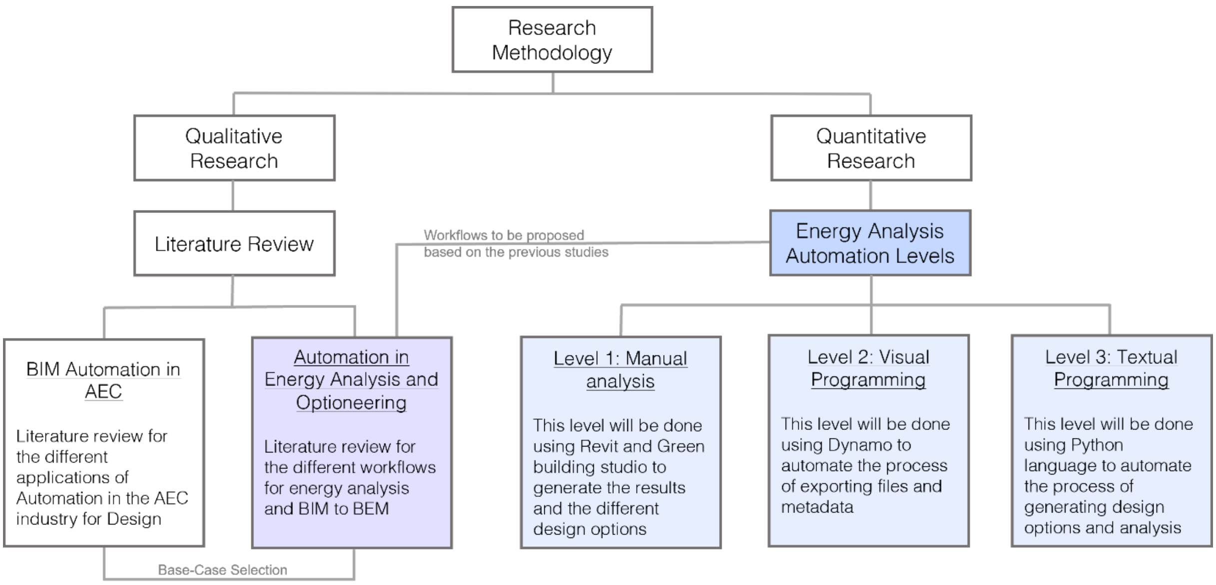



Figure 1: Methodology Graph shows the qualitative and quantitative research approaches.

## 1.4 Research Scope and Limitations

### 1.4.1 Research Scope

This study focuses on investigating and exploring the applications of BIM automation techniques in AEC industry, with a specific focus on optimizing architectural design for energy efficiency practices. The research scope encompasses the use of BIM automation during the design phase to enhance energy efficacy in buildings. It involves analyzing the potential benefits of BIM automation and its impact on energy optimization, as well as identifying practical strategies for implementing BIM automation effectively in architectural design decision-making.

The study examines different workflows to optimize the process of design options creation. Which includes the evaluation of various design options, considering factors such as building orientation, envelope design, materials, and systems. This research will focus on the building envelope and specifically the window to wall ratio (WWR). This research also explores the use of data-driven approaches and automation workflows to support efficient design decision-making and energy optimization processes.

### 1.4.2 Research Limitations

It is essential to acknowledge the limitations of this study to ensure the appropriate interpretation and generalization of the research findings. This research aims to investigate and explore the various applications of BIM automation, with a specific focus on optimizing the energy efficiency. The study aims to identify and analyze the potential benefits of implementing BIM automation during design to enhance energy efficacy in buildings. It includes one base case for examining the different workflows. Analyzing different cases for different building types will be complicated and time consuming. The base case is a simple two stories gallery building, and it is totally developed by the author. The selection of the base case designed to have the flexibility in design to have different WWR and wall types. The design of the base case takes into consideration to include as many building elements as possible, such as stairs, walls, and openings. The building’s shape and layout were fixed throughout the simulation stages in order to focus the study on the building envelope and WWR in specific, and to avoid extreme research time.

Despite these limitations, this study aims to provide valuable insights and recommendations for the implementation of BIM automation techniques in architectural design to achieve energy efficiency goals. The research findings can contribute to the existing knowledge base and serve as a foundation for future research and improvements in the field of BIM automation and energy optimization in architectural design.

The study will be conducted using Revit Software as the modeling tool. For the energy simulation, Green Building Studio/ Energy Plus and Climate Studio will be used. The automation will be done using visual programming language Dynamo and Grasshopper, and Python scripts will be added inside the visual programming language environment.

### 1.5 Research Structure

The thesis is composed of five chapters organized as follows:

The first chapter includes the introduction of the research. This chapter of the study has provided the research background, problem statement, aims and objective, methodology, research scope and limitations and the structure of the research.

The second chapter includes the literature review and theoretical framework of the study. This chapter reviews the relevant literature, which explains subjects related to BIM automation techniques and design optioneering. This chapter consists of four sections including the overview in the first section. The second section reviews the BIM automation techniques in AEC industry which includes four subsections below: BIM automation applications in the AEC industry, Definition and significance of BIM automation, Overview of key concepts such as parametric modeling, generative design, and rule-based design automation, and Discussion on the advantages and potential of BIM automation for design optioneering and optimization. The third section of the chapter reviews the overview of Energy efficiency practices in architectural design within the context of BIM. This section includes two subsections: BIM automation in energy optimization practices: BIM to BEM, and general review of the BEM tools. The fourth section of the chapter focused on the Previous Studies on BIM-based design optioneering and energy optimization. This section includes one subsection; and it reviews the analysis of methodological workflows employed in previous studies.

The third chapter includes the research methodology. This chapter consists of five main sections. The first section is the overview. The second section cover the selected base-case building and design optioneering strategy. This section includes two subsections: the first part includes the base-case building description as it includes the architectural drawings and the physical characteristics of the building. The second part includes the design optioneering strategy and the design variations options. The third section includes the energy analysis automation levels. This section includes three sections, the first covers the examination of the manual workflow, the second subsection covers the automated workflow using visual programming (Dynamo). The third part examining the visual and textual programming automation workflow. The fourth section includes the data analysis for the results and visualization. the last section includes the summary of the chapter.

The fourth chapter reviews the research outcomes and discussion. This chapter includes two main sections; the first section is the overview. The second section is the workflow comparison. The final chapter (chapter five) includes the conclusions of the research, ended with the future research.

# 2 LITERATURE REVIEW AND THEORETICAL FRAMEWORK

## 2.1 Overview

As concerns about energy consumption and environmental sustainability continue to grow, so does the pressure on the AEC industry to adopt innovative solutions for energy-efficient building design. Building Information Modeling (BIM) has emerged as a powerful technology that revolutionizes traditional design and construction practices. Leveraging the potential of BIM automation for energy optimization offers a practical solution to address these challenges. This chapter provides a comprehensive literature review and theoretical framework for the thesis. The chapter includes four sections, the first section is the overview of the chapter. The second section reviews the BIM automation techniques in the AEC industry. The third section includes an overview for the energy efficiency practices in architectural design within the context of BIM; this section provides an overview of energy efficiency practices in architectural design that can be implemented using BIM. The last section reviews the previous studies on BIM-based design optioneering and energy optimization. This chapter will cover the qualitative research part as shown in the methodology graph below.

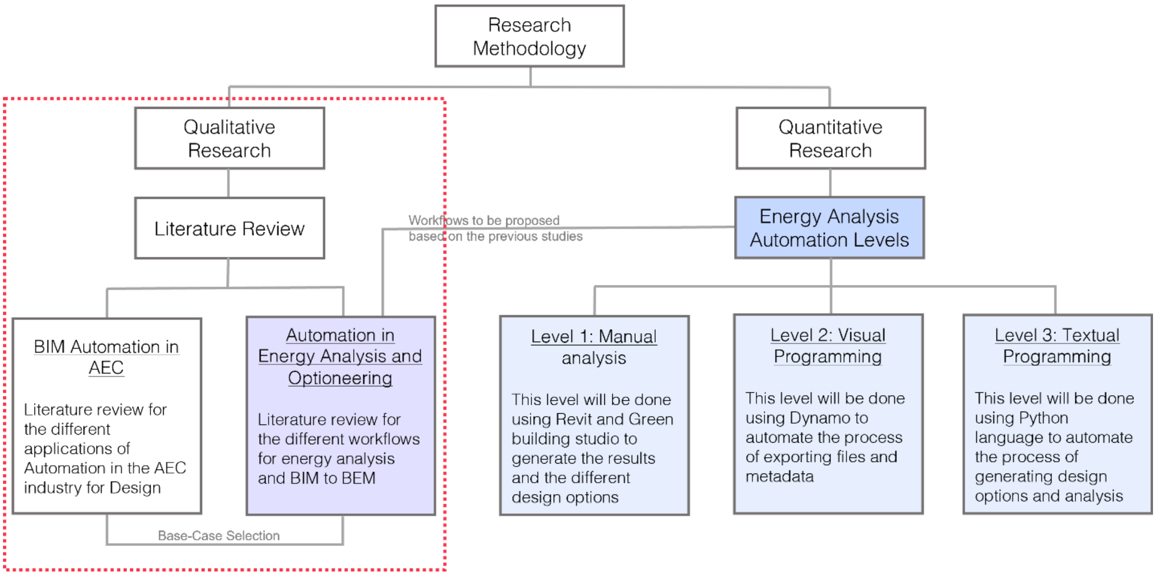



Figure 2: Research Methodology graph shows the Qualitative Research covered by this chapter (focused area within the red rectangle)

## 2.2 Overview of BIM Automation Techniques in AEC Industry

BIM is an advanced technology that has had a huge impact on the AEC industry in the recent years [7]. BIM has enabled a significant change in the design and construction methods in the AEC industry [8]. One of the important areas where BIM has demonstrated remarkable potential is in the realm of automation, which has significantly improved the design and optimization practices. This section presents a literature review on the definition, and significance of BIM automation in architectural design, along with an overview of key concepts such as parametric modeling, generative design, and rule-based design automation. Furthermore, it discusses the advantages and potential of BIM automation for design optioneering and energy optimization. The research entails a comprehensive review of 27 scholarly papers. This review, including 10 papers related to the domain of BIM automation within the AEC industry, 6 papers focused on parametric design, 4 papers on generative design, and 7 papers that explore the intersection of BIM-based energy simulation, design optioneering, and optimization.

### 2.2.1 BIM Automation Applications in the AEC Industry

The AEC industry is very competitive, and companies that adopt the latest technologies will have an edge over their rivals because of their readiness to benefit from it and adjust to these advancements. While the building sector is rapidly growing in Europe and worldwide, it is only just beginning its long-awaited transition from traditional methods to automated processes [9]. As a result, there is a need to develop tools and techniques in the AEC industry to facilitate and improve the design process, as this will allow for advanced design and construction methodologies.

One of the most notable and promising developments in the AEC sector is the use of BIM as a digital information management. This is due to BIM's ability to represent a fundamental change in the way data is managed in a digital format for use throughout the entire life cycle of a project [10]. The adoption of BIM automation in the AEC industry has been a gradually growing over the past 10 years. In Handerson Engineers they are focusing on using BIM to automate process toward efficiency and optimization designs. For instance, In HVAC design BIM automation employs pre-calculated design parameters to automate the system equipment placement with different sizes and capacities. In the image below it shows an example of using a Dynamo script to identify the equipment location above the ceiling tiles using data from the architectural model. This data is stored in individual ceiling elements, enabling automated placement of access tile family for ceiling design [11]. The automated methodologies allow engineers to easily adjust with design changes and focus more on the engineering work itself, while still generating high-quality models. The increased efficiency gained through BIM automation results in time and cost savings for clients without compromising the design quality [11]. Augmenta (AI Platform) on the other is working on a new solution for the AEC industry that will automate buildings design process. This advanced technology will employ specific techniques to optimize the design process and making it more efficient. While the use of AI technology in the AEC industry is not a new concept, it has primarily been applied during the construction phase. Augmenta, is focusing on the design stage, specifically on the different disciplines such as structural, mechanical, plumping, and electrical. Their goal is to automatically generate detailed, code-compliant, and construction design documents that meet the clients' criteria for these designs [12]. Although all of these advanced technologies and applications of BIM, still as [13] mentioned the AEC industry is one of the least regarding the digitalization of human activities. The next section reviews the definition of BIM automation and why it is important in the architectural design context.

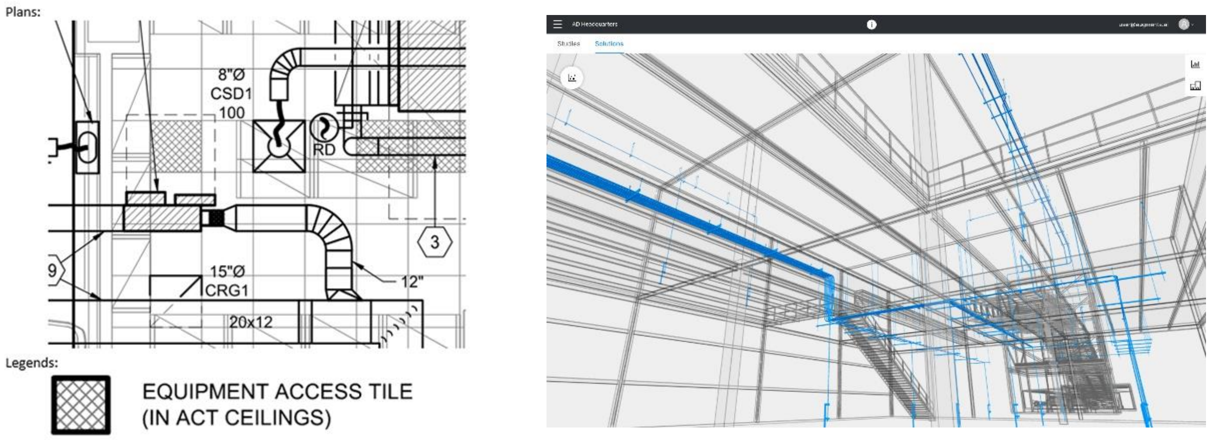



Figure 3: On the left; A Ceiling plan shows the automated coordination between HVAC and ceiling tiles design [11], on the right; A detailed design of an electrical system automatically created by Augmenta [12].

### 2.2.2 BIM Automation Definition and Significance

Automation is currently revolutionizing many industries. Automation has different definitions, but there has been no doubt that it is powerful and has a profound impact on humanity, while automation has the potential to bring many benefits, it also carries certain risks that must be carefully considered [14]. In the context of BIM, automation refers to the use of computational techniques and digital tools to automate repetitive and time-consuming tasks. This process involves using algorithms, scripts, and parametric modeling to automatically generate, analyze, and optimize various design alternatives. According to Autodesk, automation techniques enable you to easily utilize rule-based design without the need for coding experience [15]. BIM implementation in construction projects has standardized and expanded project information, enabling valuable analysis of times, costs, and infrastructure. However, managing this information manually has become tedious and repetitive work. BIM automation seeks efficiency and reduced operating costs as a solution [16]. The automation of tasks, such as geometry generation, energy analysis, and rule-based design, brings significant benefits to the architectural design process.

In the past decade, the prospects of automating the design synthesis process have become a prominent topic in architectural and engineering practice. This shift is primarily attributed to the increasing adoption of parametric software by architects and engineers [17]. Nowadays, by using computational technologies and automated processes, designers and manufacturers can overcome some of the technical limitations of architectural design to meet the market needs. This allows the creation of more efficient and effective designs [18]. By automating processes, designers can quickly advance projects to completion, freeing up valuable time for tasks that require expertise and engineering knowledge. Automation can help to finish projects in seconds, allowing you to focus on more complex and challenging tasks [15]. This can lead to increased productivity, improved job satisfaction, and greater innovation in the workplace. Automation and artificial intelligence (AI) have the potential to revolutionize the design methodologies, digitalizing tasks and increasing the effectiveness [19]. In this research, the term "automation" pertains to the process of generating design options without the need for manual creation of files for each variation. Instead, this automation relies on predefined lists for variables and elements, allowing for the instantaneous creation of design variations. Overall, the goal of automation is to expand the array of available design options, offering designers greater flexibility, saving valuable time, and mitigating the potential for human errors that can arise in manual workflows. Automation, in this context, can be implemented through the utilization of both visual and textual programming languages. The next section will address the key concepts such as parametric modeling, generative design, and rule-based design automation.

### 2.2.3 Overview of Key Concepts such as Parametric Modeling, Generative Design, and Rule-Based Design Automation

*Parametric Modeling*

Architects and engineers working with a classic 3D model, also known as a direct model, position pre-made objects within the model and then manipulate object parameters such as dimensions or location until the desired geometry is achieved. However, in a parametric model, the user parameterizes the objects, thereby directly influencing the model geometry itself. This implies that the objects are not predefined, and the user operates within a volume using various imposed parameters [20]. Using of parametric design of BIM, architects and engineers are able to create a library of standard parametric modular components [21]. A parametric model is, therefore, an ideal building models that can offer several solutions based on the values assigned to each parameter [20]. As mentioned by [22], parametric modeling is regarded as a "propagation" system, signifying a system of elements interconnected through relationships, evolving sequentially. This system can be envisioned as a series of mathematical equations comprising variables that, when determined, yield project proposals [23].

Underscoring the significance of parametric modeling, it provides dynamic control over geometry and components, enabling simultaneous evaluation of multiple variables [24]. [25] highlights a design challenge that extends beyond geometric complexity to include the integration of performance feedback. Their tool showcases significant enhancements in energy performance, reaching up to 50%, attributed to intricate architectural forms [26]. [26] formulated a parametrization algorithm for simulating daylight and energy consumption. This approach encompasses space-related variables such as geometry, surface reflectance, and their interactions with the urban context, including location and surroundings [27]. In summary, parametric design techniques offer a powerful means to enhance the energy performance of buildings by systematically altering key building parameters.

### *Generative Design*

Generative design (GD) is an iterative design process guided by rules, utilizing algorithmic and parametric modeling to automatically explore, iterate, and enhance design options by establishing high-level constraints and goals [28]. The integration of GD within BIM brings together an innovative design approach and automated generation of construction information [28]. This combination enhances the constructability of GD's automated design solutions while also enhancing BIM's capability in the initial design stage. Consequently, the development of GD-BIM has gained growing interest both in academic and practical contexts [28]. Therefore, generative design software is presently employed by architects and engineers to enhance the efficiency of identifying optimal design solutions [29].

The general way to implement generative design in BIM is to set-up rule-based parameters that govern the shape and placement of objects and telling the software what these parameters should apply to [30]. The usage areas of generative design are by example lighting studies, space planning and cost estimations. The design limitations set by building systems steer the development of optimal pre-engineered solutions. A common approach to integrating GD into BIM involves establishing rule-based parameters that dictate the shape and placement of objects, while instructing the software on where these parameters should be applied [29]. The parameters set by building systems guide the creation of well-suited pre-engineered solutions. By aligning with building systems, GD can enhance efficiency in off-site manufacturing processes, while maintaining the capacity for customization within the solution space [31]. In the context of mass customization, factors like complex design shapes and distinct solutions may take a backseat to prioritizing the optimization of raw material utilization and production efficiency [32]. Similarly, GD stands as a potent technique for generating design options to facilitate informed decision-making processes.

### *Rule-Based Design Automation*

Rule-based automated design check systems interpret building rules and regulations by translating them into IF (conditions) THEN (actions) clauses [33]. Automated rule checking refers to software that evaluates a building design without making modifications. Instead, it assesses the design based on object configuration, relationships, or attributes [34]. Rule-based systems employ predefined rules, constraints, or conditions to analyze a proposed design, yielding outcomes such as "pass," "fail," "warning," or "unknown" for instances where data may be incomplete or unavailable [35]. [35] summarized the structure of rule checking into four phases: rule interpretation, building model preparation, rule execution, and reporting of checking results.

Ding et al. (2006) introduced an automated approach for inspecting compliance with building codes, utilizing a 3D object-based model combined with Express language [36]. Zhang et al. (2013) developed a rule-based automated safety check integrated with BIM model representation. Their study successfully implemented an automated rule-based safety checking system, demonstrated through both sample and real models, specifically in fall protection scenarios. The research highlights the viability of incorporating safety planning during scheduling, facilitating early detection and integration of a protective safety system within BIM. This involves identifying hazardous locations, estimating quantities, and establishing schedules for the implementation of safety equipment [37]. Adopting automated rule-based design checking, it is possible to shorten the process of building design and reduce human errors. This automation aligns with the broader context of BIM automation, where similar principles can be applied to optimize energy performance in building design.

### 2.2.4 Discussion on the Advantages and Potential of BIM Automation for Design Optioneering and Optimization

BIM has emerged as a potential role in construction projects, altering the way things are done. Because of its clear advantages over traditional design methods, many design teams around the world are adopting it. Some countries are even making it a standard practice [38]. The concept of BIM can be described as a set of processes, policies and technologies which visualize the work methodology, enabling the management of 3D drawings and project data in a digital format throughout the entire building life cycle. It involves a combined approach in which the project's functional and physical aspects are managed, digitally simulating the actual construction process of the project [39]. The core of BIM revolves around project stakeholders exchanging information throughout the whole building lifecycle. In contrast to the traditional method, which is sequential, disorderly, and lacks information exchange, BIM empowers each stakeholder to work independently but also connected to a central model encompassing all building details, including architectural and technical/engineering projects. This setup enables designers to swiftly spot errors and incompatibilities, streamlining decision-making while also enhancing cost and time efficiency [38].

The parametric characteristics of BIM modeling unlock new possibilities in architectural design, especially when we take into account the emerging advancements in computational design and optimization techniques. By harnessing the capabilities of these tools together, professionals can explore number of solutions that help them in decision-making processes. A prime example of this is the new multi-criteria optimization methods based on the use of generative design [40]. BIM is bringing in working methodologies grounded in the establishment of methods and technologies aimed at ensuring digital and multidisciplinary management [41]. BIM has brought about a transformation in the AEC industry, revolutionizing how buildings are designed, constructed, operated, and even decommissioned or renovated. Throughout the whole life cycle of a building, BIM technology plays a pivotal role in furnishing precise, well-timed, and pertinent information, leading to a significant enhancement in the efficiency of asset management [42].

BIM technology is a valuable tool employed to enhance the economic and environmental sustainability of the AEC industry [43]. In this regard, digital twins of buildings are linked with Building Energy Models (BEM), enabling designers to conduct "what-if" experiments to gauge a building's energy consumption. This helps in waste reduction and overall cost efficiency. Integrating BEM into the BIM workflow permits early-stage energy analysis, facilitating more well-informed design choices [44]. Energy modeling tools rely on various parameters to estimate a building's energy performance. While some information can be sourced directly from the BIM system, a higher level of detail is often necessary for comprehensive energy modeling [43]. Indeed, BIM applications encompass a range of aspects, including visualization, scheduling, cost estimation, maintenance, sustainability, and safety. This results in various benefits, such as improved building and construction quality, ultimately leading to reduced resource consumption [44].

## 2.3 Overview of Energy Efficiency in BIM-Based Architectural Design

Energy efficiency and design optimization are crucial aspects of sustainable architectural design, and the integration of BIM automation offers a promising avenue to optimize energy performance during the design process. This section provides a comprehensive review of energy efficiency practices within the context of BIM, with a particular focus on the benefits and advantages of BIM automation in energy optimization, the challenges and potential barriers in its implementation, and the energy analysis and simulation tools used for energy performance evaluation. In this section, an extensive review conducted of approximately 12 research papers that delve into topics closely related to BIM-based parametric energy performance design, Building Energy Modeling (BEM) tools, and associated workflows.

### 2.3.1 BIM Automation in Energy Optimization Practices: BIM to BEM

Nowadays, designing sustainable and energy efficient buildings is becoming a need. The most impactful decisions for achieving this are often made during the early design stages. However, there is still a lack of suitable tools to explore design alternatives and comprehensively understand their effects on building energy performance at this crucial design phase [45]. Energy performance analysis for buildings is a complicated multi-criteria and time consuming process, therefore, there is a need for suitable tools that can help architects, designers, and engineers in exploring many design alternatives and evaluating the energy performance to select the optimum design option [46].

BIM is a cutting-edge technology that has the potential to revolutionize the AEC industry, as it changed the way buildings are planned, designed, constructed, and maintained [47]. One of the main advantages of Building Information Modelling lies in its ability to enhance the decision-making process through the execution of what-if scenarios on a 3D model of the intended design to be realized by designers as for the client [43]. BIM enables informed decision-making by providing precise energy performance evaluations for multiple design alternatives [48]. Using BIM technology enables designers to evaluate different design options at the preliminary design stage of a project life cycle. This allows them to develop effective energy strategies that fit within the design constraints [49]. To develop this there are many BIM tools and software will be integrated to develop such work.

As mentioned earlier, designing high-energy performance buildings is a highly intricate and time-consuming process. It involves evaluating numerous design options and strategies to identify the most effective one. Dealing with vast amounts of data during this traditional long methodology can lead to errors and inefficiencies. Consequently, some designers and architects may opt to forego energy efficiency measures and rely solely on general energy-saving rules, resulting in less efficient designs [46]. Currently, building energy modeling tools do not have the capability to support complex parametric relationships between building objects for simulation purposes. This means that designers may not be able to fully explore the potential of parametric modeling in sustainable building design using these tools. For this developing new tools or employing the programming and parametric design techniques is important. Through the incorporation of BIM automation techniques for energy efficiency, designers can gain accurate insights into a building's energy consumption. This valuable information enables them to make informed decisions during the design process, leading to improved sustainability and energy performance [43]. The combination of parametric modeling and BIM can greatly enhance sustainable building design. Parametric modeling allows for the exploration of a design space by manipulating parameters and their relationships, enabling designers to creatively experiment with different design options [50].

Building energy modeling (BEM) is a method used to estimate the energy consumption of a building [51]. Figure 4 shows the overall structure of building Energy system model as described by [52]. The use of BIM to BEM in the AEC industry is becoming increasingly important, as enabling seamless data transfer between different tools, a BIM-based BEM model can facilitate better collaboration. Still the BIM to BEM practice is not yet standardized, resulting in variations in the building energy models produced by different users and applications. Furthermore, these models are not yet applicable to all project's design stages [53]. To effectively analyze the limitations of the BIM-to-BEM interoperability process, it is crucial to have a thorough understanding of the various components that contribute to the process. These components include BIM tools, and BIM files, all of which play a significant role [54]. The next section will review the BEM tools, it's capabilities and limitations.

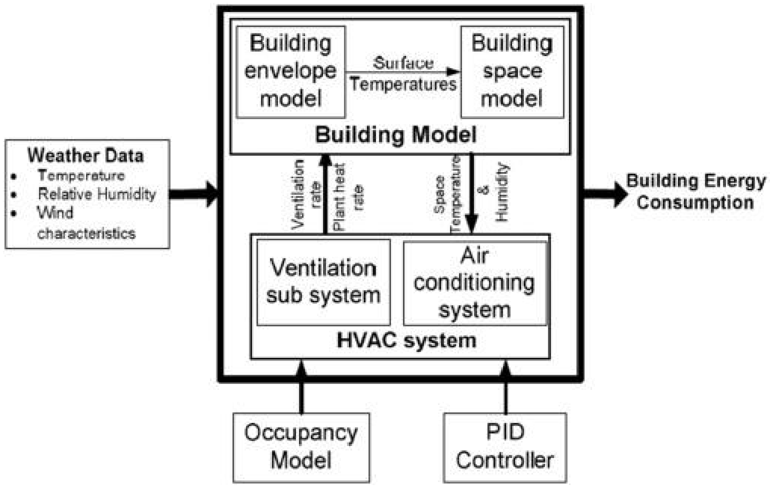



Figure 4: Building Energy System model structure [52].

### 2.3.2 Review of BEM Tools

To achieve energy optimization in the design, BIM relies on various energy analysis and simulation tools. Energy simulation tools are powerful as it can be used to analyze the energy and thermal comfort analysis of a building throughout its life cycle. There are many such tools available today, and they vary in several ways, including their thermodynamic models, graphical user interfaces, intended use, applicability throughout the building's life-cycle, and ability to exchange and transfer data with other applications [55]. These tools offer sophisticated capabilities to assess energy performance and guide design decisions. Some commonly used tools include Energy Plus, IES Virtual Environment, and Design Builder, among others. However, based on the recent research, the interoperability between BIM and energy simulation tools is still not standardized [53]. There are a variety of BEM tools available that can import BIM files for energy simulation. However, these tools have different capabilities and limitations, and it is important to investigate and categorize them to help choosing the most appropriate tool based on project typology and the analysis purpose. Additionally, issues with interoperability and data exchange between BIM and BEM tools need to be understood to develop practical solutions [54]. Table 1 shows a comparison of selected building performance simulation (BPS) tools.

The main advantage of energy simulation tools is its ability to evaluate different design options. By assessing design alternatives for their energy consumption and thermal comfort, it is possible to make informed decisions about the best design choices [55]. There are two BIM file schemas, used for the energy analysis and simulation; IFC and gbXML. These are comprehensive formats from Building Smart and Green Building Studio Inc. They offer the information needed for energy simulation [54]. Table 2 below shows the comparison between gbXML and IFC schemas.

Table 1: Comparison of selected BPS tools with respect to general properties [56].

| BPS Tools | Major Capabilities | Expertise Required | Users | Language/ Platform | License | Company/ Country | Ref |
|---|---|---|---|---|---|---|---|
| DesignBuilder | • Whole building energy simulations<br>• Load calculations<br>• HVAC system selection and sizing<br>• Parametric and optimization<br>• Air flow simulation<br>• Ratings and certificates<br>• Code compliance checking | • No steep learning curve | • Architects<br>• Engineers<br>• Building designers<br>• Building scientist<br>• Academic research and teaching | • Linux<br>• Windows | License is required, free to try | DesignBuilder software Ltd./UK | (DesignBuilder, 2019) |
| EDSL-TAS | • Whole building energy simulations<br>• HVAC system selection and sizing<br>• Parametrics and optimization<br>• Lighting simulation<br>• Airflow simulation<br>• Code compliance checking<br>• Detailed cost analysis | • Qualified engineer and architect<br>• Training courses are not necessary<br>• Includes comprehensive tutorials | • Architects<br>• Building services engineers<br>• Consulting engineers | • Windows | Free for non-commercial & academic use, free to try | Environmental Design Solutions Limited (EDSL)/UK | (EDSL, 2019) |
| EnergyPlus | • Whole building energy simulations<br>• Load calculations<br>• HVAC system selection and sizing<br>• Lighting simulation<br>• Air flow simulation<br>• Code compliance checking | • Background in building physics and mechanical engineering is helpful | • Architects<br>• Engineers (mechanical, energy, control)<br>• Building auditors and operators<br>• Energy-efficiency policy analysts<br>• Researchers | • Linux<br>• Windows<br>• Mac OS X | Free/Open source license | US Department of Energy (DOE)& National Renewable Energy Laboratory (NREL)/US | (DOE and NREL, 2019) |
| ESP-r | • Whole building energy simulations<br>• Complex buildings and systems | • Researchers and building designers having good understanding of building physics, environmental systems and controls is necessary | • Building designers<br>• Engineers<br>• Energy consultants<br>• Researchers<br>• Multi-disciplinary design firms | • Linux<br>• Windows<br>• Mac OS X | Free/Open source license | University of Strathclyde Energy Systems Research Unit (ESRU)/UK | (ESRU, 2019) |
| eQUEST | • Whole building energy simulations | • Experience with energy analysis is necessary<br>• Knowledge of building technologies is required | • Building designers<br>• Operators<br>• Owners<br>• Energy/LEED consultants | • Windows | Free/Open source license | James J. Hirsch & Associates/US | (James J. Hirsch & Associates, 2019) |
| Green Building Studio (GBS) | • Whole building energy simulations<br>• Parametrics and optimization<br>• Energy conservation measures | • No expertise is required to use Green Building Studio<br>• 3D-CAD/BIM experience is required for geometry<br>• modeling | • Architects<br>• Engineers<br>• Construction managers | • Web/SaaS | Free for non-commercial & academic use, free to try | Autodesk Inc./US | (Autodesk Inc, 2019) |

Table 2: Comparison between gbXML and IFC files [54]

| Characteristics | gbXML | IFC |
|---|---|---|
| Presentation of building's geometry | Only rectangular geometry | Any geometry |
| Data structure | XML (extensible Markup Language) | IFC, PKZIP, and XML |
| Data structure approach | Top-down approach with relatively more complex representation | Bottom-up approach with relatively more straight forward representation |
| Domain of application | Mostly energy simulation domain | Different domains such as building construction to building operation |
| Capability of defining thermal zones | Yes | Yes |
| Location | Yes | No |
| Standard for minimum content for a certain type of model and using subsets | No | Yes – there is MVD standard for IFC and IDM capabilities |
| Material thickness | Yes | Yes |
| Limited data related to HVAC system | Yes | Yes |

BEM tools could be used for, Building Energy Estimation, Consumption, Design Optimization, Evaluation, Efficiency, and Management. During the design phase, BEM functions as a tool for comparing and optimizing design iterations. In the facility management phase, it transforms into a measurement tool that forecasts a building's energy consumption [57]. BEM tools utilize defined parameters for their calculations, whether integrated with BIM software or employed externally. Typically, the input data originates from a BIM tool and includes building envelope, zones, and rooms, building equipment and operation schedules. In [58] primary BEM tools were categorized into two primary clusters. Certain tools employ calculation engines such as DOE or Energy Plus (examples include eQUEST, Design Builder, GBS, etc.), while others like TRACE 700, IES-VE (IES Virtual Environment), and IDA-ICE rely on their proprietary embedded calculation engines. The figure below shows an overview of the BEM tools data exchange capabilities. There are various options for converting and importing geometry data from CAD software into thermal simulation tools. This allows for a seamless integration of the design process and the analysis of the building's energy performance and thermal comfort.

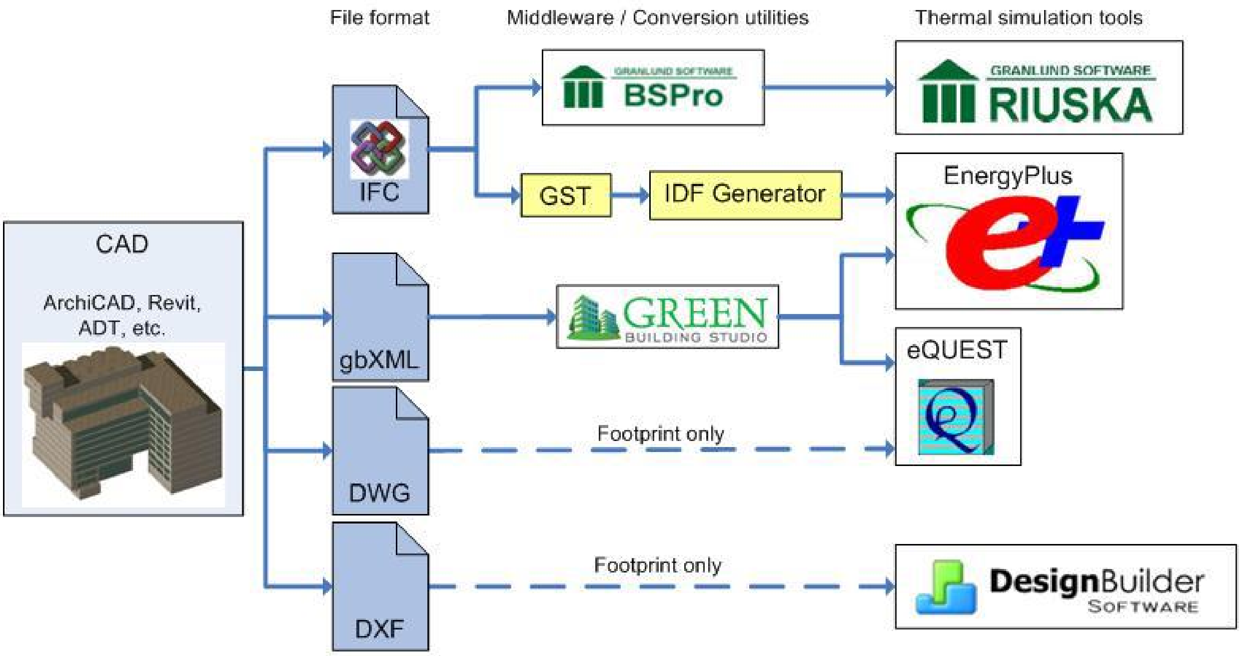



Figure 5: Overview of geometry data exchange [55].

## 2.4 Previous Studies on BIM-based Design Optioneering and Energy Optimization

This section presents a comprehensive literature review of previous studies that have explored the integration of BIM-based design optimization. It explores the methodologies and workflows employed using BIM automation to enhance energy-efficient architectural design. The analysis of these methodological workflows provides valuable insights into the strategies and techniques that have proven effective in achieving optimal energy performance through BIM automation. Moreover, this analysis will pave the way to further improvements. In this section, the review of approximately 5 research papers had been undertaken. Specifically, the attention has been directed towards the methodological workflows discussed in 3 research papers.

Based on [55] study, the ideal workflow for energy simulation tools is shown in figure 6 below. The first step in the process is to specify the location of the project, which will provide access to relevant weather data. Ideally, the second step involves importing data from a BIM Model, which should include 3D geometry, construction type and materials, and spaces categories. The next step is to assign occupancy loads, such as lighting, heating, and cooling loads. Once all the data has been defined and additional simulation-specific parameters have been input, a simulation can be performed [59].

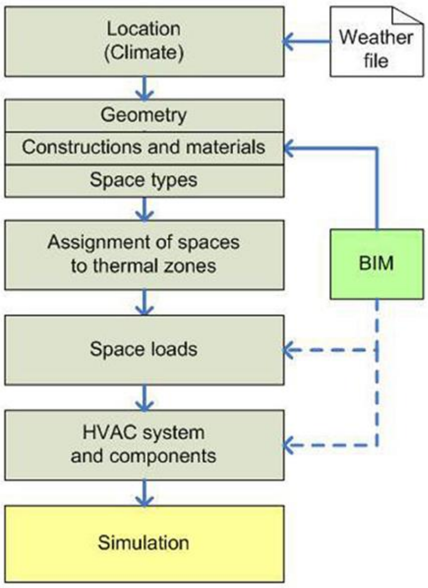



Figure 6: Ideal workflow for BEM tools [55].

### 2.4.1 Analysis of Methodological Workflows Employed in Previous Studies

This subsection takes a closer look at the methodological workflows used in previous studies that combine BIM-based design optioneering with energy optimization. By breaking down these workflows, the aim is to extract important insights and patterns in how the creation of design options merges with energy-efficient goals. The three studies use Autodesk Revit as a modelling tool, and Green Building Studio (GBS) as a simulation tool, while the design option creation process took different approaches.

*Methodological Workflow One*

In this study, [43] aimed to automatically generate design options for analysis to find the best design choice. The initial step involved a manual workflow, followed by the execution of codes and scripts. However, the manual approach was time-consuming. To address this, the primary focus shifted towards reducing manual effort, generating extensive design option datasets, and preventing errors.

In the subsequent step, Artificial Neural Networks (ANNs) and Transfer Learning methods were utilized to speed up the process of creating datasets. This approach led to the creation of an equivalent dataset with remarkable accuracy, using only 30% of the original data.

Figure 7 shows the Automation workflow for creating design options. Figure 8 shows the dynamo script used for running the gbXML files in Green Building Studio (GBS). Figure 9 shows the summary for the methodological workflow employed in this research.


Figure 7: Automation of design options creation workflow [43].

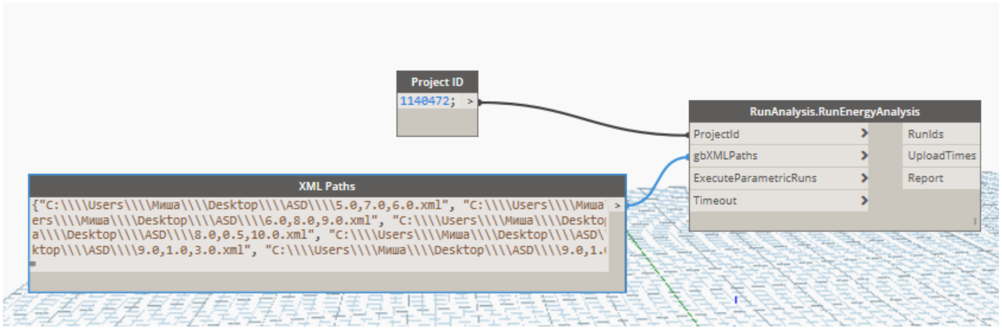



Figure 8: Dynamo node linking the gbXML files to the Green Building Studio [43].


Figure 9: The workflow is presented by the author based on [43] research

### *Methodological Workflow Two*

In this study, [59] employed a BIM approach to create a parametric model aimed at enhancing building energy efficiency across various climatic zones. The research focused on different building components, including the building's location, external walls, roof, and window systems. Figure 10 shows the general framework for the enhancing the energy performance for projects.

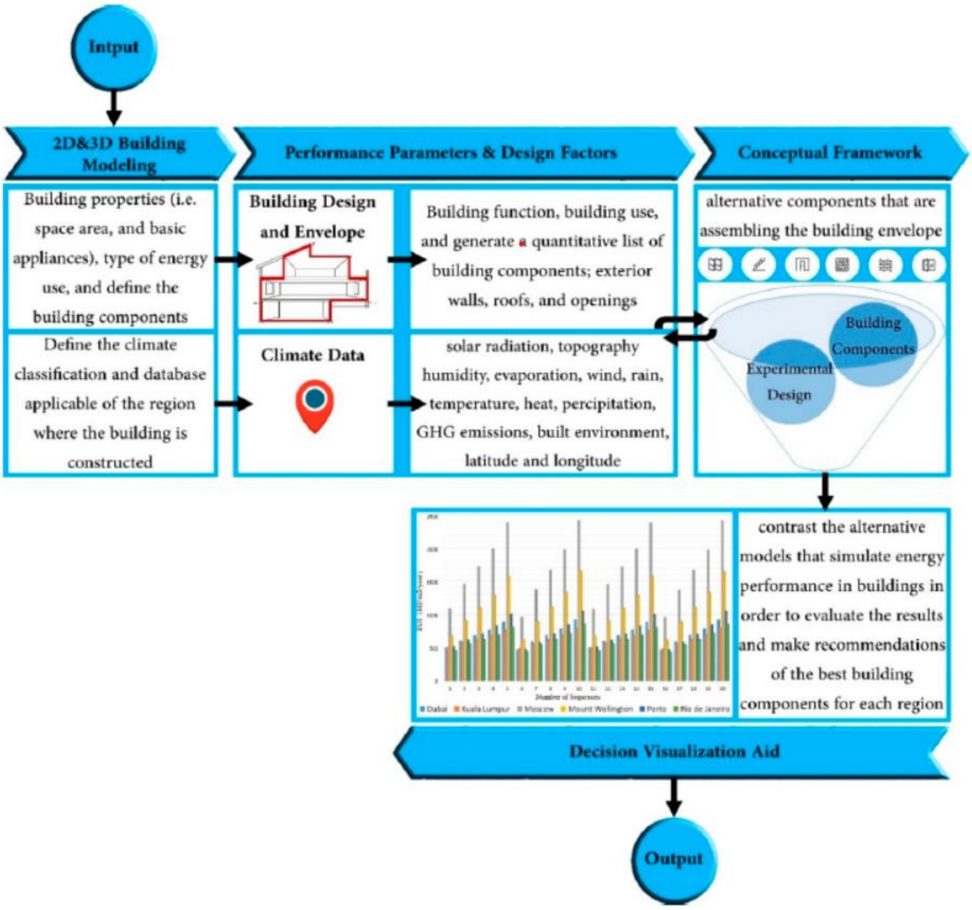



Figure 10: The Framework for energy performance enhancement [59].

The workflow commenced with BIM modeling in Autodesk Revit, followed by inputting climatic data through the GBS weather station. The subsequent step involved applying experimental design, which utilized linear regression in Minitab to estimate anticipated variables. These variables were then simulated using GBS.

The final stage encompassed evaluating the chosen database through GBS and integrating the outcomes via Minitab. The results demonstrated that design modifications led to an energy consumption improvement of approximately 15%, specifically regarding factors like the window-to-wall ratio (WWR), regardless of the building's location.

Figure 11 shows the general framework link for the components. Figure 12 shows the summary for the methodological workflow employed in this research.

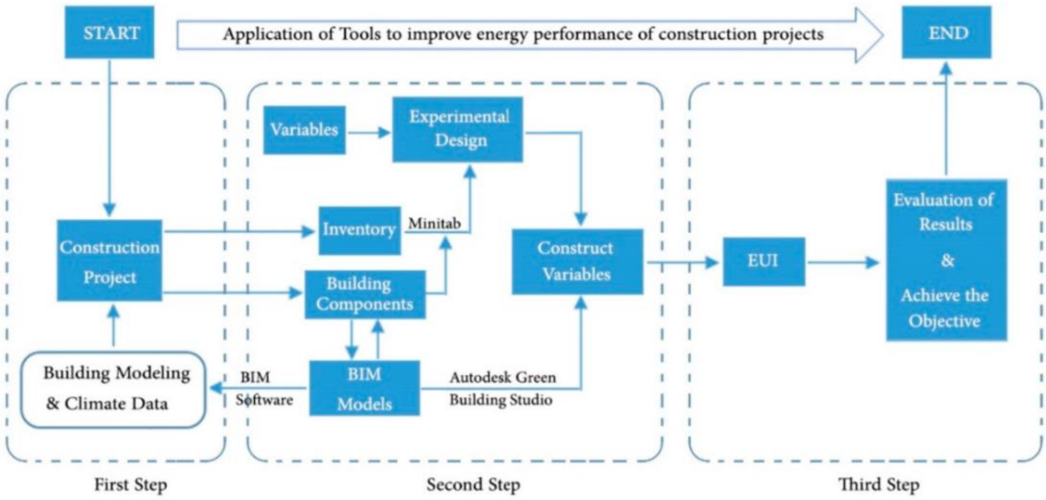



Figure 11: Framework components linkage.

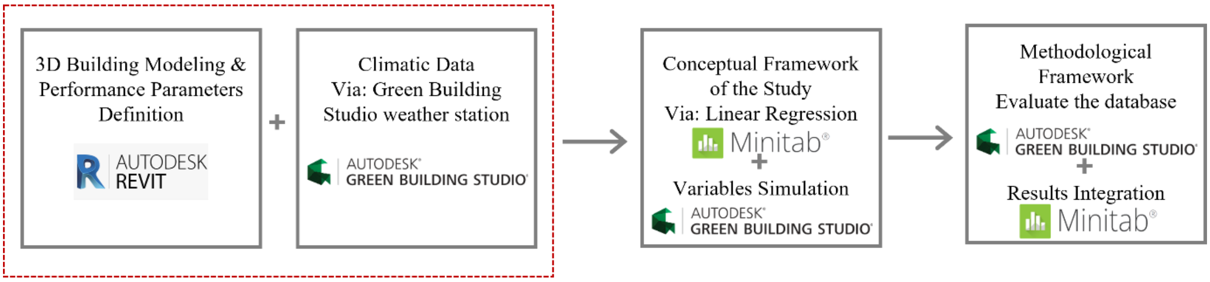



Figure 12: The workflow is presented by the author based on [59] research

### *Methodological Workflow Three*

In this study [45] introduces a novel tool designed to create a parametric BIM model that enhances its capabilities for sustainable building design. The newly developed tool, named Revit2GBSOpt, combines a parametric BIM model with energy simulation. This integration empowers designers to automatically generate various alternatives within the BIM environment to explore simulation outcomes. The goal is to identify the most optimized design choice, which subsequently updates the BIM model accordingly.

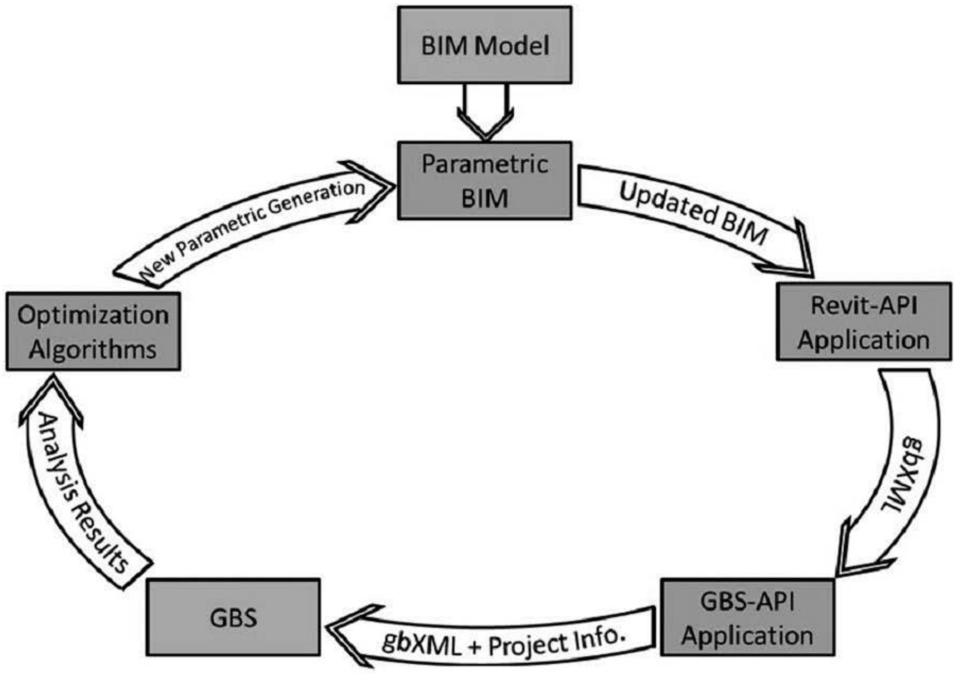



Figure 13: The overall architecture of Revit2GBSOpt application

Figure 14 shows the summary for the methodological workflow employed in this research.


Figure 14: The workflow is presented by the author based on [45] research

# 3 RESEARCH METHODOLOGY

## 3.1 Overview

This research aims to investigate the potential benefits of implementing BIM automation to enhance energy efficacy in buildings during the earlier design stages, with a specific focus on optimizing architectural Buildings' envelope for energy efficiency practices. The study aims to identify and analyze the potential benefits of implementing BIM automation in the design phase to enhance energy efficacy in buildings. Therefore, several qualitative and quantitative methods will be applied, as shown in the graph below. These methods can be summarized into; analysis of previous studies methodologies, selection of the base case, and then examine the proposed automation workflows.

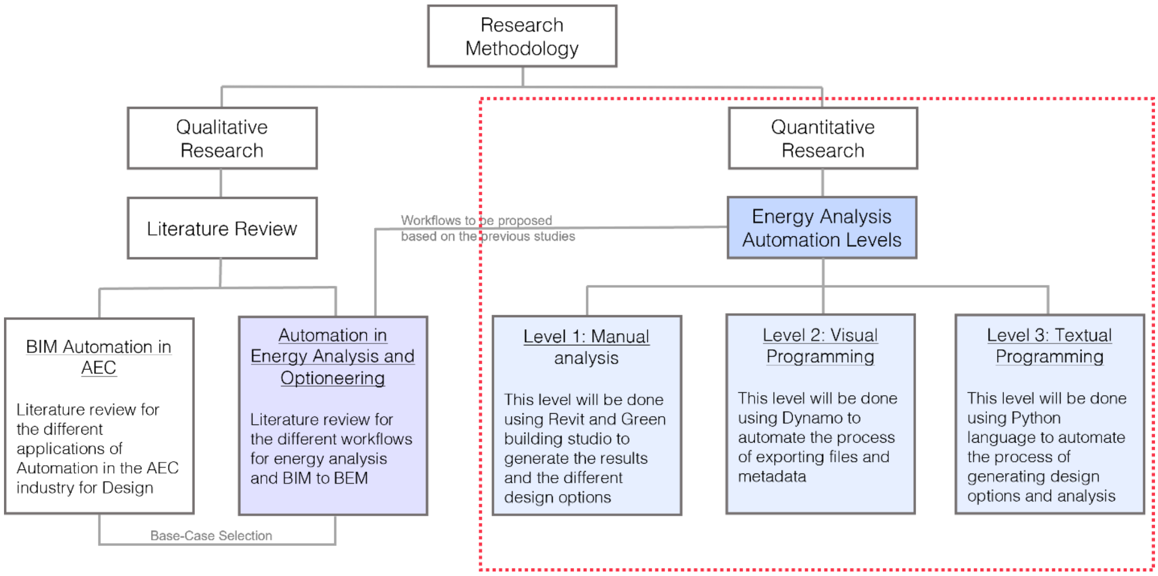



Figure 15: Research Methodology Graph shows the Quantitative Research covered by this chapter (focused area within the red rectangle)

The previous chapter (Chapter 2) covers the qualitative research part that leads to the base-case selection and the proposed workflows that will be explained in this chapter. This chapter includes the quantitative part. The chapter will include the methodology employed using BIM automation to investigate and examine different workflows towards design optioneering, and energy optimization. It will explain the organized steps taken to automate the process of energy-efficient architectural design using BIM technology. The chapter will carefully break down the methods used to better understand the design strategies and analytical approaches driving the research forward.

The chapter includes five sections; the first section is the overview of the chapter. The second section includes the base-case building description. The third section include the energy analysis automation levels. The fourth section includes the data analysis and visualization. The last section includes the summary of the chapter.

## 3.2 Base-Case Building and Design Optioneering Strategy

This section will include the description for the selected base case building and the optioneering strategy. The base case for this research designed by the author and is not a real project from a company. As discussed in the introduction chapter the limitations of the research due to the time requires to study a simple building and not complicated project to facilitate examining and applying the workflows. The study case building is a show gallery for a company. The drawings and detailed description for the design will be detailed in the following subsection. The reason for choosing gallery and offices building, not other building type, is to have the flexibility in the elevations design and to create different design options with different windows sizes. Also, it will cover all the critical cases such as double volume, and curtain walls for the future research development.

This section is divided into two parts; the first one reviews the architectural drawings which includes the floor plans, elevations, and sections. Additionally, it will cover the physical characteristics of the building. The second part includes the design optioneering strategy and the parameters definition for the selected elements that will be iterated with different values to create the design options.

### 3.2.1 Base-Case Building Description

The selected building for the study is a show gallery for a company. The study-case is two stories building: ground floor and mezzanine floor. The construction of the building is blockwork, with reinforced concrete structure. This subsection reviews the base-case building description. The architectural drawings of the study-case were prepared by the author based on the general case for construction in Slovenia. The figures below show the architectural drawings for the Study-Case building.

## *Architectural Drawings:*

## 3D Perspectives

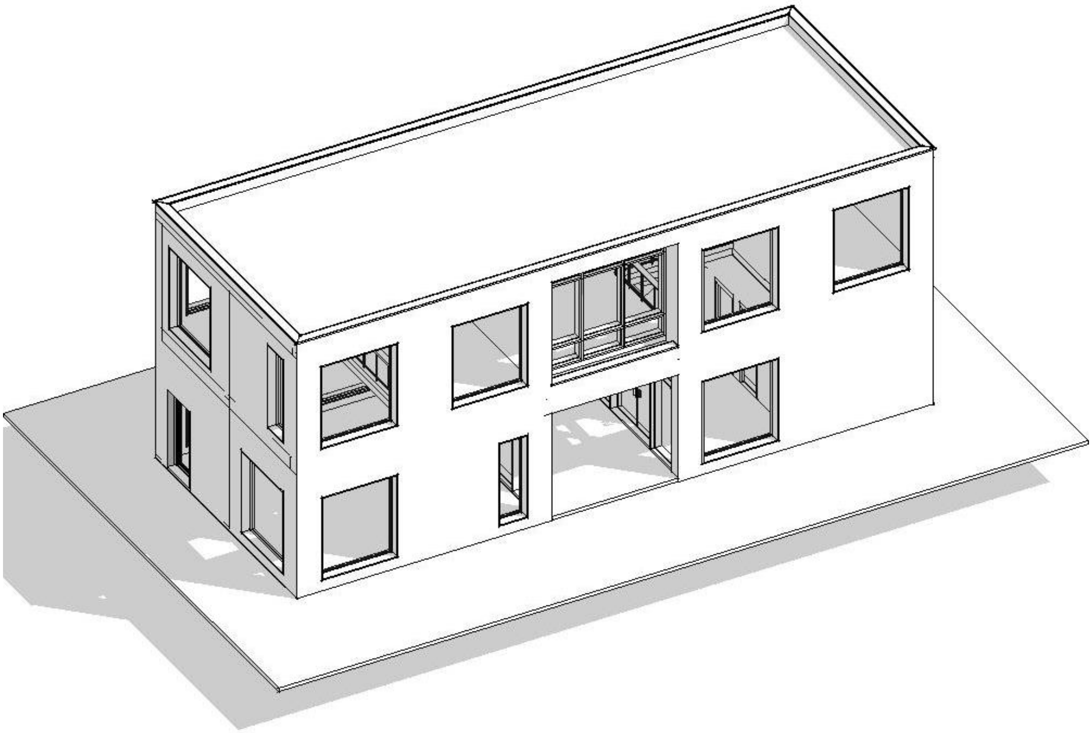


Figure 16: 3D view

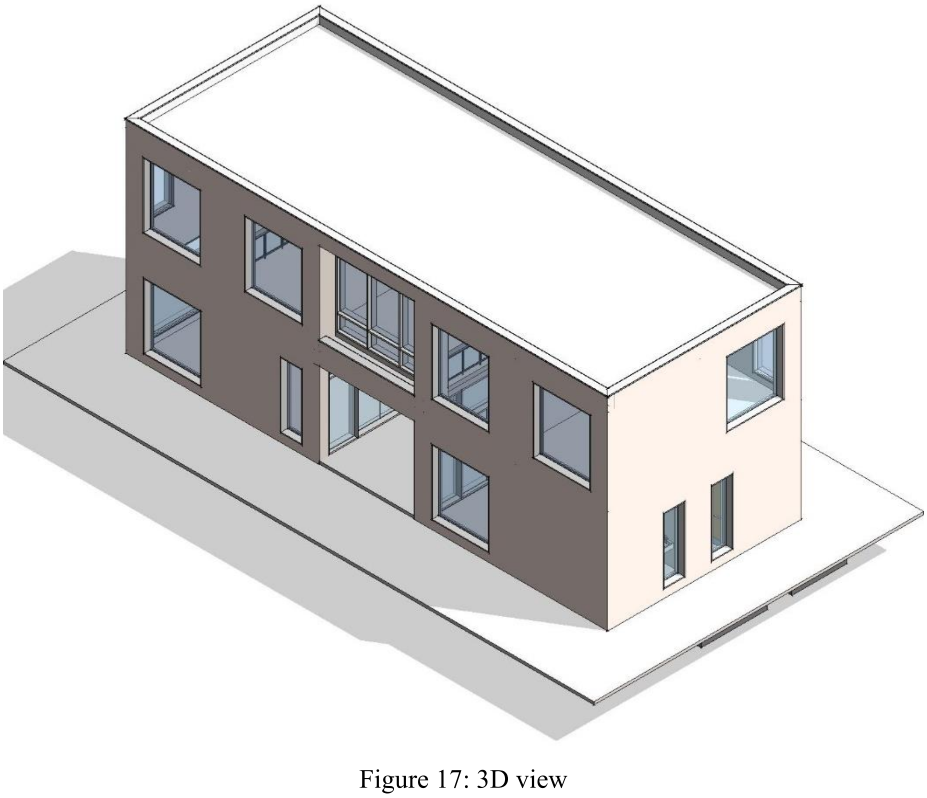


Figure 17: 3D view

## Floor Plans

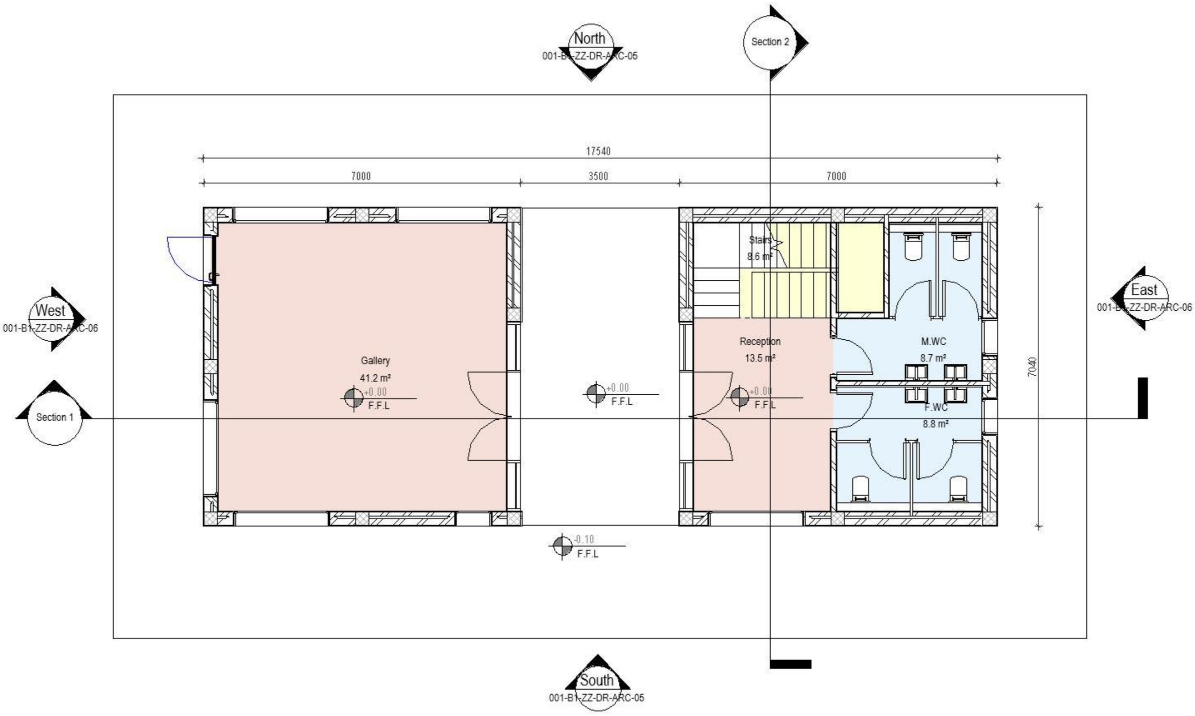



Figure 18: Ground Floor Plan

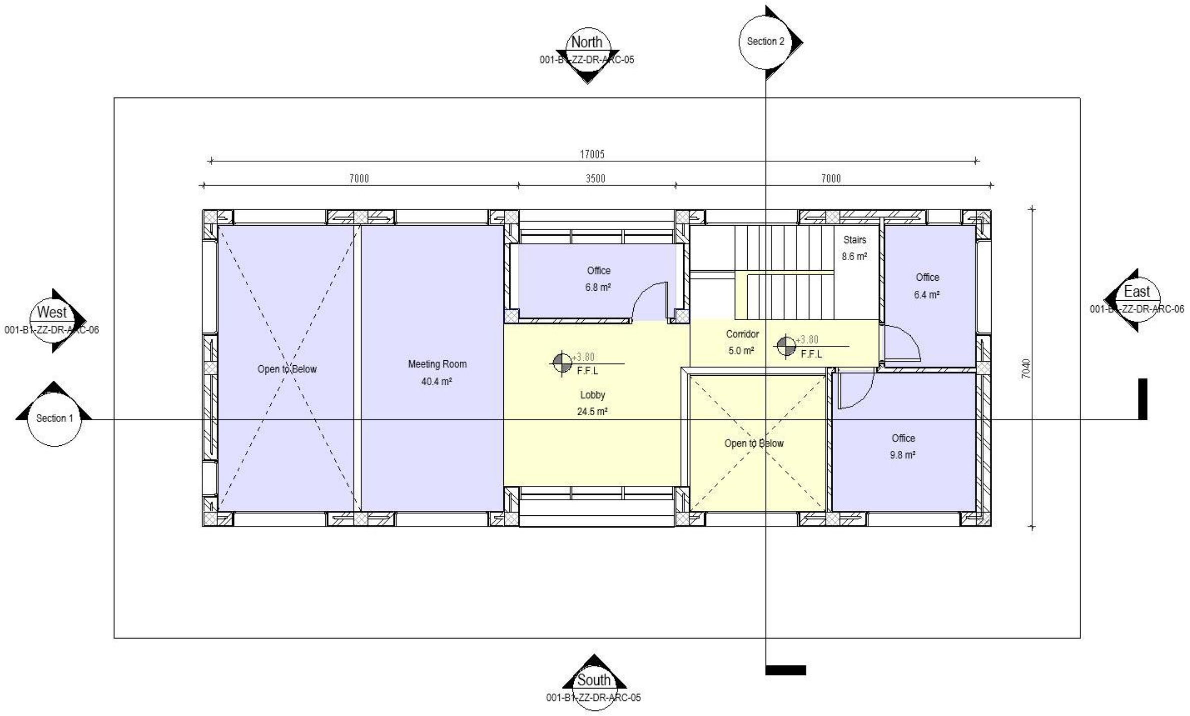



Figure 19: Mezzanine Floor Plan

## Sections

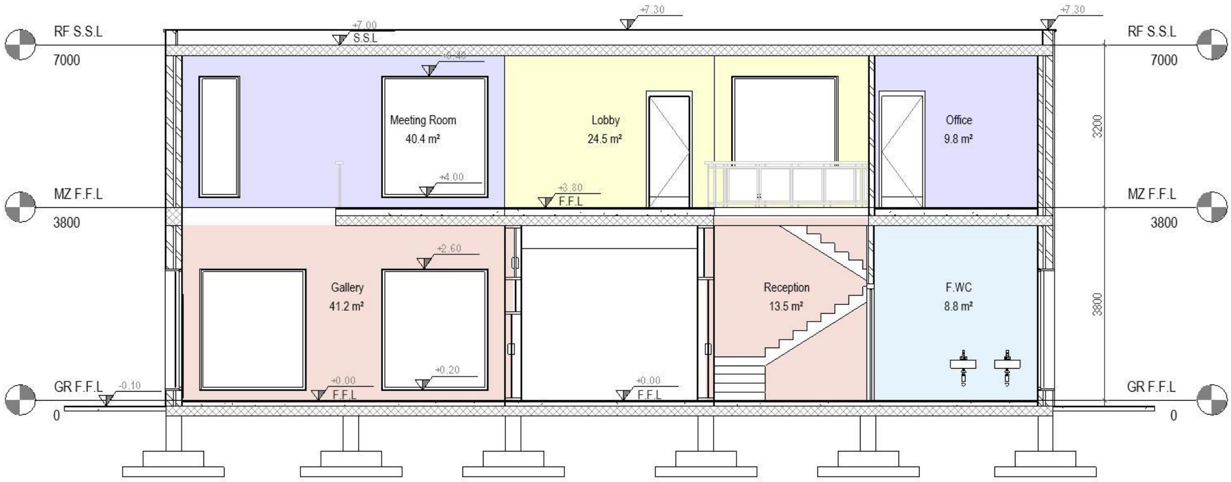



Figure 20: Longitudinal Building Section


Figure 21: Cross Section 1

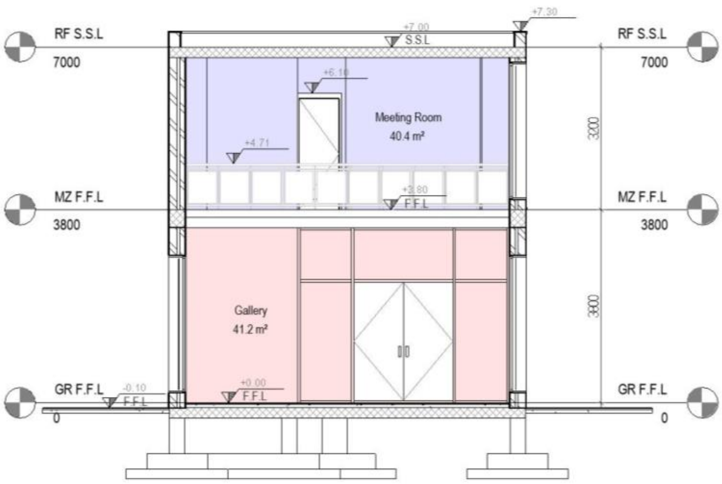



Figure 22: Cross Section 2

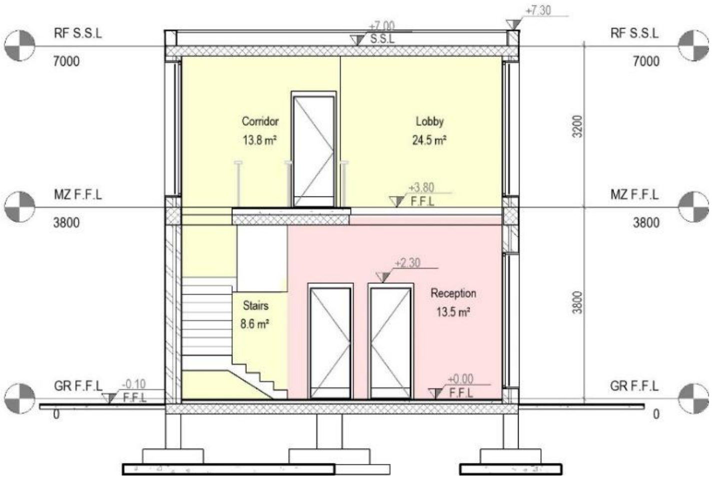



Figure 23: Cross Section 3

## Elevations


Figure 24: Front Elevation


Figure 25: Side Elevation 1

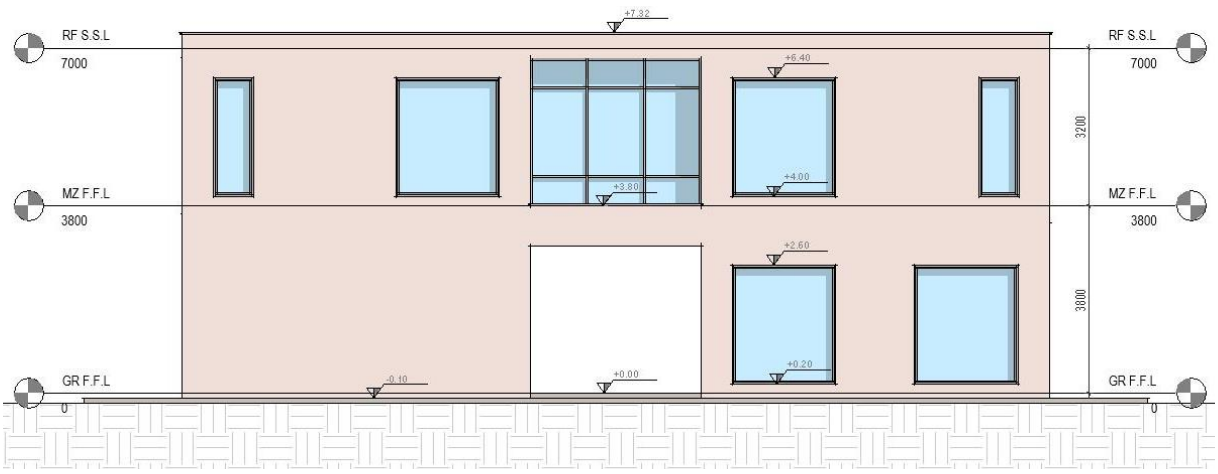



Figure 26: Back Elevation

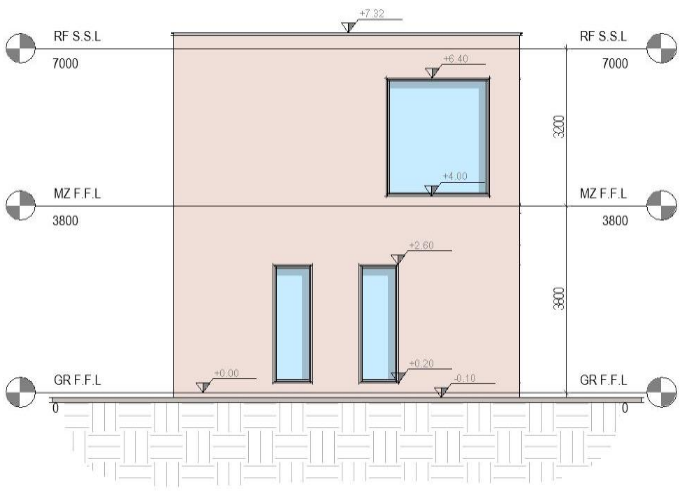



Figure 27: Side Elevation 2

### *Building Physical Characteristics*

The physical characteristics of the base-case include many aspects, building configuration, spaces ratio, envelope characteristics like, walls and roof types, openings system.

### Building Configuration:

The building configuration shows main characteristics of the building layout. Table 3 summarizes the building configuration of the study-case. Table 4 shows the rooms schedule.

Table 3: Configuration of the study-case building

| No. | Parameter | Value |
|---|---|---|
| **1.** | **Area** | **247 m$^2$** |
| **2.** | **Shape of the plan** | **Rectangle** |
| **3.** | **Number of rooms** | **Ground Floor:** <br> **5 rooms; 2 toilets areas, Reception, stairs, and the gallery area** |
| | | **Mezzanine Floor:** <br> **6 rooms; 3 offices, Lobby, stairs, and meeting room** |
| **4.** | **Orientation** | **Depends on the site** |
| **5.** | **Number of stories** | **Two story building** |
| **6.** | **Number of Occupants** | **Ground Floor: Max. 10 people** <br> **Mezzanine Floor: 13 people** |
| **7.** | **Building height** | **7.30m** |
| **8.** | **Clear Floor Height (Top floor finish to bottom slab finish)** | **Ground Floor: 3.45m** <br> **Mezzanine Floor: 3.00m** |

Table 4: Base-Case Building Rooms Table

| | Number | Room Name | Department | Area |
|---|---|---|---|---|
| **GR Floor** | 1 | Reception | Gallery Department | 14 m² |
| | 2 | Gallery | Gallery Department | 41 m² |
| | 14 | Stairs | Circulation | 9 m² |
| | 17 | Male WC | Services | 9 m² |
| | 18 | Female WC | Services | 9 m² |
| **MZ Floor** | 8 | Office | Administration | 10 m² |
| | 9 | Office | Administration | 6 m² |
| | 10 | Office | Administration | 7 m² |
| | 11 | Meeting Room | Administration | 40 m² |
| | 12 | Lobby | Circulation | 25 m² |
| | 16 | Corridor | Circulation | 14 m² |

## Building Envelope Characteristics:

### Walls and Roof Types:

The wall system of the external walls of base-case is composed of five layers with 340mm total thickness wall as per the figure below. The U-Value of the wall is 0.38 W/m$^2$-K.

The roof system of the base-case house is composed of four layers with total thickness 320mm. the U-Value of the roof is 1.59 W/m$^2$-K.

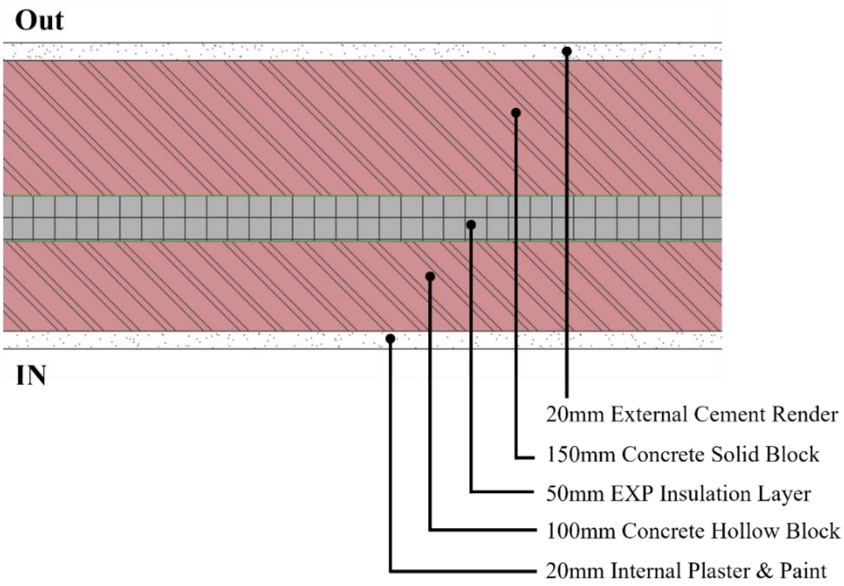



Figure 28: External Walls System

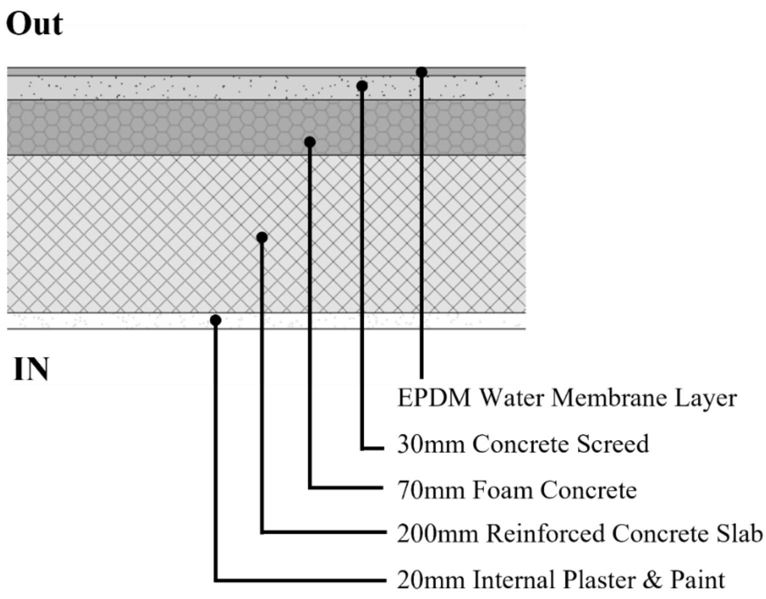



Figure 29: Roof System

### Opening Systems:

Windows, doors, and Curtain wall systems for the base-case as the following:

- Frame: Aluminum Framing
- Glass: Double glazing – 6mm thick - blue-green/low-E (e = 0.05) glass
- Internal doors are laminate wooden doors

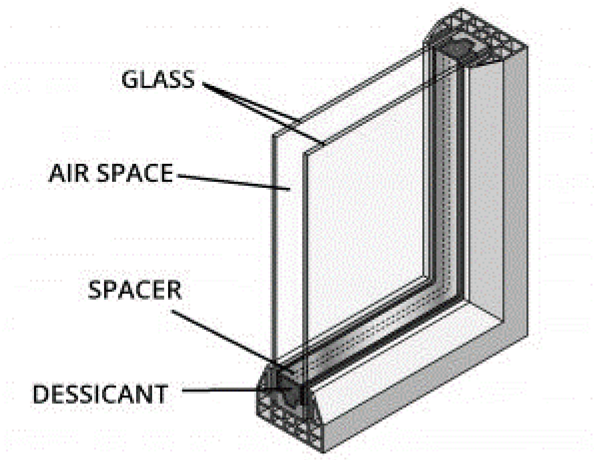



Figure 30: Glass System

### Natural Ventilation:

The natural ventilation is considered as a major source to change the inner air by manual opening of doors and windows to get the thermal comfort and the fresh air.

### 3.2.2 Design Optioneering Strategy

The aim of this study is to examine BIM automation techniques in the design phase to enhance energy efficacy in buildings. The study will investigate the design optioneering process using automation. The research will focus on investigating different design options for Building Envelope and how it could affect the energy consumption. The building envelope design options include the following elements (Figure 31):

- External Walls systems
- Roof system
- Openings/ Ratio and types (Doors, Windows and Curtain Walls)
- Shading Elements and louvers
- Foundation
- Orientation

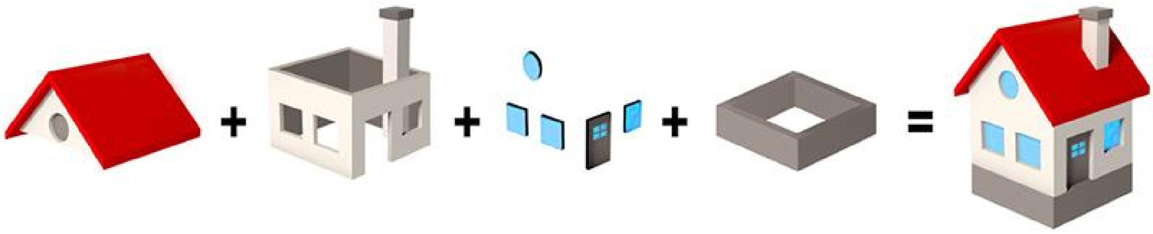


Figure 31: Building Envelope Elements (Reference: www.iko.com)

As mentioned in the introduction chapter, due to the time limitation and the complexity of including all the envelope elements; this research will examine one element. The study will focus on creating different design options based on changing the window to wall ratio (WWR), as it will be applied by changing the windows size (Width and Height). In the next section different workflows will be applied to create the design options and then run the simulation and analyze the results.

### *Parameters Definition*

The design optioneering strategy based on examining different sizes of windows. The changes will be based on creating lists for width and height for a specific family window, as it is the typical window used in the base-case building. The figure below shows the window family parameters. The width and height parameters are instance parameters to make accessible by Dynamo for modifying the dimensions.

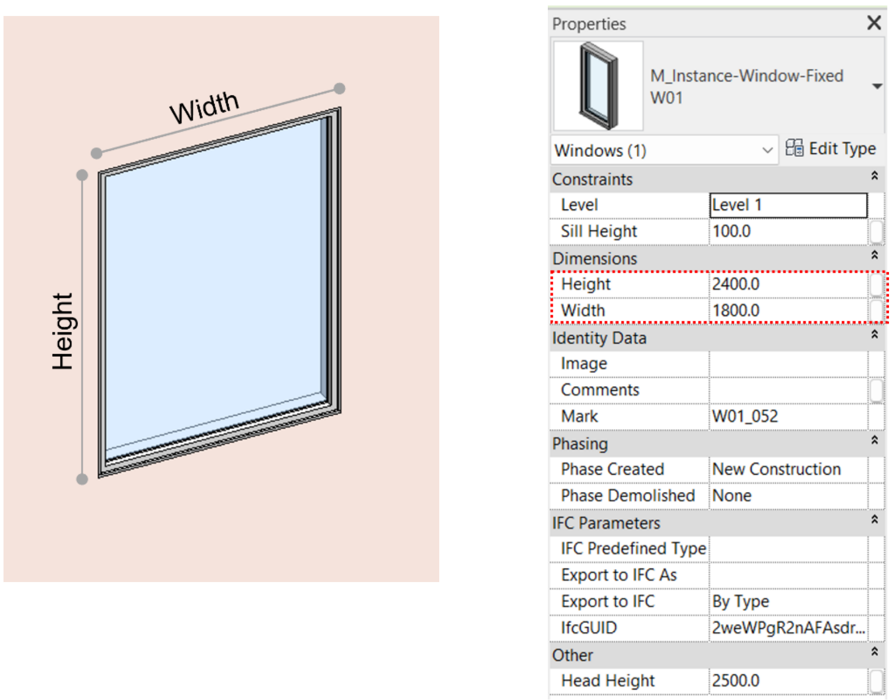



Figure 32: Window type parameters (Instance parameters).

### *Design Options: Window Variations*

The study will examine different window sizes, lists of five widths and five heights is created. As the following:

- Window Width List (mm): 600, 900, 1200, 1800, 2400
- Window Height List (mm): 600, 1200, 1800, 2400, 2700

In total the number of variations will be 5 x 5 = **25 design option**. As per the table below.

Table 5: Design Options for Windows Variations, Gray Highlighted square is the base-case variation.

| Design Options for Windows Variations | | Width List (mm) | | | | |
|---|---|---|---|---|---|---|
| | | 600 | 900 | 1200 | 1800 | 2400 |
| Height List (mm) | 600 | V1 | V2 | V3 | V4 | V5 |
| | 1200 | V6 | V7 | V8 | V9 | V10 |
| | 1800 | V11 | V12 | V13 | V14 | V15 |
| | 2400 | V16 | V17 | V18 | V19 Base-Case | V20 |
| | 2700 | V21 | V22 | V23 | V24 | V25 |

### *Software Definition*

This subsection will identify the list of software and tools used in this study. The table below shows the tools list, with the version numbers. There are some minor tools used for analysis work, the list includes the BIM software and tools list.

Table 6: BIM software and Tools used in the study

| No. | Software | Logo | Function |
|---|---|---|---|
| 1 | Autodesk Revit 2023 | | Modeling Software |
| 2 | Dynamo (Built in Revit) Version 2.0 | | Visual Programming |
| 3 | Green Building Studio (GBS) | | Energy Analysis |
| 4 | Rhino 7 | | Modeling Software |
| 5 | Grasshopper (Built in Rhino) | | Visual Programming |
| 6 | Python 3.9 | | Textual Programming |
| 7 | Open Studio 3.6.0 | | Energy Analysis |
| 8 | Jupyter Notebook 7.0.2 | | Data Analysis |

## 3.3 Energy Analysis Automation Levels

In this section the examination of different workflows for energy efficient design will be applied. This section will be divided into three parts. The first part will include the Manual workflow where all the process of creating options and running the analysis will be done manually as the traditional process without any automation process. This part is important as it will be fixed as a base line for the automation work. The second part will include the automated workflow using visual programming (Dynamo). This workflow will help to list the parameters and provide the proper interface for applying automated process. However, the visual programming languages are very limited and rigid in terms of automation. The third part is the automated process using both visual & textual programming languages (Dynamo/ Grasshopper and Python). This workflow will help to save time for creating the design options as well as for running the energy analysis and generating the results.

The automation process summarized into three main steps (Figure 33); the design options creation, energy simulation and daylight analysis and the data analysis.

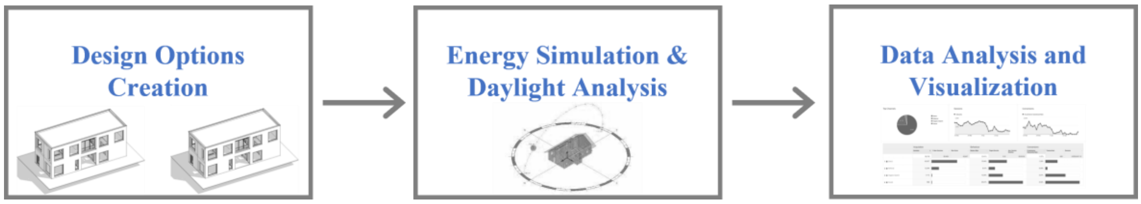



Figure 33: The Automation Strategy.

### 3.3.1 Level One: Manual Workflow Analysis

In The manual workflow the same traditional process/ method will be applied. Simply it will include the modeling the project then exporting the files from the authoring tool one by one (manually) then import it in the energy analysis tool or through using the insight inside Revit. The figure below shows the first draft of the manual workflow.

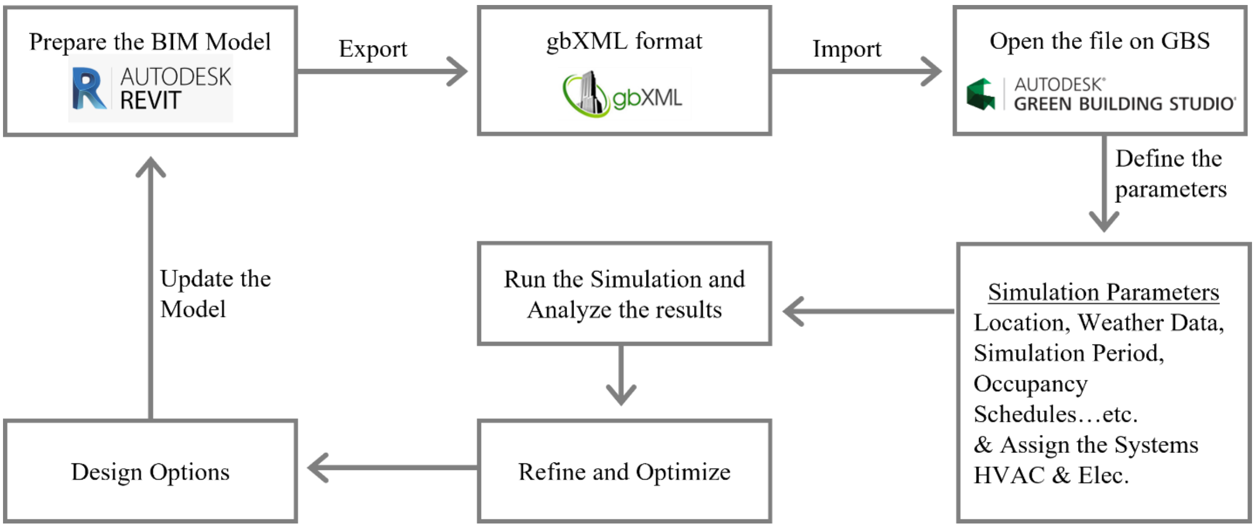



Figure 34: Manual Workflow (Revision 00)

The manual workflow is important for the research not only to show the time will be saved by automating the process, but it will also help to understand the breakdown of the process to simplify the automation accordingly. It will also help to test the model and identify errors before proceeding with more complex stages of the process. The following part will be showing in detail the process of manually creating options then execute the energy analysis and extracting the results.

*Prepare the Model:*

The first step is to prepare the Revit model before exporting the model and creating the analysis model. Before starting the process, it is important to ensure that there is no error in the model, if so, it is crucial to fix it before starting the process of exporting the files. For preparing the model first, we need to check that the area computation is taking the volume into consideration as per the figure below. For energy analysis the spaces are computed based on the volume not the areas to accurately calculate the electromechanical loads.

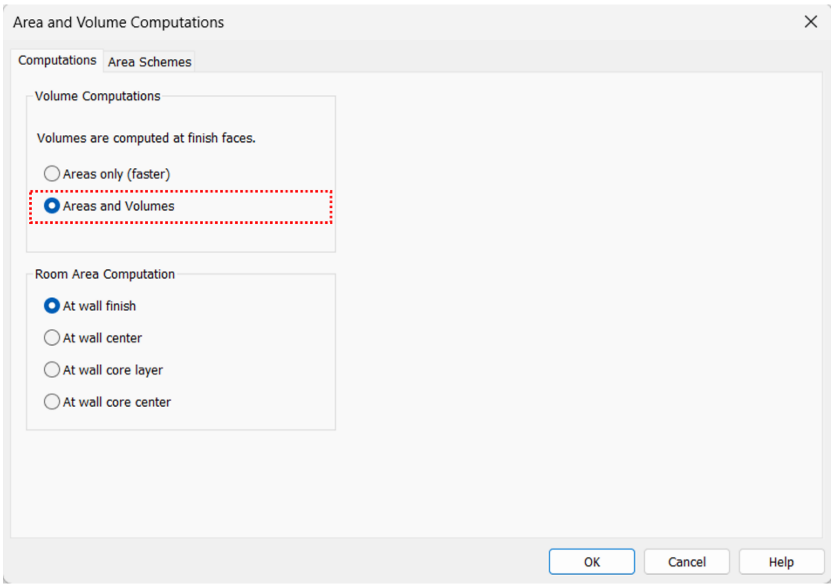



Figure 35: Area and Volume Computation (Areas and Volumes)

Checking the volumes on the section views to make sure that the full height is included. This default setting will be offset from the actual height, this will also depend on if there is a false ceiling, the room volume should be calculated up to the ceiling level. Otherwise, the room should be from slab finish to slab finish. The sections below show the difference between the default rooms height and the updated ones.

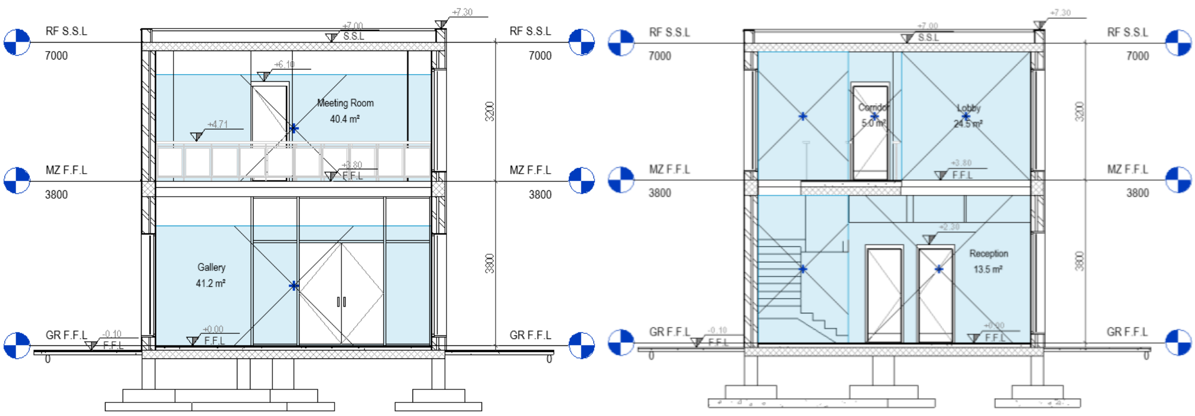



Figure 36: Cross Sections of the building, on the left the default rooms height (Not full height). On the right the rooms volumes up to the full height.

### *Set Energy Settings:*

Before creating the energy model, the energy settings should be specified. The following figures shows the settings to be specified, like the location (For weather data), Energy Analytical model mode, there are three modes for the developed models the building elements model should be selected. The last settings and the most important is to specify the building data (Occupancy), like the building type, and schedule.

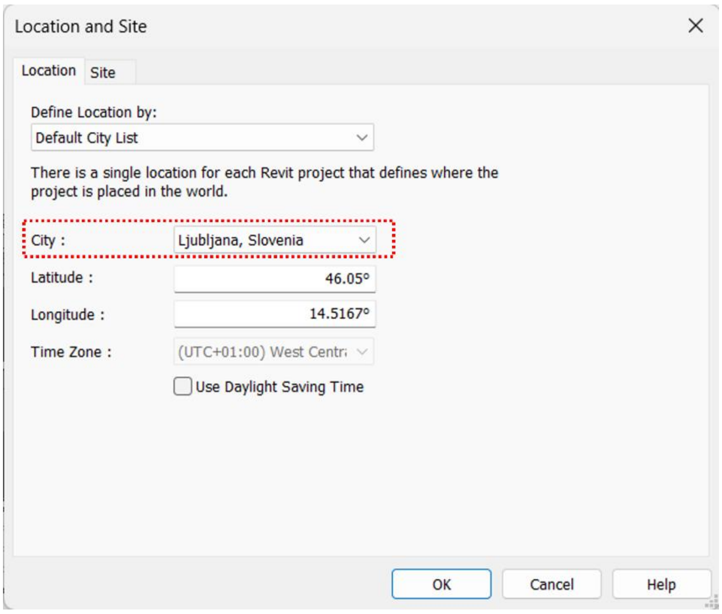



Figure 37: Specifying the location

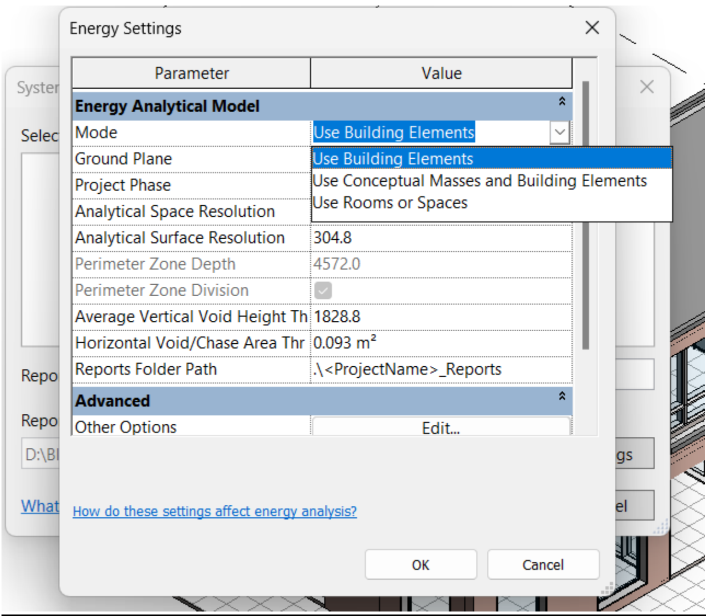



Figure 38: Specifying the energy analytical model mode.

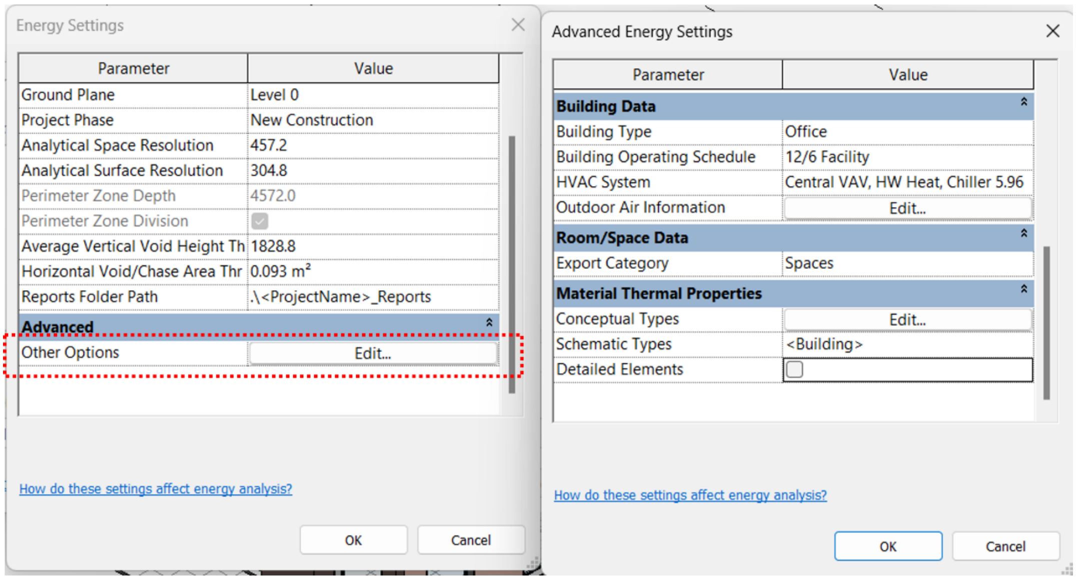



Figure 39: Specifying the Building Data

## *Manually Design Options Creation:*

For this workflow, the design options will be created manually. Based on the windows dimensions' lists, 25 models should be created. This will be applied by manually Changing the window sizes every time before exporting the gbXML files or running the energy analysis through the insight. The following figures shows the process for changing the files then exporting the models.

Note: The following figures show the process for creating one file. This process should be repeated 25 times in this workflow.

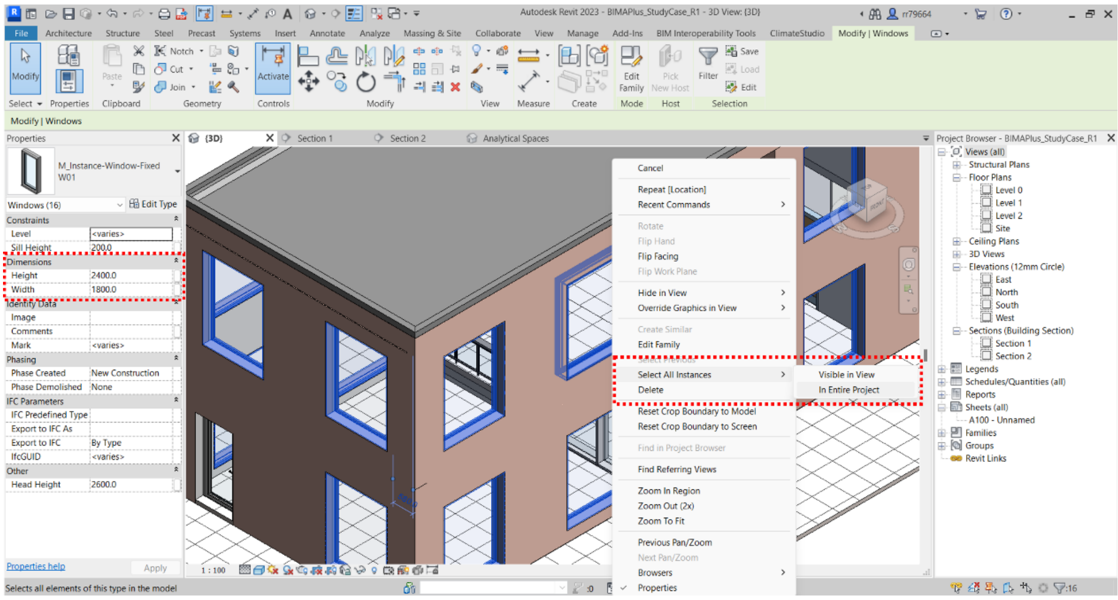


Figure 40: Change the windows size manually.

### *Exporting gbXML Files:*

After specifying all the required settings and changing the window sizes, an energy models should be created. Once creating the energy model through the analyze tab; two 3D models will be created. The Analytical spaces model and the System zones model. The figures below show the process and the sample for the models created. The system zones are directly related to the mechanical system applied in the model. It will help to analyze the heating and cooling systems in spaces.

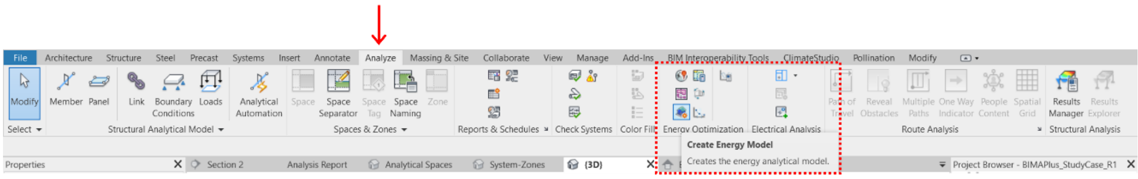


Figure 41: Creating the energy model

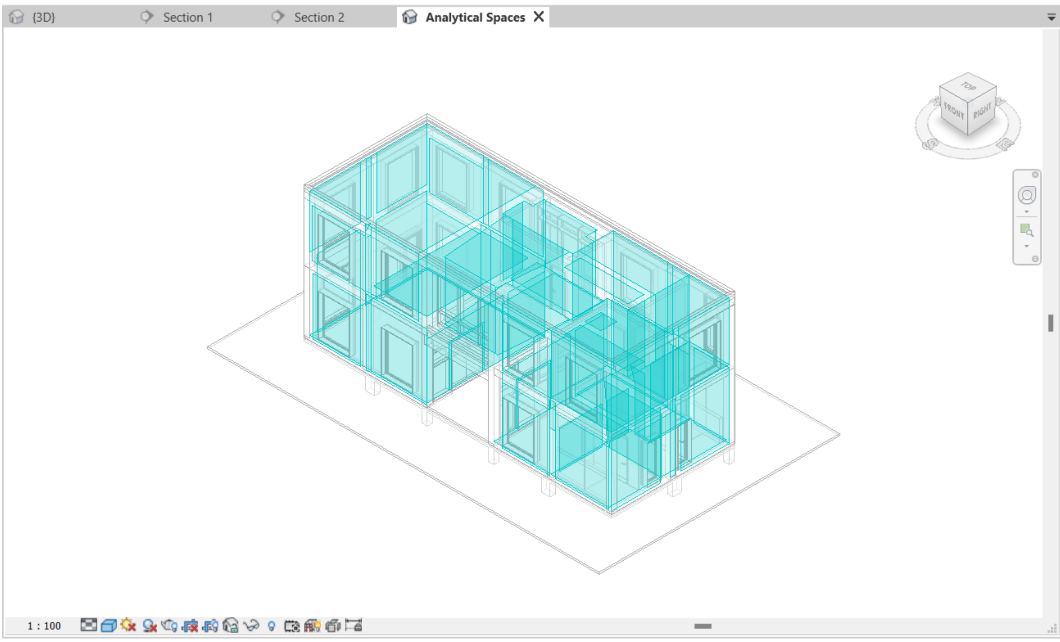



Figure 42: Energy Model: Analytical Spaces

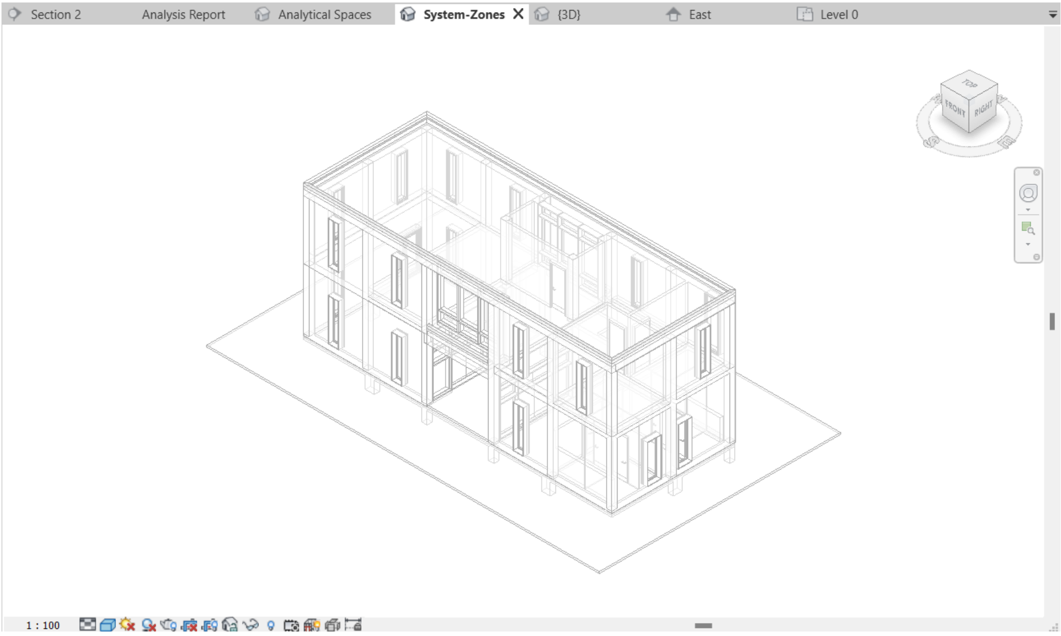



Figure 43: Energy Model: System Zones

Once the energy models have been created, there are two options for running simulations; export the model as gbXML file then import it to Green Building Studio (GBS) or upload the model directly into Autodesk Insight.

1- Export the model to gbXML, then imported into Green Building Studio (GBS).

The model should be on the 3D view to find the export to gbXML in the export tab. The following figure shows the export model to gbXML options.

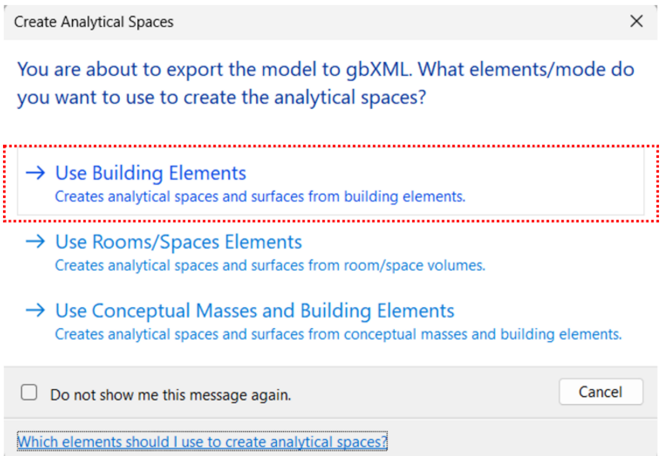



Figure 44: Export using Use Building Elements option.

*Green Building Studio (GBS):*

Green Building Studio (GBS) is a cloud based online platform for energy simulation. Before importing the gbXML files new project should be created on the platform (Figure 45).

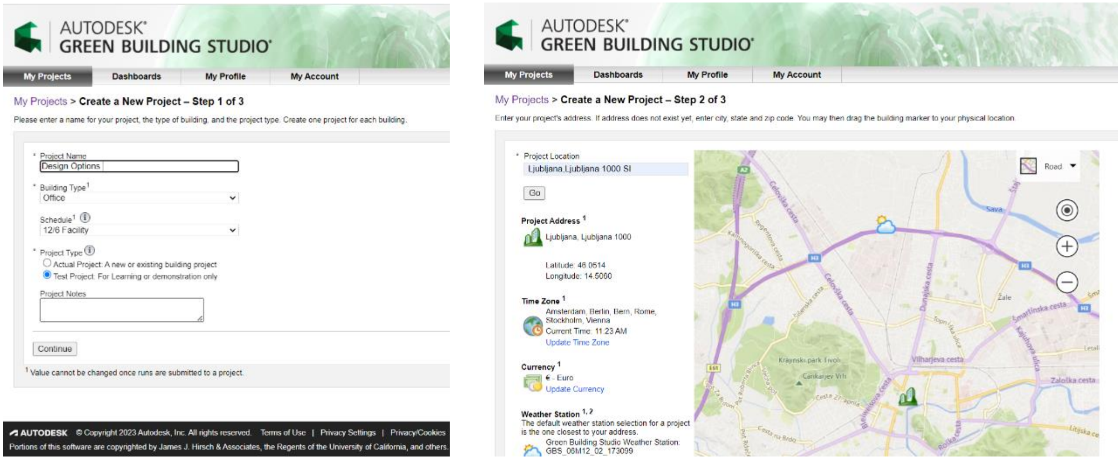



Figure 45: Create a new project on GBS

After exporting the gbXML file from Revit and creating a new project, the files will be imported into GBS. This step is very important to be done manually as it will show the errors or any problems in the model. There are some errors regarding to the DOE-2 simulation. Autodesk had posted some solutions for such errors. The following figures show the error type, and the proposed solutions by Autodesk.

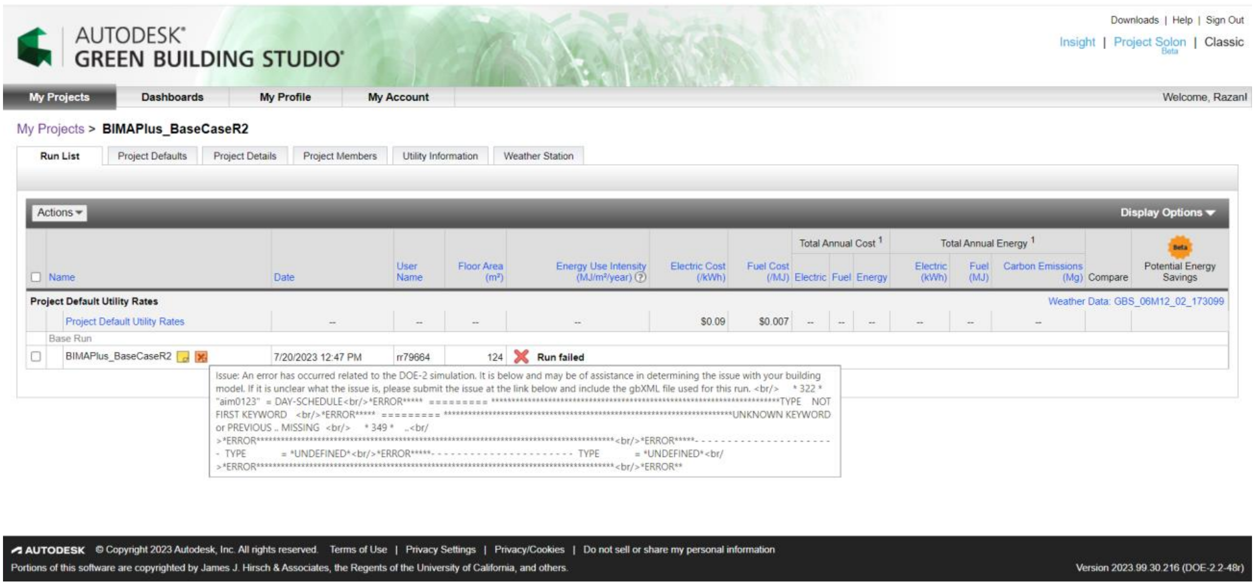



Figure 46: GBS page showing the DOE-2 simulation error

**Causes:**

One of the following:

- A small element (such as a stud) having thermal properties, resulting in too small of an element size to calculate properly.
- Some element on the model has incorrect thermal properties assigned to it, causing the analysis engine to detect it as unrealistically thick.

**Solution:**

**Deselect Detail Elements**

1. Click Analyze tab > Energy Optimization panel > (Energy Settings).
2. Click Edit, next to Other Options.
3. Deselect Detail Elements under Material Thermal Properties.
4. Click OK.
5. Generate new energy model.
6. Select Update Energy Analytical Model option.

**Causes:**

The model contains small surfaces and is located too far from the origin 0,0,0

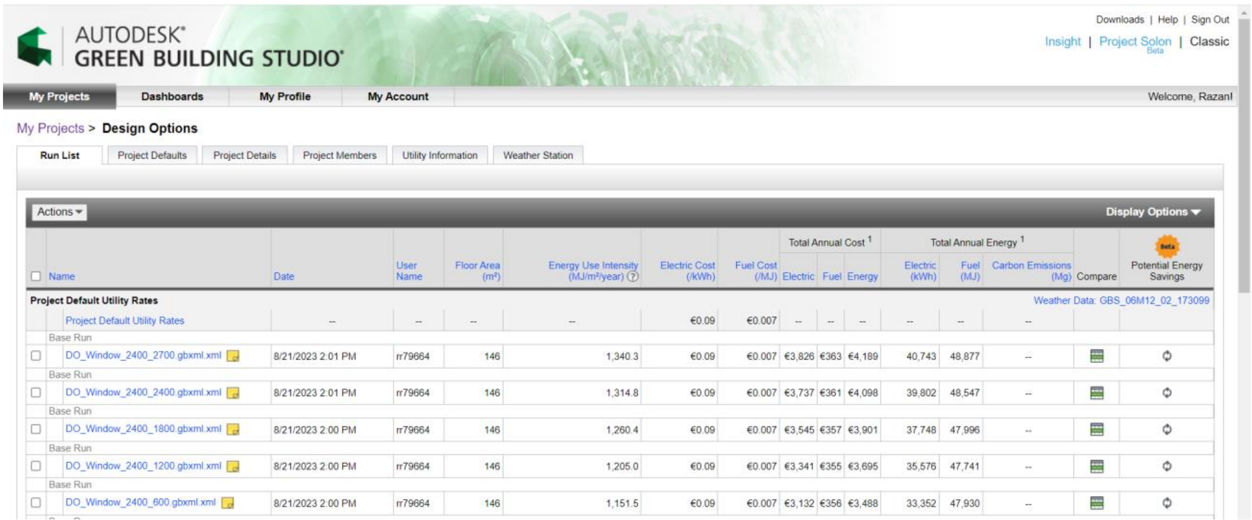
**Solution:**

To resolve this error:

1. In Revit, go to Analyze tab > Energy Settings > set a larger number for Analytical Space Resolution and Analytical Surface Resolution.
2. Go to Manage, Coordinates, Specify Coordinates at Point, select a point somewhere in the middle of the model, and set N/S and E/W to 0,0.
3. Then delete the energy model, create it again, and try generating an Insight analysis again.

Figure 47: Autodesk DOE-2 Simulation Error causes and solution.

After importing the file into GBS, the analysis results will be accessible in the dashboard for each file. The following figure show the uploaded files with the results from the dashboards tap.




| Name | Date | User Name | Floor Area (m²) | Energy Use Intensity (MJ/m²/year) | Electric Cost (/kWh) | Fuel Cost (/MJ) | Total Annual Cost [1] Electric | Total Annual Cost [1] Fuel | Total Annual Cost [1] Energy | Total Annual Energy [1] Electric (kWh) | Total Annual Energy [1] Fuel (MJ) | Carbon Emissions (Mg) | Compare | Potential Energy Savings |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Project Default Utility Rates** | | | | | | | | | | | | | | |
| Project Default Utility Rates | -- | -- | -- | -- | €0.09 | €0.007 | -- | -- | -- | -- | -- | -- | | |
| Base Run | | | | | | | | | | | | | | |
| DO_Window_2400_2700.gbxml.xml | 8/21/2023 2:01 PM | rr79664 | 146 | 1,340.3 | €0.09 | €0.007 | €3,826 | €363 | €4,189 | 40,743 | 48,877 | -- | | |
| Base Run | | | | | | | | | | | | | | |
| DO_Window_2400_2400.gbxml.xml | 8/21/2023 2:01 PM | rr79664 | 146 | 1,314.8 | €0.09 | €0.007 | €3,737 | €361 | €4,098 | 39,802 | 48,547 | -- | | |
| Base Run | | | | | | | | | | | | | | |
| DO_Window_2400_1800.gbxml.xml | 8/21/2023 2:00 PM | rr79664 | 146 | 1,260.4 | €0.09 | €0.007 | €3,545 | €357 | €3,901 | 37,748 | 47,996 | -- | | |
| Base Run | | | | | | | | | | | | | | |
| DO_Window_2400_1200.gbxml.xml | 8/21/2023 2:00 PM | rr79664 | 146 | 1,205.0 | €0.09 | €0.007 | €3,341 | €355 | €3,695 | 35,576 | 47,741 | -- | | |
| Base Run | | | | | | | | | | | | | | |
| DO_Window_2400_600.gbxml.xml | 8/21/2023 2:00 PM | rr79664 | 146 | 1,151.5 | €0.09 | €0.007 | €3,132 | €356 | €3,488 | 33,352 | 47,930 | -- | | |

Figure 48: GBS project with the uploaded gbXML files.

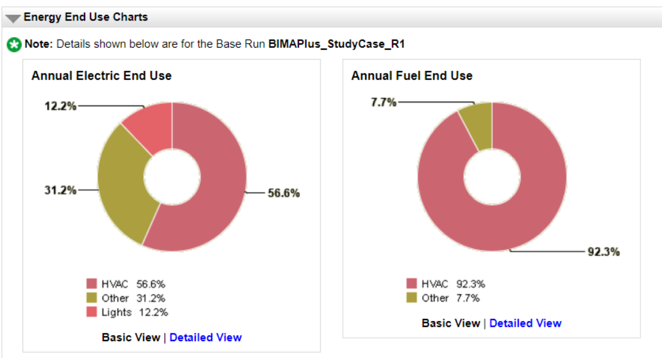



Figure 49: Energy Use chart.

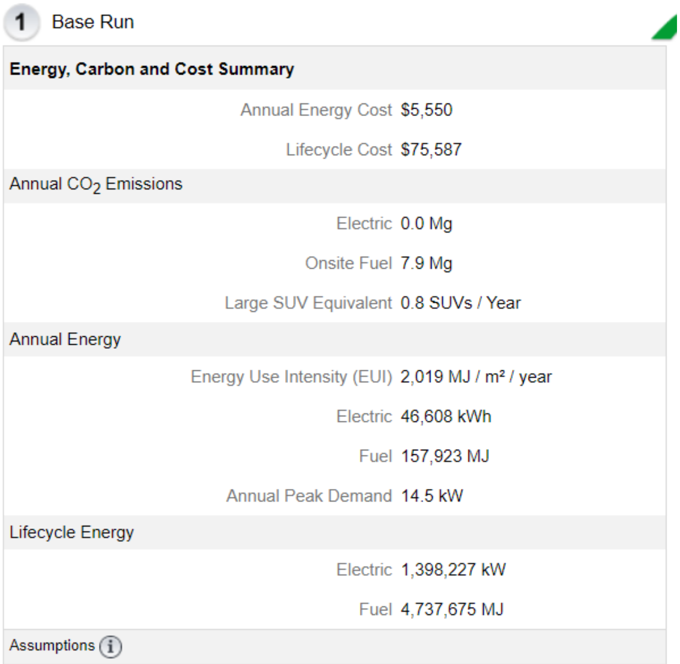



Figure 50: Annual Summary for the Base Run

2- Generate the design options in Autodesk insight

Autodesk Insight is cloud-based add-in available for Revit 2023. This tool provides designers with insights as a guidance for better energy performance buildings during early-stage design. Uploading the model to the Insight creates generative design options. This will upload the original gbXML file and the potential scenarios for improving the energy performance. In this case the project will created automatically on GBS. This tool is still under development, as the future releases will allow designers to create different scenarios based on a set of variables.

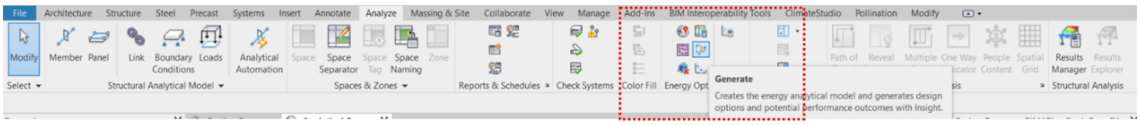



Figure 51: Generate the model through the Insight.

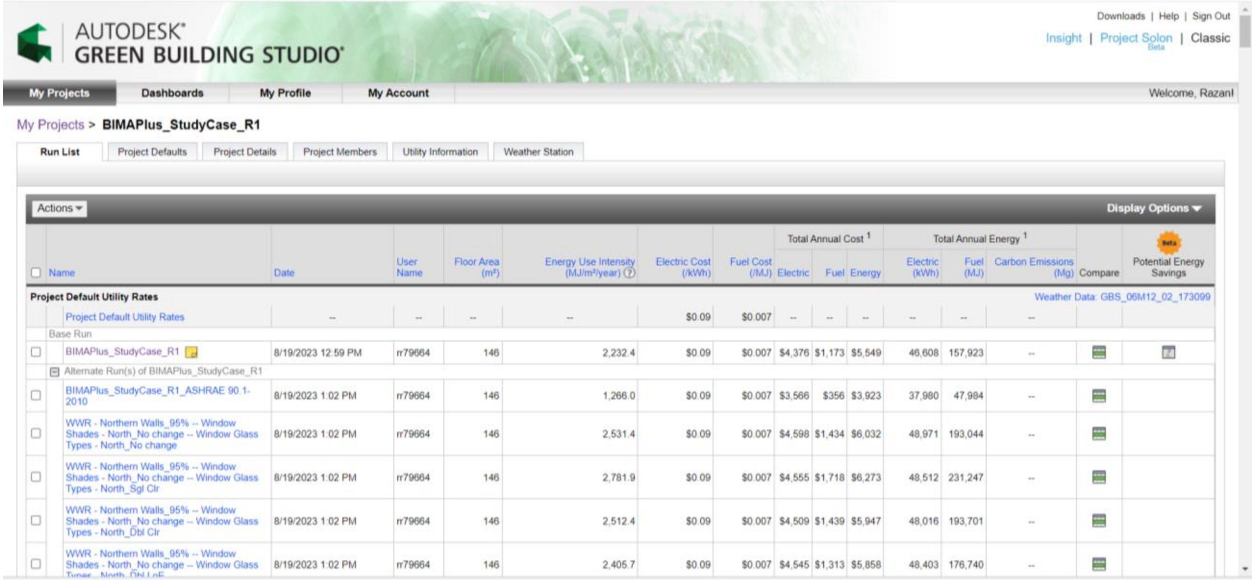


Figure 52: The uploaded model on GBS

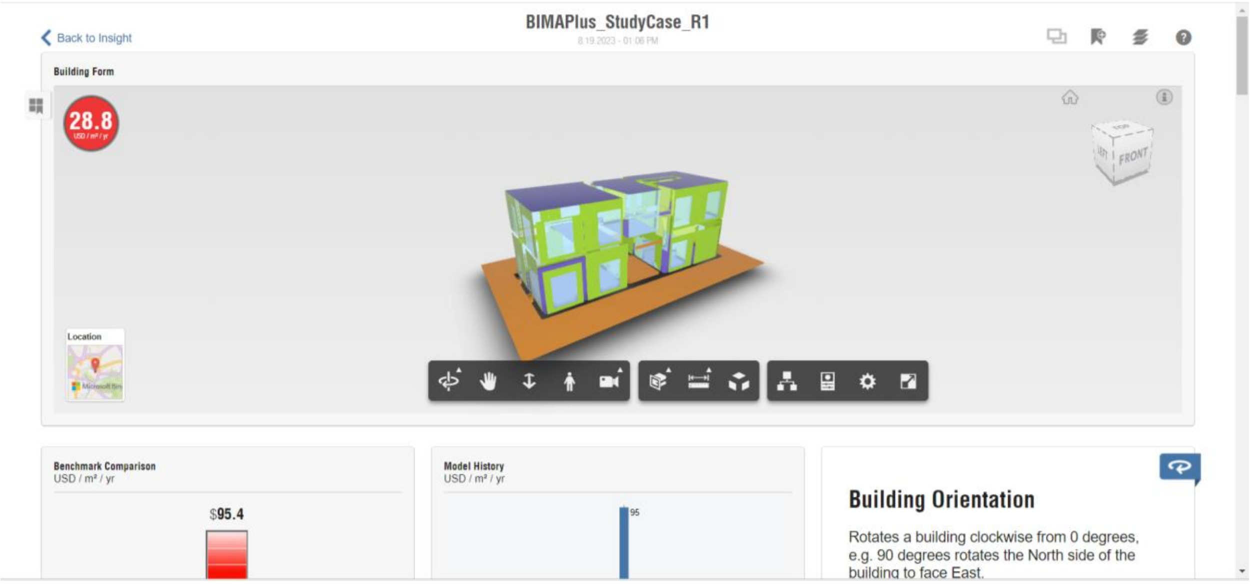


Figure 53: The model uploaded to the Insight

### *Updated Manual Workflow:*

The final workflow was developed after testing the process. The workflow is smooth and direct to the point when it is applied for one file but exporting the files and running the analysis manually is time consuming process. The following graph shows the final workflow for the manual workflow for BIM based energy efficient design.

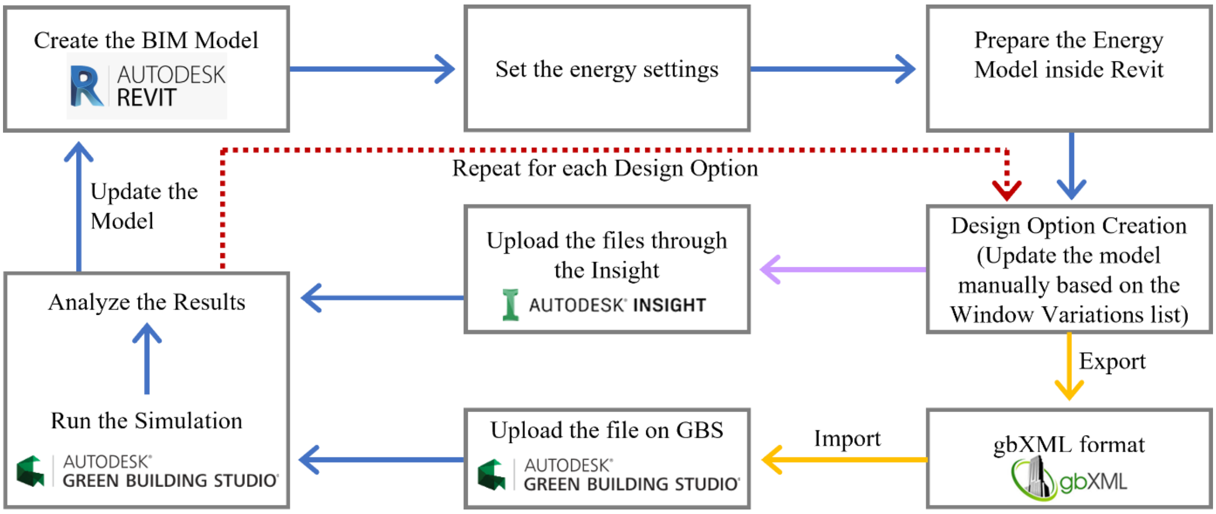



Figure 54: The Revised Manual Workflow (Revision 01)

### 3.3.2 Level Two: Automated Level – Visual Programming Workflow

In this part of the research the automated workflow will be applied using visual programming languages. The manual process will be automated using Dynamo software. The following workflow will examine the automation using Dynamo. This workflow developed based on the previous studies and research taken into consideration the capabilities of the tool used.

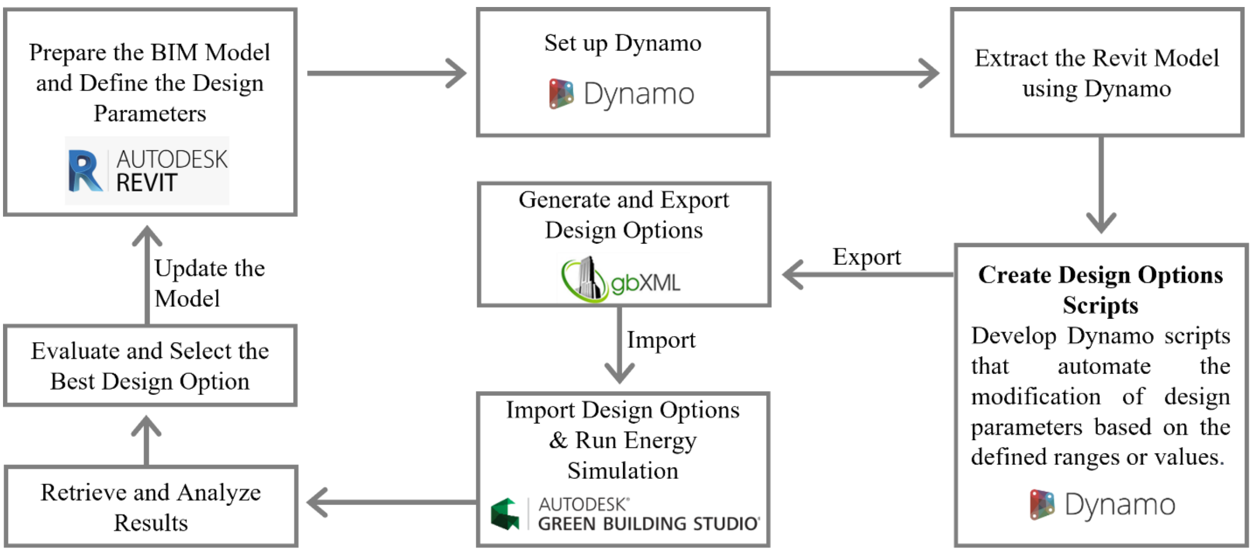



Figure 55: Automated Workflow using Visual Programming Language (Dynamo)

*Visual* Programming *Languages in BIM:*

Visual Programming languages are programming languages that enable users to generate programs by graphically manipulating program components, instead of writing textual codes. In BIM, Designers usually use computer programming to make their complicated tasks and designs easier by using techniques like for-loops and if-else statements. However, visual programming interfaces offer an alternative way to the traditional complex textual coding. They use a visual way of connecting small blocks, each performing a specific task, to create a complete system or process [60]. Visual programming lets people create computer programs by moving and connecting graphical elements, instead of writing textual code. The research shows that visual programming approach could be easier for beginners or those who don't specialize in coding, such as architects [46]. The commonly used visual programming tools in BIM are Dynamo/ Autodesk Revit and Grasshopper/ Rhinoceros.

### *Proposed Workflow using Dynamo:*

The common Dynamo Package used for energy analysis inside Dynamo is Energy Analysis for Dynamo as shown in the figure below. This package is very powerful as it allows to export the zones/mass to gbXML and set the energy settings. It also allows to run the energy analysis for multiple files by submit it to GBS and export the results.

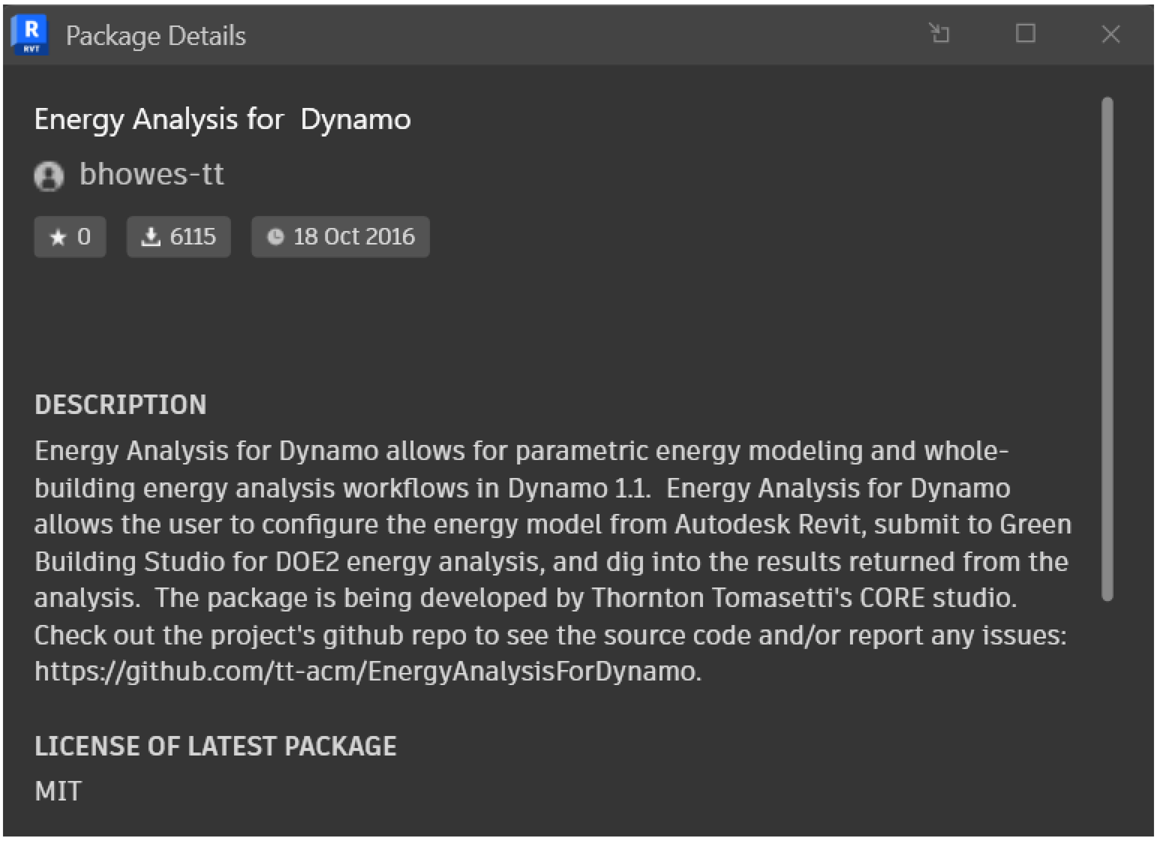



Figure 56: Energy Analysis for Dynamo Package, last update 2016.

Many of the previous studies like [43], and [61] built their methodologies and conclusions based on this package. Unfortunately, this package is not working on the recent versions of Revit as the last update was in 2016. For this, based on all given information and trials results; this workflow using Dynamo is failed. The package is dated due to using old Revit API and the access to GBS API is denied. To be concluded that visual programming languages specially Dynamo is very rigid and limited when it comes to energy analysis automation. The following figures shows analysis of the workflow and the limitation of available nodes used for this trial.

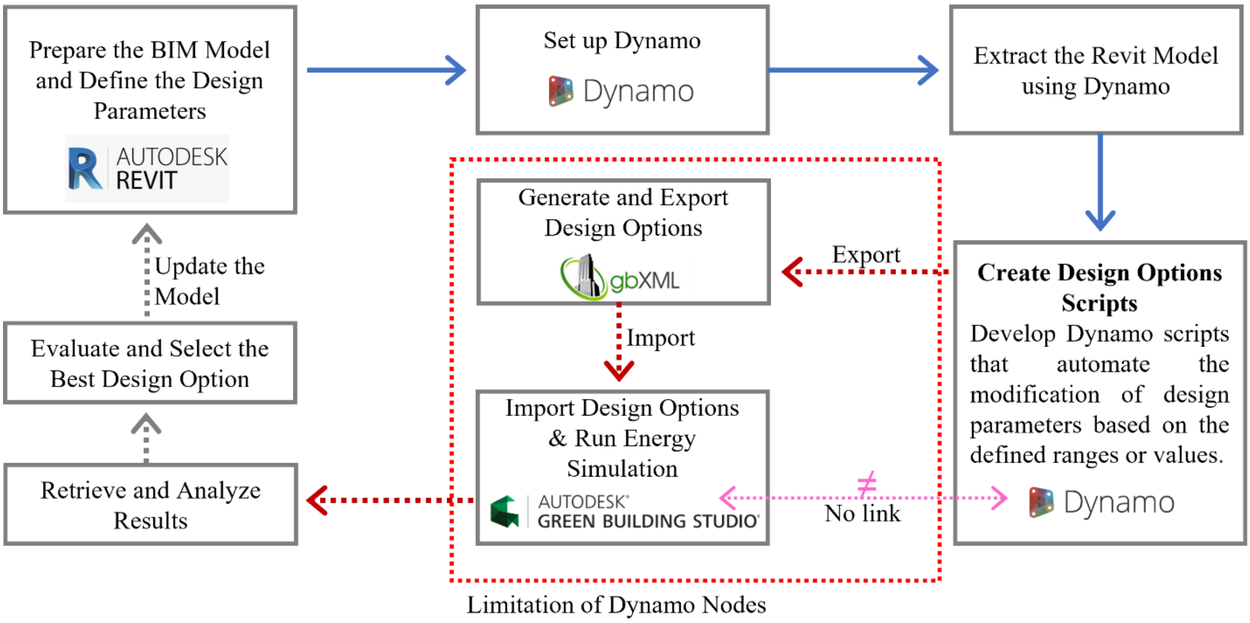



Figure 57: Revised Workflow, red squared the limitation of the available packages.

As shown in figure 57, the revised workflow shows the red squared part in the workflow had been failed. Basically, first exporting the files through Dynamo nodes is not available and limited only for schematic designs, not detailed building elements. Running the energy analysis through Dynamo is not available in the recent Revit versions, and it returns Null values. The following figures shows the available nodes and its limitation.

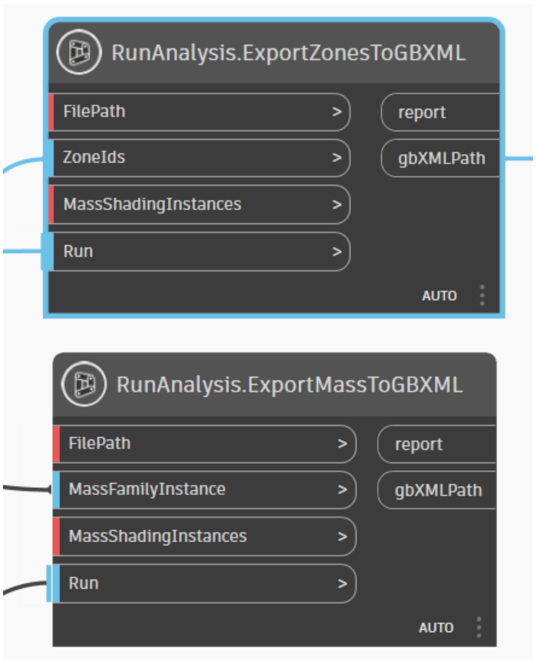



Figure 58: Export to gbXML nodes, fails to export files in the recent Revit versions.

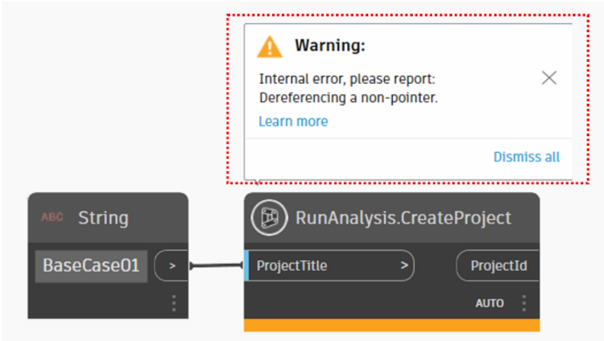



Figure 59: Create project on GBS node, fails to create project.

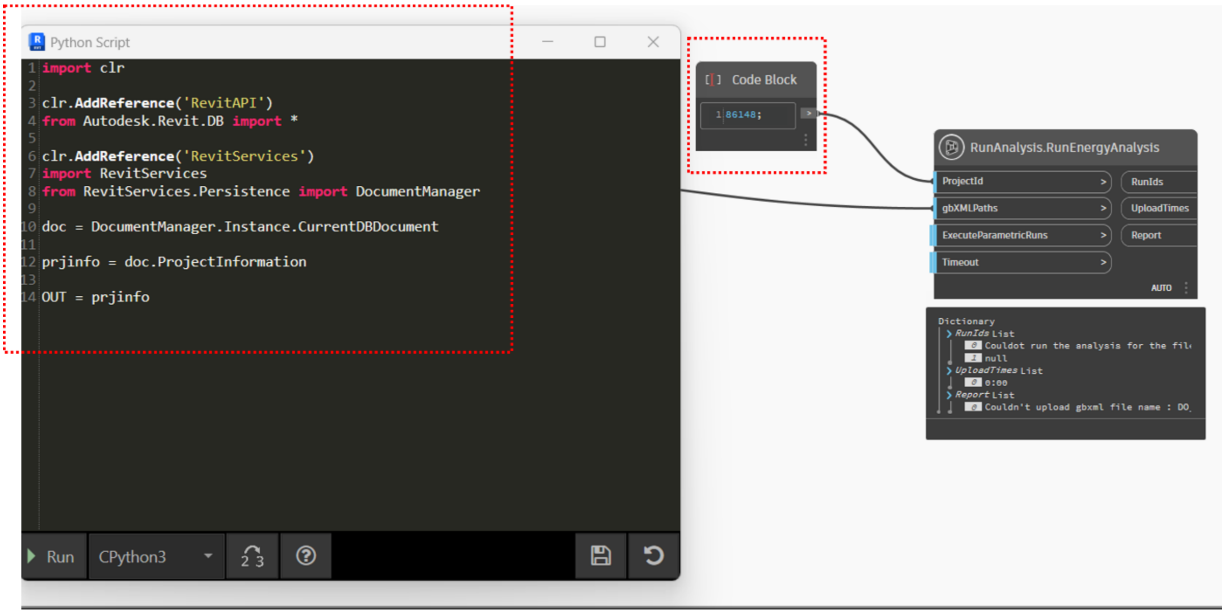



Figure 60: Alternative Python script to create project and return the Project Id number

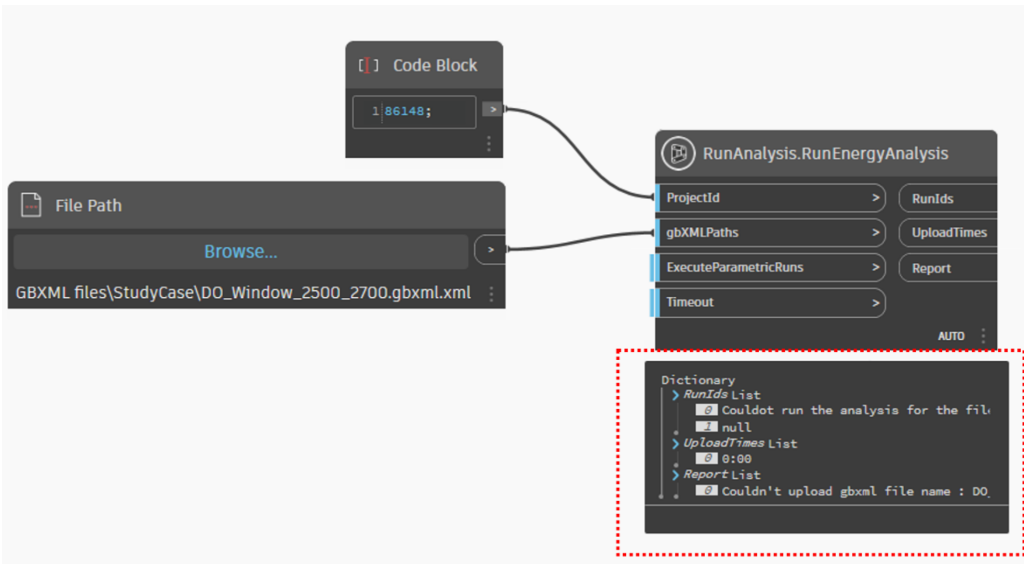



Figure 61: Run Energy Analysis node, returns Null values.

### 3.3.3 Level Three: Automated Level – Visual and Textual Programming

In this part of the research the automated workflow will be applied using both visual and textual programming languages. The full process will be automated using python scripts inside the visual programming interface. The following workflow will examine the automation using Dynamo and Python. This workflow developed based on the previous studies and research taken into consideration the capabilities of the tool used.

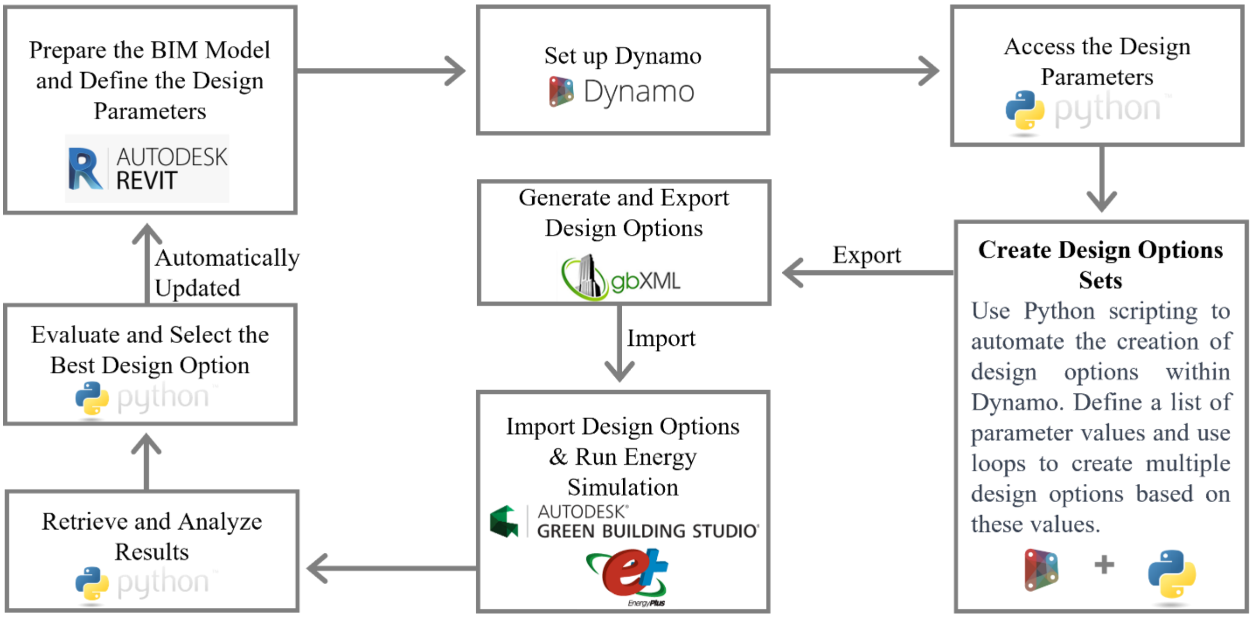



Figure 62: Automated Workflow: Visual and Textual Programming Language (Revision 00)

The automation work will be done using Python inside the visual programming interface (Dynamo, Grasshopper). The process mainly concluded into three main steps as the following:

1. Create the design options: based on the specified design variations.
2. Run the energy simulation for the created design variations.
3. Analyze the energy simulation results to select the best design option.

*Design Options Creation*

This part of the work will create the design options for the base-case model based on the variations mentioned in the previous section. The work will be done in Dynamo inside Revit, as for the automation Python script is developed. The first step is to define the input and the output of the Python script. The figure below shows the Dynamo Code Structure used to create the files.

## Dynamo Code Structure:

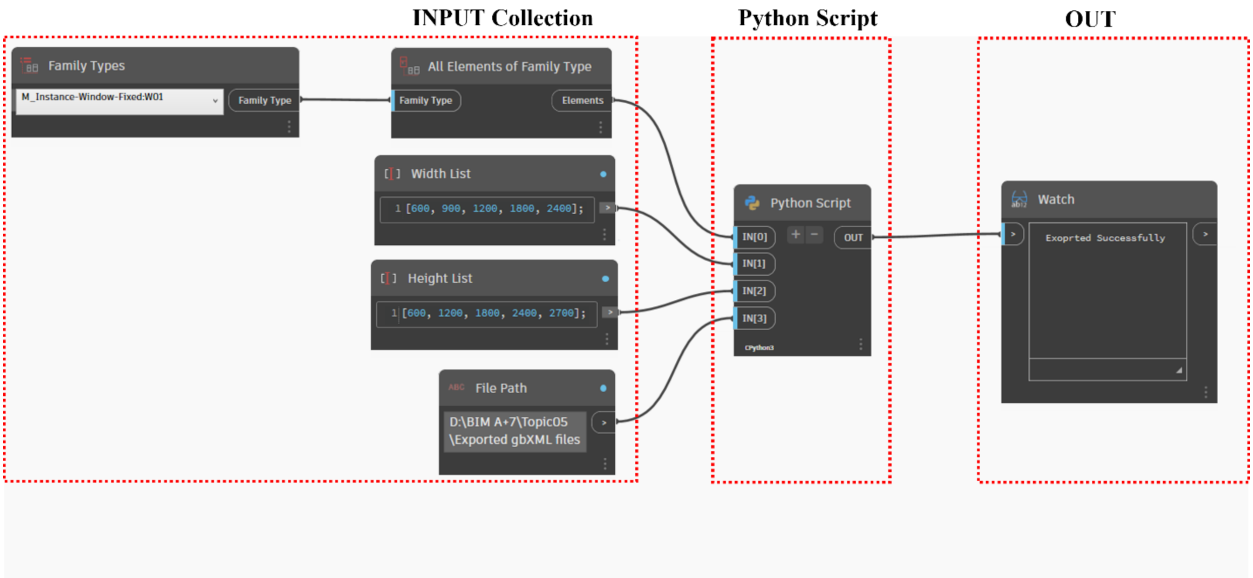



Figure 63: Dynamo Code Structure

The input of the code includes the selected elements for change (Windows), the parameters to be changed for the selected windows (width and height lists), and the file path where the exported files will be saved. The return of the code will the exported gbXML files.

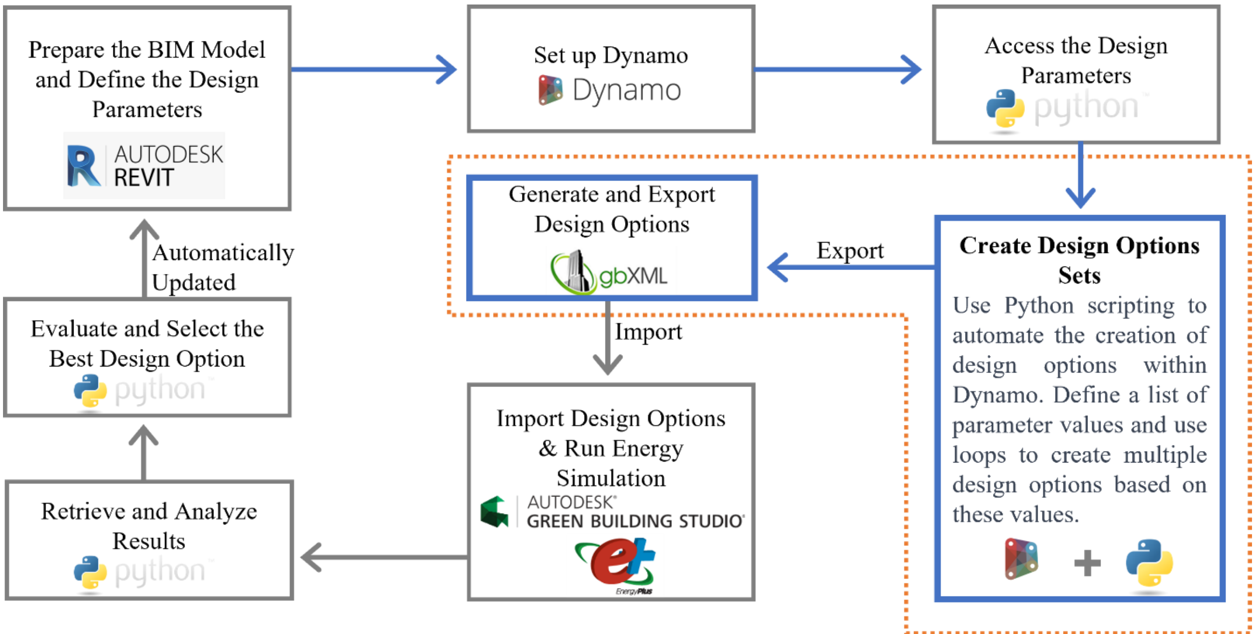



Figure 64: The automated workflow, the red bounded area shows the Dynamo Code part (Revision 01)

As showed in the graph the provided code solved the creation part. The following figures explains the python script parts.

## Python Script Structure:

1. The first part of any python codes includes importing the necessary libraries.

```
# Import necessary modules
import clr
clr.AddReference('RevitAPI')
clr.AddReference('RevitAPIUI')
import Autodesk
from Autodesk.Revit.DB import *

clr.AddReference('RevitServices')
from RevitServices.Persistence import DocumentManager
from RevitServices.Transactions import TransactionManager

import os

doc = DocumentManager.Instance.CurrentDBDocument
uiapp = DocumentManager.Instance.CurrentUIApplication
app = uiapp.Application

```

Figure 65: Import the Required Libraries.

2. The second part is to access the current Revit Document, UI Application, and Application objects.

```
# Import necessary modules
import clr
clr.AddReference('RevitAPI')
clr.AddReference('RevitAPIUI')
import Autodesk
from Autodesk.Revit.DB import *

clr.AddReference('RevitServices')
from RevitServices.Persistence import DocumentManager
from RevitServices.Transactions import TransactionManager

import os

doc = DocumentManager.Instance.CurrentDBDocument
uiapp = DocumentManager.Instance.CurrentUIApplication
app = uiapp.Application

```

Figure 66: Access the Current Revit Document and applications

3. Define the Inputs for the code

```
doc = DocumentManager.Instance.CurrentDBDocument
uiapp = DocumentManager.Instance.CurrentUIApplication
app = uiapp.Application

# Get the window elements from Dynamo
windows = UnwrapElement(IN[0])

# Get the lists of width and height values from Dynamo
width_list = IN[1]
height_list = IN[2]

path = IN[3]

# Function to modify window dimensions
def modify_window_dimensions(window, width, height):
    width_parameter = window.LookupParameter('Width')
    height_parameter = window.LookupParameter('Height')
```

Figure 67: Define the inputs for the code.

4. Modify Windows Function

```
# Get the window elements from Dynamo
windows = UnwrapElement(IN[0])

# Get the lists of width and height values from Dynamo
width_list = IN[1]
height_list = IN[2]

path = IN[3]

# Function to modify window dimensions
def modify_window_dimensions(window, width, height):
    width_parameter = window.LookupParameter('Width')
    height_parameter = window.LookupParameter('Height')

    if width_parameter and height_parameter:
        # Start a transaction to modify the model
        TransactionManager.Instance.EnsureInTransaction(doc)

        # Set the width and height parameters of the window
        width_parameter.Set(width/304.8)
        height_parameter.Set(height/304.8)

        # Commit the changes to the model
        TransactionManager.Instance.TransactionTaskDone()
        doc.Regenerate()
    else:
        raise ValueError("One or both of the specified parameters not 
        found.")
```

Figure 68: Modify Window Function

5. The main Function of the Code, this part of the code consists of the following:
   - The loops: The loops that will be executed within the provided lists.

- Delete and re-create the energy model.
- Export the gbXML files.

```
# Main script
def main():
    # Loop through each window and create variations
    for width in width_list:
        for height in height_list:
            # Modify the dimensions of all windows for this variation
            for window in windows:
                modify_window_dimensions(window, width, height)

            # Export the variation to gbXML format
            filename = "DO_Window_{}_{}.gbxml".format(width, height)

            # Delete any existing Energy Analysis Detail Model
            eadm = Autodesk.Revit.DB.Analysis.EnergyAnalysisDetailModel.GetMainEnergyAnalysisDetailModel(doc)
            if eadm is not None:
                doc.Delete(eadm.Id)

            # Create a new Energy Analysis Detail Model
            energyOptions = Autodesk.Revit.DB.Analysis.EnergyAnalysisDetailModelOptions()
            energyOptions.EnergyModelType = Autodesk.Revit.DB.Analysis.EnergyModelType.BuildingElement
            eadm = Autodesk.Revit.DB.Analysis.EnergyAnalysisDetailModel.Create(doc, energyOptions)

            # Export the gbXML file
            GBopt = GBXMLExportOptions()
            GBopt.ExportEnergyModelType = ExportEnergyModelType.BuildingElement
            doc.Export(path, filename, GBopt)
            doc.Regenerate()

# Run the main script
main()
OUT = "Exoprted Successfully"
```

Figure 69: The main Function of the Code

After executing this code all the gbXML files will be generated and saved in the provided path. In this case 25 gbXML files created, with the naming convention as shown in the code.

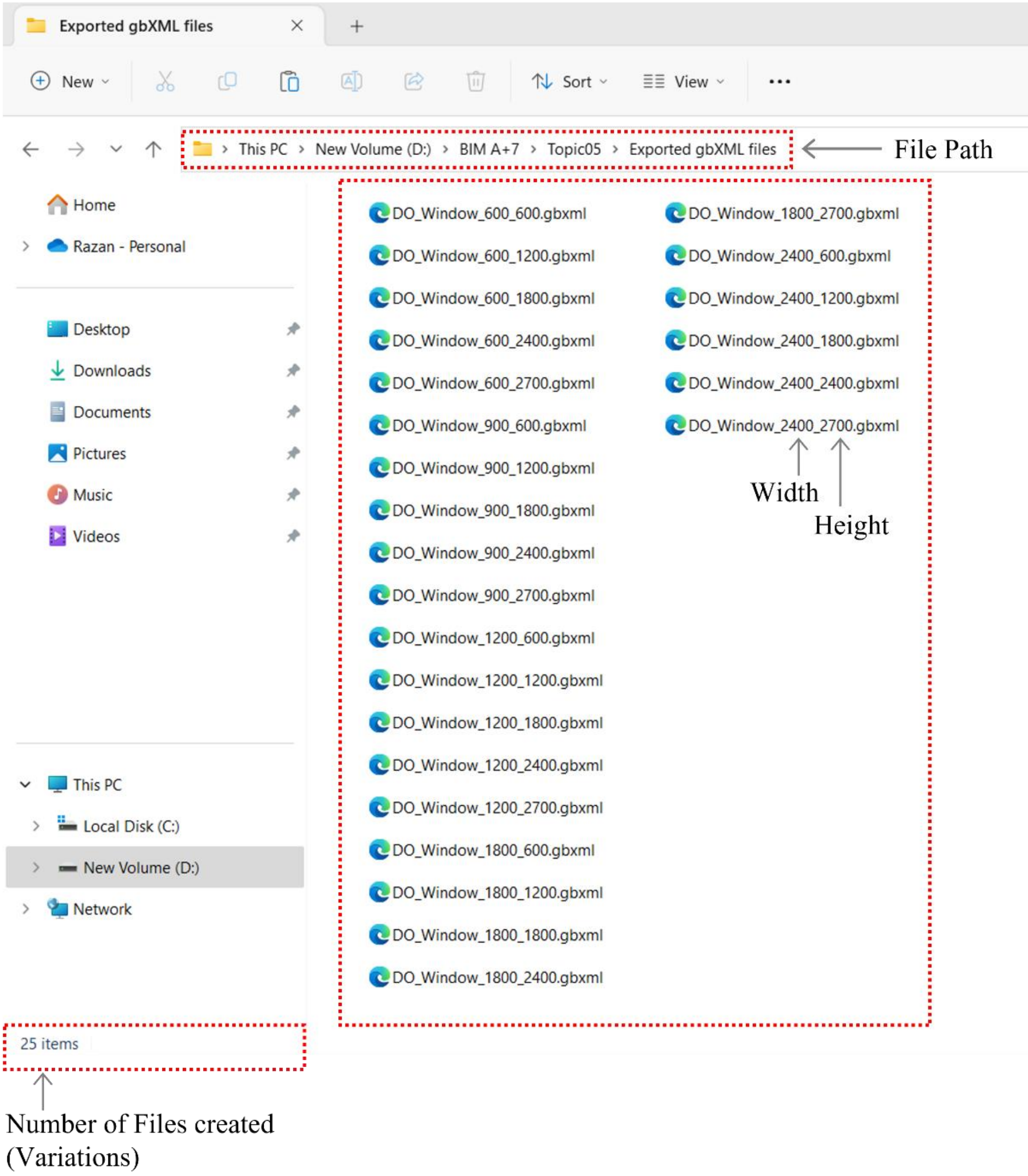



Figure 70: The created gbXML files

### *Run the Energy Analysis*

After creating the design options, the next step is to run the energy simulation for the created design variations. This process is quite complicated as it will connect the models with the energy analysis tools.

To start with the proposed workflow, to use the Dynamo package for energy analysis, as mentioned earlier this package is available for Revit 2016 and Dynamo 1.1.

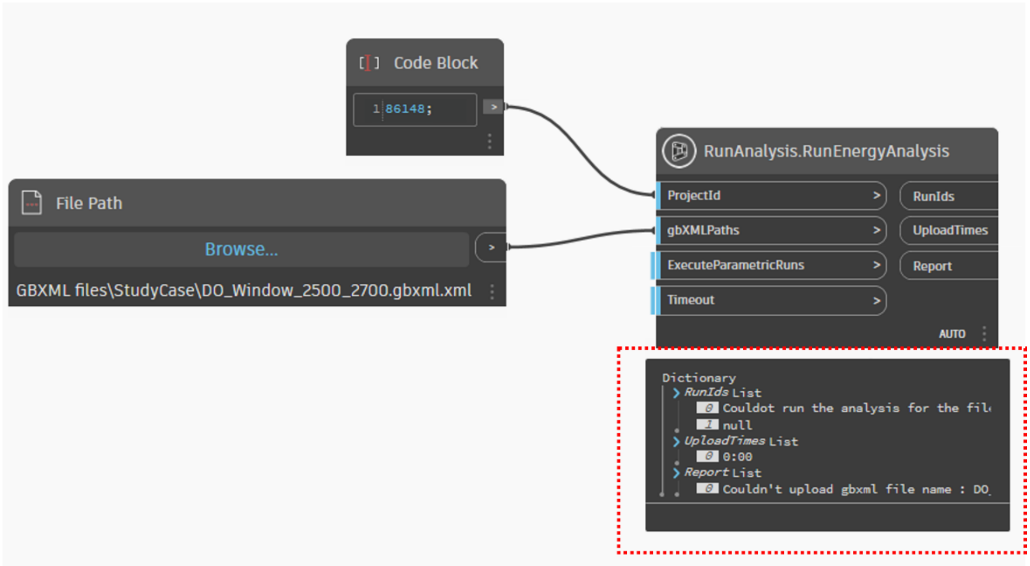



Figure 71: Run Energy Analysis node

In the same manner the access to Green Building Studio (GBS) API is denied. For this the proposed workflow is updated to work in a different direction. The process of importing the files and running the simulation changed. The figure below shows the revised workflow.

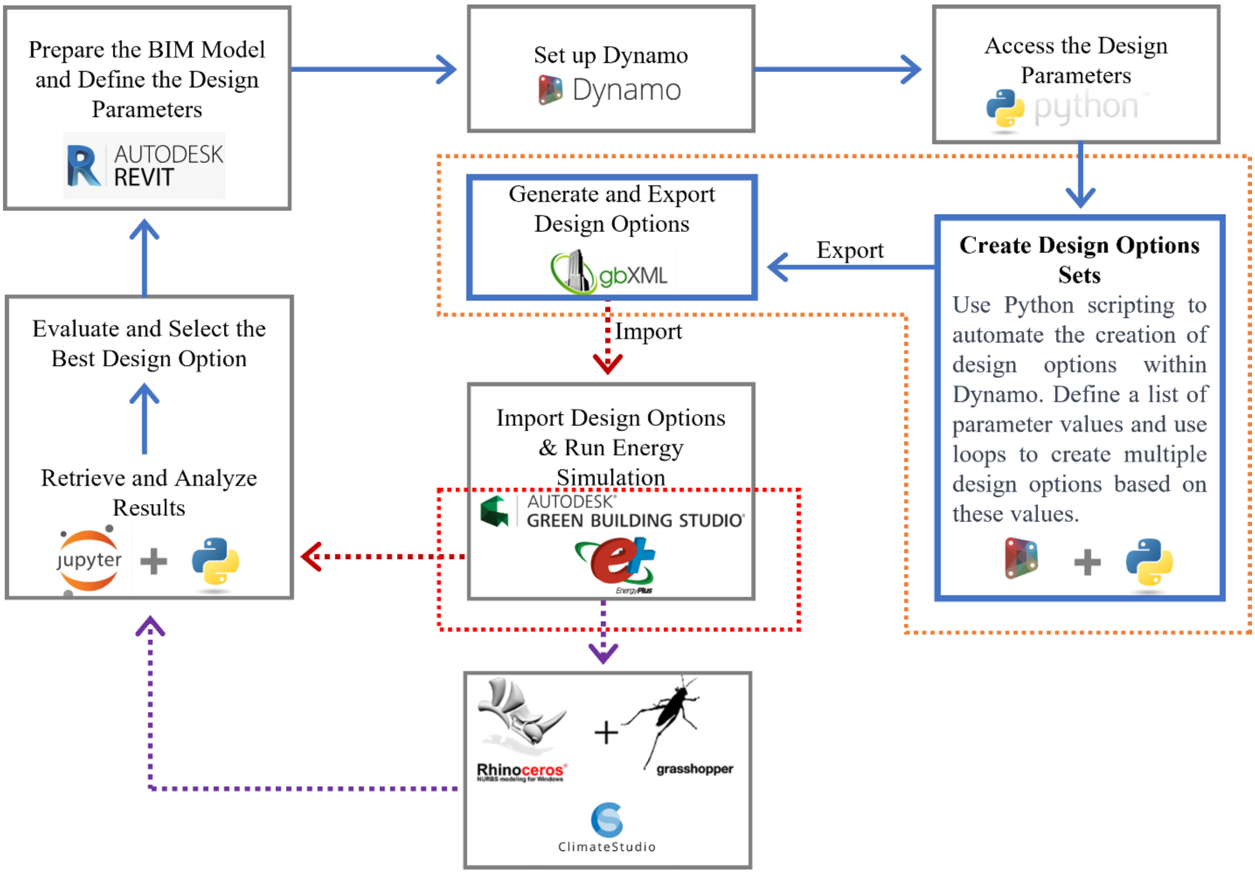



Figure 72: The Revised Automated Workflow using both Visual and Textual Programming Languages (Revision 02)

The red squared area where the workflow failed to automate importing the files using Green Building Studio, instead the process will be done using Grasshopper. In Grasshopper, for running the energy simulations a number of libraries should be installed like, Ladybug, Butterfly, Climate Studio, and Open Studio. The following graph shows the alternative Grasshopper Script for running the energy analysis.

### Grasshopper Script Structure

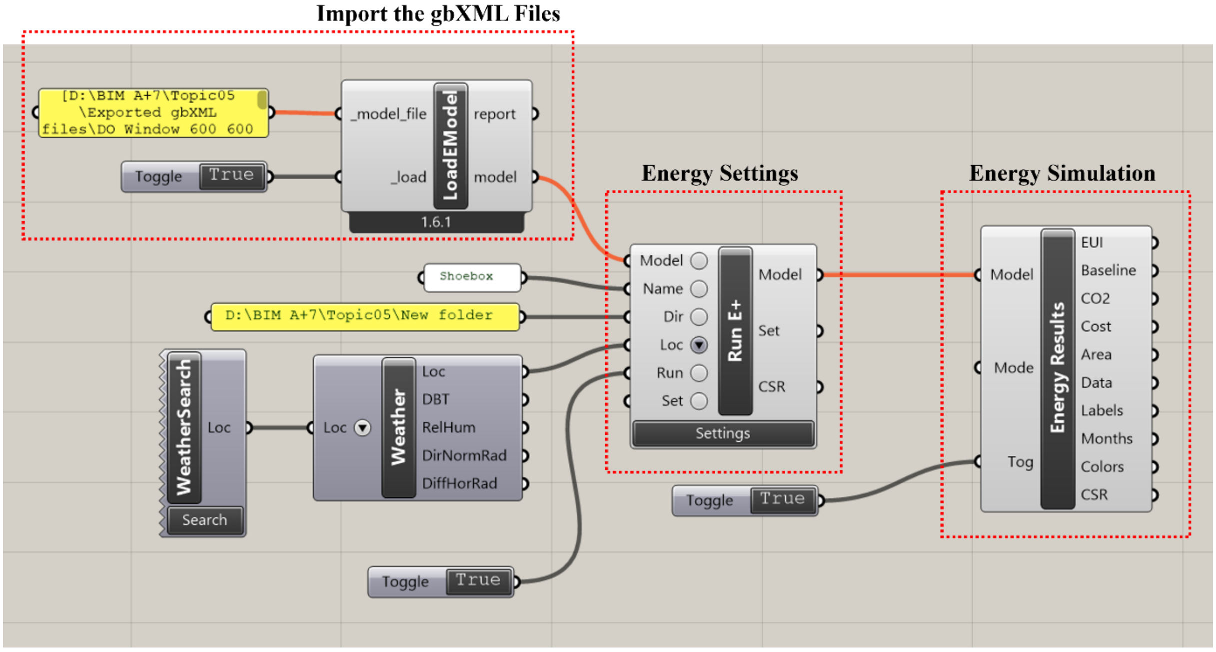



Figure 73: Grasshopper Script Structure

The script is simply composed of two parts, the first part is importing the gbXML files into Grasshopper and change the models into energy models. The second part is done by using Climate Studio Add-In to run the energy simulation and extract the results.

#### *Analyse the Energy Simulation Results*

After analysing the different design options, the results should be analysed to set the conclusions based on it. In this part the extracted data analysis for the simulation runs will be done by using python inside Jupyter. Simple codes will be done to get the best design option. Usually, the criteria of the selection will be based on the following:

- The Best Energy Performance: Least Energy Consumption (Energy Efficient).
- Daylight Availability and Occupant Visual Comfort.
- The best Cost-Efficient option.

In this study the focus will be on the energy performance and the daylight and visual comfort, as the cost factor is not included in this study. Based on [62] most of the ideal window to wall ratio (WWR) values for office buildings can be found in a relatively narrow range (0.30 < WWR < 0.45).

The data analysis will be done by writing simple scripts to conclude the findings and specify the results. The following figure shows an example of a script for extracting the first rows in the data.

In [1]:
```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
import seaborn as sns
df = pd.read_csv('csv-Design Options.csv')
df.head()
```

Out[1]:

| | RunID | AltRunID | DateAdded | Username | Title | StatusID | BuildingType | FloorArea | AnnualElecCost | AnnualFuelCost | AnnualElec |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1910421 | 0 | 8/21/2023 12:00:42 PM | rr79664 | DO_Window_2400_2700.gbxml.xml | 4 | Office | 145.901574 | 3825.741511 | 363.055741 | |
| 1 | 1910420 | 0 | 8/21/2023 12:00:31 PM | rr79664 | DO_Window_2400_2400.gbxml.xml | 4 | Office | 145.901574 | 3737.406023 | 360.600297 | |
| 2 | 1910419 | 0 | 8/21/2023 12:00:22 PM | rr79664 | DO_Window_2400_1800.gbxml.xml | 4 | Office | 145.901574 | 3544.557954 | 356.506925 | |
| 3 | 1910418 | 0 | 8/21/2023 12:00:13 PM | rr79664 | DO_Window_2400_1200.gbxml.xml | 4 | Office | 145.901574 | 3340.552686 | 354.613997 | |
| 4 | 1910416 | 0 | 8/21/2023 12:00:01 PM | rr79664 | DO_Window_2400_600.gbxml.xml | 4 | Office | 145.901574 | 3131.795140 | 356.018169 | |

Figure 74: Extracting the first rows in the data file.

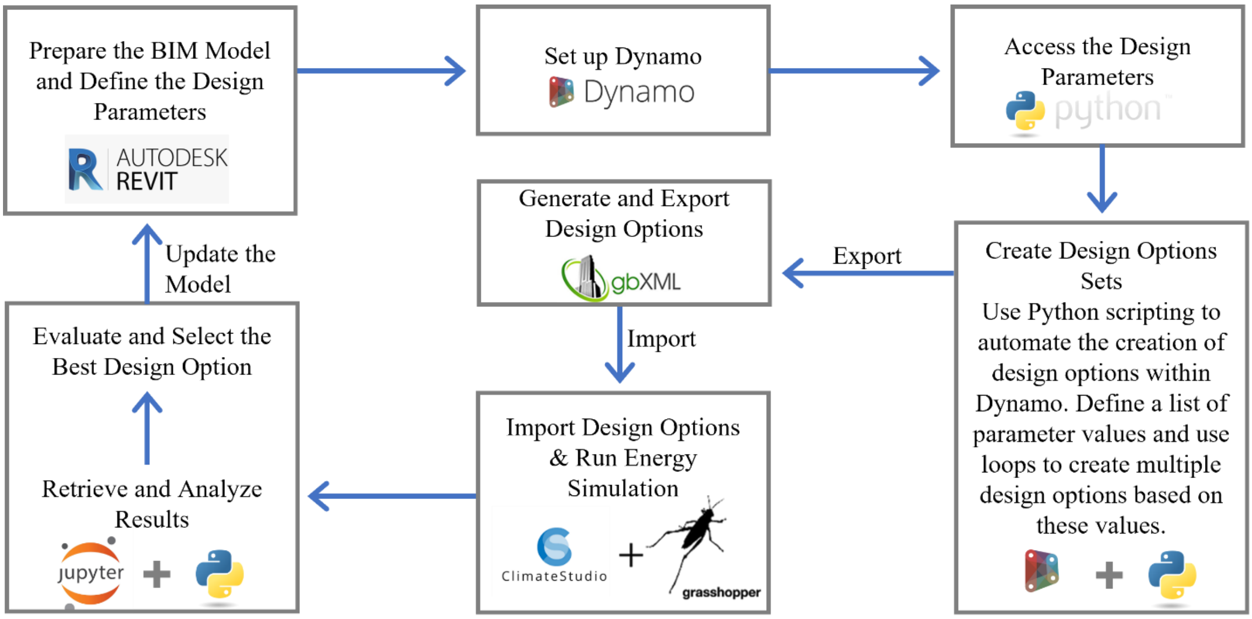



Figure 75: The Automated Workflow (Revision 03)

## 3.4 Data Analysis and Visualization

This section reviews the analysis outcomes, upon the automated workflow detailed in the preceding section. The automated workflow facilitated the generation of results for various design iterations. In this section, the data generated was subjected to comprehensive analysis using Python within the Jupyter environment to ascertain the optimized solutions.

In [2]:
```
# Print the first 25 rows of the ordered DataFrame
df.head(25)
```

Out[2]:

| | RunID | AltRunID | DateAdded | Username | Title | StatusID | BuildingType | FloorArea | AnnualElecCost | AnnualFuelCost | AnnualElecDemand | AnnualElecUse | AnnualFuelUse | EUI | WWR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1910370 | 0 | 8/21/2023 9:24:38 AM | rr79664 | DO_600_600 | 4 | Office | 145.901574 | 3026.890057 | 359.426390 | 11.734 | 32235.25 | 48388.64 | 1127.030614 | 0.0450 |
| 1 | 1910371 | 0 | 8/21/2023 9:24:48 AM | rr79664 | DO_600_1200 | 4 | Office | 145.901574 | 3060.533489 | 357.516601 | 11.917 | 32593.54 | 48131.53 | 1134.108907 | 0.0900 |
| 2 | 1910372 | 0 | 8/21/2023 9:25:11 AM | rr79664 | DO_600_1800 | 4 | Office | 145.901574 | 3099.184608 | 356.523415 | 12.112 | 33005.16 | 47997.82 | 1143.348848 | 0.1350 |
| 3 | 1910373 | 0 | 8/21/2023 9:25:24 AM | rr79664 | DO_600_2400 | 4 | Office | 145.901574 | 3141.567313 | 355.854235 | 12.299 | 33456.52 | 47907.73 | 1153.868310 | 0.1800 |
| 4 | 1910374 | 0 | 8/21/2023 9:25:52 AM | rr79664 | DO_600_2700 | 4 | Office | 145.901574 | 3168.028334 | 355.311775 | 12.451 | 33738.32 | 47834.70 | 1160.320947 | 0.2000 |
| 5 | 1910376 | 0 | 8/21/2023 9:30:01 AM | rr79664 | DO_900_600 | 4 | Office | 145.901574 | 3041.773207 | 358.375787 | 11.808 | 32393.75 | 48247.20 | 1129.972049 | 0.0675 |
| 6 | 1910377 | 0 | 8/21/2023 9:30:12 AM | rr79664 | DO_900_1200 | 4 | Office | 145.901574 | 3097.618356 | 356.572885 | 12.105 | 32988.48 | 48004.48 | 1142.982930 | 0.1350 |
| 7 | 1910378 | 0 | 8/21/2023 9:30:25 AM | rr79664 | DO_900_1800 | 4 | Office | 145.901574 | 3165.656420 | 355.564175 | 12.436 | 33713.06 | 47868.68 | 1159.930575 | 0.2000 |
| 8 | 1910379 | 0 | 8/21/2023 9:30:34 AM | rr79664 | DO_900_2400 | 4 | Office | 145.901574 | 3250.076278 | 354.050516 | 12.952 | 34612.10 | 47664.90 | 1180.716944 | 0.2700 |
| 9 | 1910380 | 0 | 8/21/2023 9:30:42 AM | rr79664 | DO_900_2700 | 4 | Office | 145.901574 | 3291.033581 | 353.606327 | 13.193 | 35048.28 | 47605.10 | 1191.069458 | 0.3000 |
| 10 | 1910395 | 0 | 8/21/2023 10:14:05 AM | rr79664 | DO_1200_600 | 4 | Office | 145.901574 | 3058.628258 | 357.470176 | 11.902 | 32573.25 | 48125.28 | 1133.565431 | 0.0900 |
| 11 | 1910396 | 0 | 8/21/2023 10:14:12 AM | rr79664 | DO_1200_1200 | 4 | Office | 145.901574 | 3137.958736 | 356.022031 | 12.284 | 33418.09 | 47930.32 | 1153.074912 | 0.1800 |
| 12 | 1910397 | 0 | 8/21/2023 10:14:22 AM | rr79664 | DO_1200_1800 | 4 | Office | 145.901574 | 3246.491176 | 354.230494 | 12.932 | 34573.92 | 47689.13 | 1179.940955 | 0.2700 |
| 13 | 1910398 | 0 | 8/21/2023 10:14:39 AM | rr79664 | DO_1200_2400 | 4 | Office | 145.901574 | 3357.923248 | 353.830575 | 13.573 | 35760.63 | 47635.29 | 1208.853022 | 0.3600 |
| 14 | 1910399 | 0 | 8/21/2023 10:14:49 AM | rr79664 | DO_1200_2700 | 4 | Office | 145.901574 | 3409.384205 | 353.796036 | 13.858 | 36308.67 | 47630.64 | 1222.343582 | 0.4050 |
| 15 | 1910402 | 0 | 8/21/2023 10:34:40 AM | rr79664 | DO_1800_600 | 4 | Office | 145.901574 | 3094.966620 | 356.475208 | 12.093 | 32960.24 | 47991.33 | 1142.196002 | 0.1350 |
| 16 | 1910403 | 0 | 8/21/2023 10:35:04 AM | rr79664 | DO_1800_1200 | 4 | Office | 145.901574 | 3241.427149 | 354.446275 | 12.901 | 34519.99 | 47718.18 | 1178.809384 | 0.2700 |
| 17 | 1910408 | 0 | 8/21/2023 10:43:21 AM | rr79664 | DO_1800_1800 | 4 | Office | 145.901574 | 3404.769959 | 354.206056 | 13.827 | 36259.53 | 47685.84 | 1221.509431 | 0.4050 |
| 18 | 1910409 | 0 | 8/21/2023 10:44:45 AM | rr79664 | DO_1800_2400 | 4 | Office | 145.901574 | 3560.047698 | 355.754849 | 14.646 | 37913.18 | 47894.35 | 1263.740984 | 0.5400 |
| 19 | 1910410 | 0 | 8/21/2023 10:44:55 AM | rr79664 | DO_1800_2700 | 4 | Office | 145.901574 | 3631.896224 | 357.061641 | 15.020 | 38678.34 | 48070.28 | 1283.826483 | 0.6000 |
| 20 | 1910416 | 0 | 8/21/2023 12:00:01 PM | rr79664 | DO_2400_600 | 4 | Office | 145.901574 | 3131.795140 | 356.018169 | 12.265 | 33352.45 | 47929.80 | 1151.451735 | 0.1800 |
| 21 | 1910418 | 0 | 8/21/2023 12:00:13 PM | rr79664 | DO_2400_1200 | 4 | Office | 145.901574 | 3340.552686 | 354.613997 | 13.474 | 35575.64 | 47740.76 | 1205.011432 | 0.3600 |
| 22 | 1910419 | 0 | 8/21/2023 12:00:22 PM | rr79664 | DO_2400_1800 | 4 | Office | 145.901574 | 3544.557954 | 356.506925 | 14.564 | 37748.22 | 47995.60 | 1260.364694 | 0.5400 |
| 23 | 1910420 | 0 | 8/21/2023 12:00:31 PM | rr79664 | DO_2400_2400 | 4 | Office | 145.901574 | 3737.406023 | 360.600297 | 15.558 | 39801.98 | 48546.68 | 1314.816581 | 0.7200 |
| 24 | 1910421 | 0 | 8/21/2023 12:00:42 PM | rr79664 | DO_2400_2700 | 4 | Office | 145.901574 | 3825.741511 | 363.055741 | 16.013 | 40742.72 | 48877.25 | 1340.294264 | 0.8100 |

Figure 76: The extracted dataset in Jupyter Environment

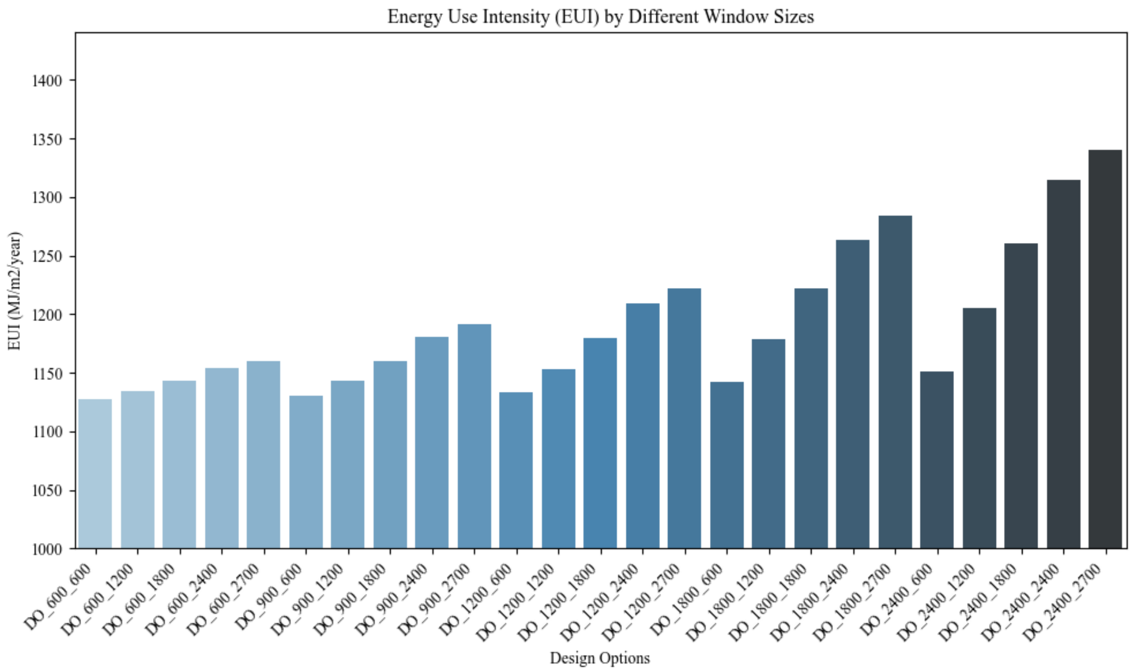



Figure 77: Energy Use Intensity (EUI) for different design options.

The selection criteria employed for identifying the optimal design options revolved around achieving the lowest possible Energy Use Intensity (EUI), while simultaneously adhering to the acceptable window-to-wall ratio (WWR) range of 30% to 45% [59]. This approach aimed to strike a balance between energy efficiency and architectural aesthetics. The figure below shows the EUI for different design options.

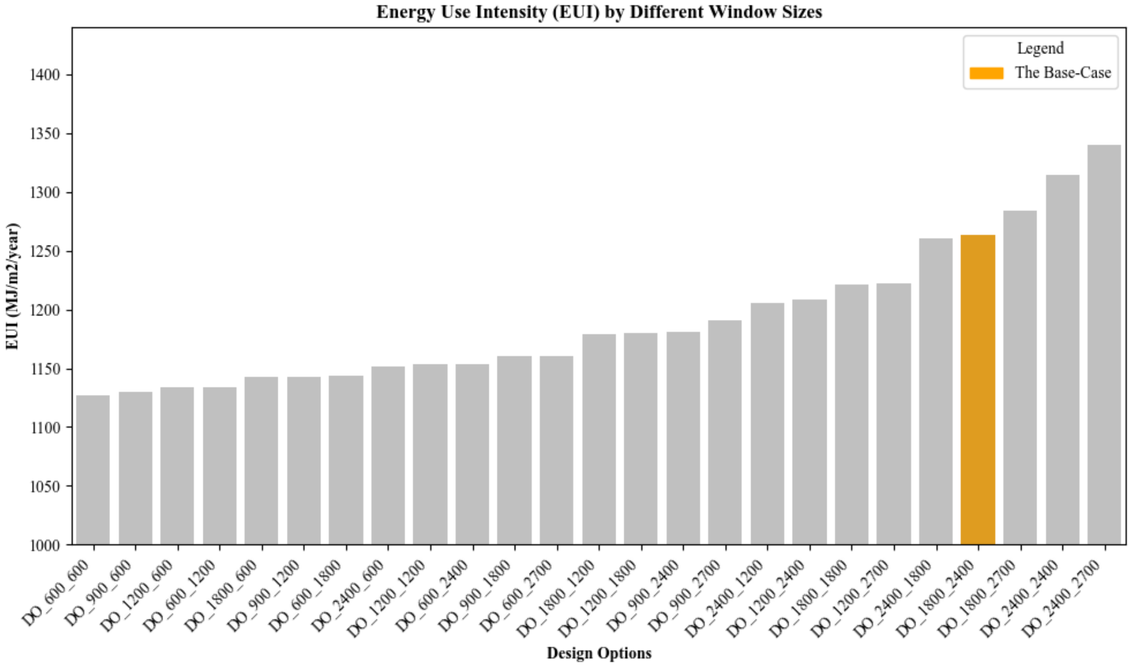



Figure 78: Energy Use Intensity (EUI) for different design options, ordered by EUI.

The results show that there is a positive correlation between the Energy Use Intensity (EUI) and the size of windows in the design options. As for the WWR ratio, the figure below shows the design options within the acceptable WWR range.

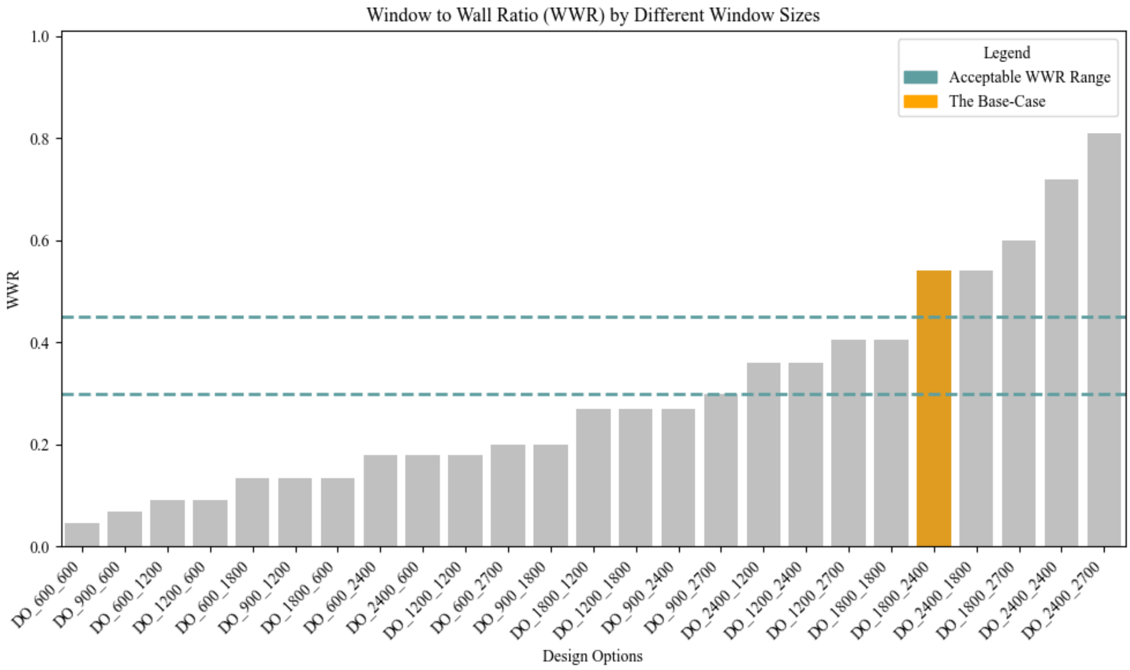



Figure 79: Window to Wall Ratio (WWR) for different design options.

The figure below shows the acceptable WWR design options (Colored in Green).

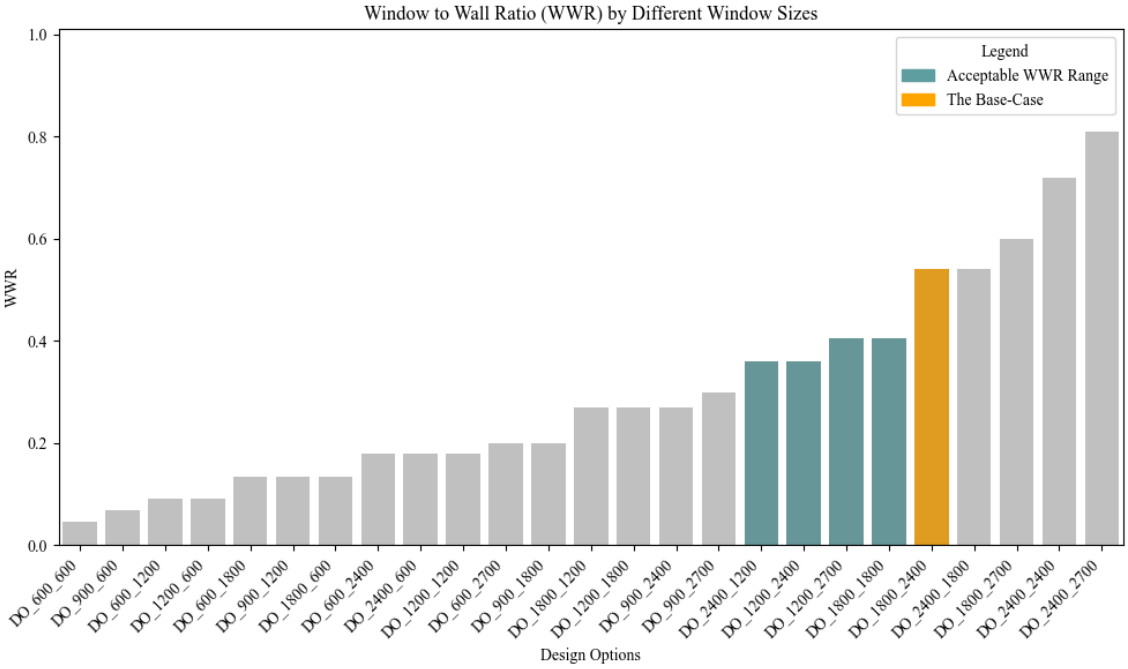



Figure 80: Window to Wall Ratio (WWR) for different design options, shows the acceptable WWR

It can be concluded that only four option lies under the acceptable WWR range. The Base-Case is above this range. The figure below shows the difference in EUI compared to the base-case building values.

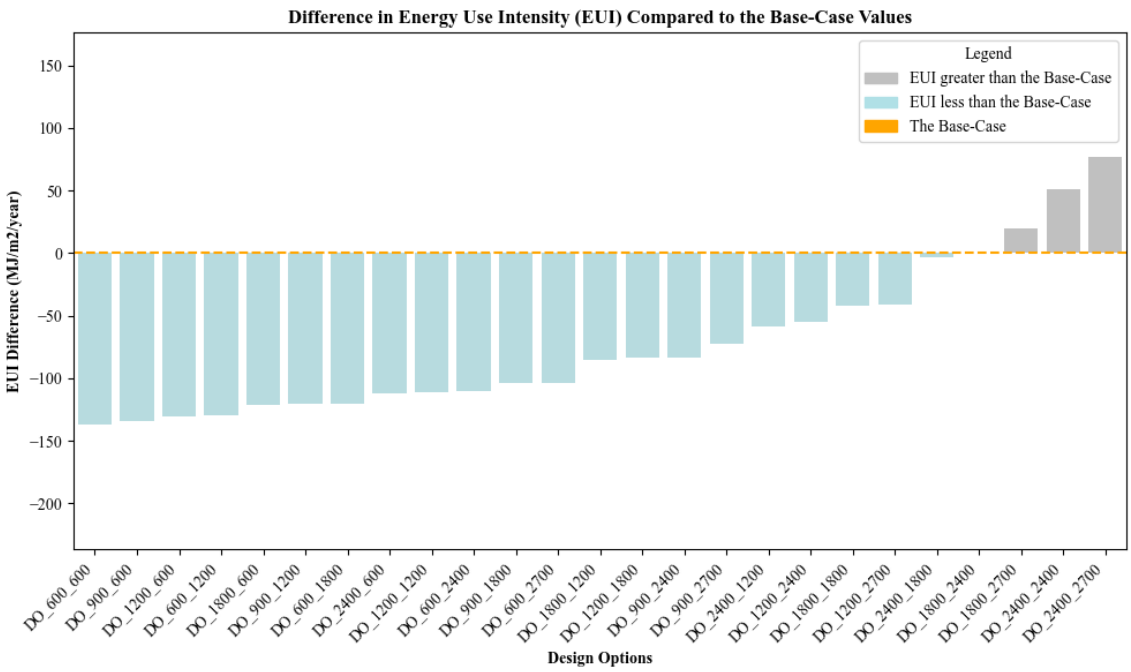



Figure 81: The EUI compared to the Base-Case values

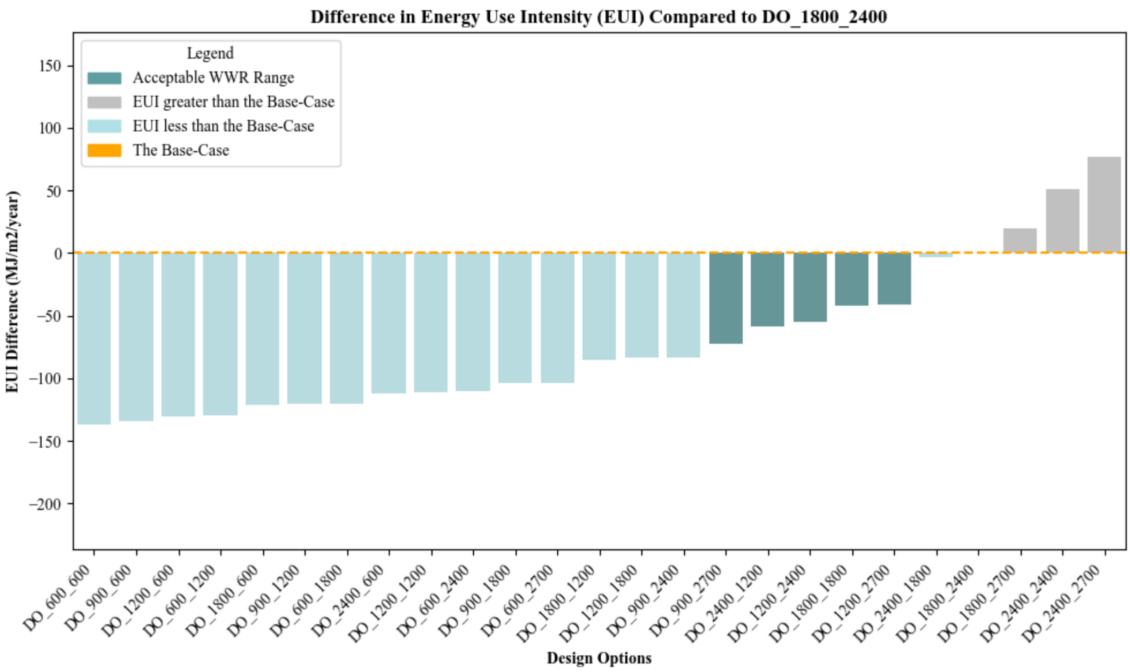



Figure 82: The EUI compared to the Base-Case values, shows the acceptable WWR ranges

```
In [10]: # Filter the DataFrame to only include rows with WWR between 0.3 and 0.45
         df_filtered = df[(df['WWR'] >= 0.3) & (df['WWR'] <= 0.45)]

         # Sort the filtered DataFrame by EUI in ascending order
         df_sorted = df_filtered.sort_values(by='EUI')

         # Extract the first 3 rows of the sorted DataFrame
         result = df_sorted.head(3)['Title']

         # Print the result
         print(result)

         9      DO_900_2700
         21     DO_2400_1200
         13     DO_1200_2400
         Name: Title, dtype: object
```

Figure 83: Extracting the three Lowest EUI option within the acceptable WWR range.

The results shows that the lowest EUI option is the window size of 900*2700mm.

Figure 84: The Base-Case building based on the selected Design Option

In summary, the automated workflow emerges as a clear preference, offering streamlined results and informed decision-making with relative ease.

### 3.5 Summary

This Chapter presents a thorough research methodology that aims for investigating the potential benefits of implementing BIM automation to enhance energy efficiency in building designs. The chapter is organized into several sections, each contributing to different research approach. Both qualitative and quantitative research methods are utilized for this purpose.

The selection of the base-case building serves as the base for the study application, with its detailed description encompassing physical characteristics, building configuration, and envelope elements. The design optioneering strategy revolves around changing window sizes to explore their impact on energy consumption. Software tools like Autodesk Revit, Dynamo, Grasshopper, and others are employed for the study.

The exploration of three levels of energy analysis automation showcases the progression from manual workflows to advanced automated processes. The manual workflow analysis, acting as a benchmark, emphasizes the steps involved in creating design options, exporting simulation files, and analyzing results. The attempt to harness visual programming languages, like Dynamo, reflects the ongoing challenges in achieving comprehensive automation due to software limitations. Consequently, the integration of both visual and textual programming languages emerges as a viable solution to address these limitations, offering more control and flexibility.

In summary, this chapter outlines a comprehensive research methodology that covers the selection of the base-case building, design optioneering strategy, and various levels of automation using both visual and textual programming languages. This chapter sets the foundation for the practical implementation of the research goals and insights into how BIM automation can optimize energy efficiency in building design.

# 4 RESEARCH OUTCOMES AND DISCUSSION

## 4.1 Overview

The aim of this study is to investigate and explore the various applications of BIM automation techniques and design optioneering using BIM for design optimization and energy efficiency practices. The study aims to identify and analyze the potential benefits of implementing BIM automation in the design phase to enhance energy efficacy in buildings. The study examines different workflows starting from the manual workflow, then the automated workflow using visual programming (Dynamo) and last the automated work using both visual and textual programming languages. The following section includes the evaluation of the applied workflows.

## 4.2 Workflow Comparison

It should be considered that the manual workflow offers simplicity but is constrained by its time-consuming nature, potential for human errors, and limited scope for exploring design options. On the other hand, the automated workflow, while requiring some technical setup, excels in terms of efficiency, accuracy, and the breadth of design options it can analyze simultaneously. The challenges and limitations of automation underscore the need for careful tool selection, integration, and ongoing maintenance.

In conclusion, both workflows offer distinct advantages and challenges, and the choice between them should be based on the specific goals of the design process, the complexity of the project, available resources, and the desired level of accuracy and exploration. Summary of the positive and negative aspects of each workflow shown in table 7.

Table 7: Comparison between the Manual and Automated Workflows

| Workflow | Aspects |
|---|---|
| **Manual Workflow** | Pros:<br>• Requires no prior coding experience.<br>• Easy to visually verify results.<br>Workflow Challenges and Limitations:<br>• Time-consuming due to repetitive tasks.<br>• Limits the number of design options due to practical constraints.<br>• Susceptible to human error during data entry and analysis.<br>• Difficulty in drawing conclusive insights due to complexity. |
| **Automated Workflow** | Pros:<br>• Saves significant time compared to manual approaches.<br>• Removes limitations on the number of design options explored.<br>• Offers accuracy by eliminating human errors.<br>• Enables simultaneous creation of all design variations.<br>• Facilitates easier conclusions due to streamlined analysis.<br>Workflow Challenges and Limitations:<br>• Initial setup and configuration may require technical knowledge.<br>• Dependent on the functionality and capabilities of the automation tools used.<br>• Challenges may arise from data interoperability issues between different software.<br>• Continuous maintenance and updates may be required to adapt to evolving software versions. |

# 5 CONCLUSION AND FUTURE RESEARCH

## 5.1 Conclusion

The research aims to delve into the diverse applications of BIM automation techniques in design optimization and energy efficiency practices. By focusing on a carefully selected base-case building, the research investigated various design optioneering strategies, with particular emphasis on the WWR as a key factor affecting energy efficiency. This base-case building allowed for controlled experimentation and accurate assessment of the impact of different design options on energy consumption.

The research includes three distinct levels of energy analysis automation: manual, visual programming (Dynamo), and a combined approach involving visual and textual programming (Python). Based on that it can be conclude the following:

- The Manual Workflow: It is a time-consuming and prone to errors. However, it plays a pivotal role in this research. It is not only showcasing potential time savings achievable through automation but also facilitates the process breakdown for streamlined automation. Additionally, it serves as a valuable tool for model testing and error identification before progressing into more complex stages of the process.
- The Visual Programming Level: The visual programming level shows promise but also exposes limitations that obstruct full automation. Dynamo, as a tool, has its constraints, with limited built-in nodes and the need for further development in packages. Although Dynamo helps connect with Revit models and modify parameters, it falls short in creating and exporting files. Energy simulation nodes may also encounter issues. On the other hand, Grasshopper exhibits more development in energy components but faces challenges in interoperability with Revit models, leading to potential data loss when importing files.
- The Visual and Textual Programming Level: This level emerges as a promising approach that provides enhanced control over the automation process, enabling the implementation of complex and comprehensive energy optimization strategies. Python, with its extensive and well-developed libraries, simplifies the creation of intricate design options. It also excels in data analysis and visualization, facilitating the generation of informed conclusions based on the gathered data.

The investigation conducted in this thesis confirm the significant potential of BIM automation techniques in enhancing architectural design for energy efficiency. By integrating BIM automation, designers and architects can streamline their decision-making processes, explore a wider range of design options, and ultimately create buildings that are not only aesthetically pleasing but also sustainable. While BIM automation holds immense promise, there are still some challenges and limitations that need to be overcome, especially when aiming for comprehensive automation. The combination of visual and textual programming emerged as a more effective approach to achieving this goal. The results also emphasized that achieving full automation process requires a careful consideration of software limitations, interoperability issues, and the need for interdisciplinary collaboration among architects, engineers, and energy experts.

## 5.2 Future Research

This thesis sheds light on the potential of BIM automation for energy optimization in architectural design, there is an area where several avenues for future research and development. These research areas could be summarized in the following points:

*Case Studies:* Expanding the research to encompass a wider array of design variables (wall systems, roof systems, and other envelope characteristics), building types, contexts, and climates would offer a more comprehensive understanding of the applicability of BIM automation for energy optimization across different scenarios.

*Software Development:* The limitations encountered in the visual programming tools like Dynamo indicate the need for software advancements that facilitate more intricate automation. Future research could focus on developing software tools that better cater to the complexities of energy optimization.

*Cost-Benefit Analysis:* A thorough analysis of the economic implications of implementing BIM automation for energy optimization, considering factors such as initial cost, operational costs, and return on investment, could provide an overall view of its viability.

*Advanced Energy Simulation:* Incorporating advanced energy simulation tools and machine learning techniques could enhance the accuracy and predictive capabilities of BIM automation for energy optimization. Research could explore the integration of real-time data and dynamic simulation methods.

*Long-Term Performance:* Investigating the long-term performance of buildings designed using BIM automation techniques would provide insights into the durability and sustainability of the proposed solutions over time.

In conclusion, this thesis contributes to the body of knowledge surrounding BIM automation and its potential for energy-efficient architectural design. By exploring different levels of automation and their implications, the research offers valuable insights and a platform for further exploration of this promising topic. Through continuous research and innovation, the AEC industry can harness the power of BIM automation to design buildings that not only inspire but also contribute to a sustainable and energy-efficient future.

# 6 REFERENCES

[1] A. Ibrahim, H. Ali, and R. Rasheed, 'Evaluation Of Nearly Zero Energy Residential Buildings Design Strategies In Three Climatic Zones In Jordan', *IJEEP*, vol. 12, no. 5, pp. 378–391, Sep. 2022, doi: 10.32479/ijeep.13268.

[2] Razan Rashid, H. Ali, and A. Ibrahim, 'THE ECONOMIC SUSTAINABILITY: EVALUATION OF NEARLY ZERO ENERGYRESIDENTIAL BUILDINGS DESIGN STRATEGIESIN JORDAN', Master Thesis, Jordan University of Science and Technology, 2019. [Online]. Available: https://www.academia.edu/74427640/THE_ECONOMIC_SUSTAINABILITY_EVALUATION_OF_NEARLY_ZERO_ENERGY_RESIDENTIAL_BUILDINGS_DESIGN_STRATEGIES_IN_JORDAN_THE_ECONOMIC_SUSTAINABILITY_EVALUATION_OF_NEARLY_ZERO_ENERGY_RESIDENTIAL_BUILDINGS_DESIGN_STRATEGIES_IN_JORDAN

[3] M. R. Asl, M. Bergin, A. Menter, and W. Yan, 'BIM-based Parametric Building Energy Performance Multi-Objective Optimization', presented at the eCAADe 2014: Fusion, Newcastle upon Tyne, UK, 2014, pp. 455–464. doi: 10.52842/conf.ecaade.2014.2.455.

[4] T. Han, Q. Huang, A. Zhang, and Q. Zhang, 'Simulation-Based Decision Support Tools in the Early Design Stages of a Green Building—A Review', *Sustainability*, vol. 10, no. 10, p. 3696, Oct. 2018, doi: 10.3390/su10103696.

[5] F. Jalaei and A. Jrade, 'INTEGRATING BUILDING INFORMATION MODELING (BIM) AND ENERGY ANALYSIS TOOLS WITH GREEN BUILDING CERTIFICATION SYSTEM TO CONCEPTUALLY DESIGN SUSTAINABLE BUILDINGS', Nov. 2014, [Online]. Available: https://www.itcon.org/paper/2014/29

[6] R. Ayman, Z. Alwan, and L. McIntyre, 'BIM for sustainable project delivery: review paper and future development areas', *Architectural Science Review*, vol. 63, no. 1, pp. 15–33, Jan. 2020, doi: 10.1080/00038628.2019.1669525.

[7] 'Front Matter', in *BIM Handbook*, Hoboken, New Jersey: John Wiley & Sons, Inc., 2018, pp. i–xxv. doi: 10.1002/9781119287568.fmatter.

[8] R. Lovreglio, P. Thompson, and Z. Feng, 'Automation in Fire Safety Engineering Using BIM and Generative Design', *Fire Technol*, vol. 58, no. 1, pp. 1–5, Jan. 2022, doi: 10.1007/s10694-021-01153-7.

[9] S. Alizadehsalehi, A. Hadavi, and J. C. Huang, 'From BIM to extended reality in AEC industry', *Automation in Construction*, vol. 116, p. 103254, Aug. 2020, doi: 10.1016/j.autcon.2020.103254.

[10] R. Volk, J. Stengel, and F. Schultmann, 'Building Information Modeling (BIM) for existing buildings — Literature review and future needs', *Automation in Construction*, vol. 38, pp. 109–127, Mar. 2014, doi: 10.1016/j.autcon.2013.10.023.

[11] A. Roth, 'BIM AUTOMATION: WHERE EFFICIENCY AND OPTIMIZATION CONVERGE', *Henderson Engineers*, p. 2, Jul. 08, 2021.

[12] L. Khemlani, 'Augmenta: Automated Building Design Using Generative AI', *AECbytes*, May 03, 2023. www.aecbytes.com/review/2023/Augmenta.html

[13] J. Růžička, J. Veselka, Z. Rudovský, S. Vitásek, and P. Hájek, 'BIM and Automation in Complex Building Assessment', *Sustainability*, vol. 14, no. 4, p. 2237, Feb. 2022, doi: 10.3390/su14042237.

[14] S. Y. Nof, Ed., *Springer Handbook of Automation*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009. doi: 10.1007/978-3-540-78831-7.

[15] Autodesk, *Practical Applications of Design Automation*. 2021. [Online]. Available: www.autodesk.com/solutions/design-automation

[16] C. Shan, 'BIM Automation: Why is it important and what tools exist?', *BIM Community*, Mar. 11, 2022. www.bimcommunity.com/technical/load/25676/bim-automation-why-is-it-important-and-what-tools-exist

[17] A. Andia, 'Automated Architecture: Why CAD, Parametrics and Fabrication are Really Old News', in *Proceedings of the XVII Conference of the Iberoamerican Society of Digital Graphics - SIGraDi: Knowledge-based Design*, Valparaiso, Chile: Editora Edgard Blücher, 2013, pp. 83–86. doi: 10.5151/despro-sigradi2013-0013.

[18] A. Brasil and A. Martinez, 'Potential for Social Housing Mass Customization in Brazil through the Integration between BIM and Algorithmic-Parametric Modeling', presented at the eCAADe 2022: Co-creating the Future - Inclusion in and through Design, Ghent, Belgium, 2022, pp. 347–356. doi: 10.52842/conf.ecaade.2022.2.347.

[19] F. Panella and A. Julia, 'Adoption of Generative Design in the Architecture Design Process', Tampere University of Applied Sciences, 2023. [Online]. Available: www.theseus.fi/bitstream/handle/10024/792337/Festino%20Panella_Ailin%20Julia.pdf?sequence=4&isAllowed=y

[20] A. Girardet and C. Boton, 'A parametric BIM approach to foster bridge project design and analysis', *Automation in Construction*, vol. 126, p. 103679, 2021, doi: 10.1016/j.autcon.2021.103679.

[21] Y. Sun, J. Wu, J. Fan, J. Wang, and X. Wang, 'Public-Private Partnership for affordable housing delivery in Ghana: Experience of the Ghana national housing project and policy implications', in *Proceeding of the 43rd Australasian Universities Building Education Association (AUBEA) Conference*, 2019, pp. 426–433.

[22] R. (Robert F. Woodbury, *Elements of parametric design*. Routledge, 2010. [Online]. Available: https://cir.nii.ac.jp/crid/1130282272949074176

[23] R. Woodbury, *Elements of parametric design*, vol. 1. 2010.

[24] P. Zardo, L. A. Ribeiro, and A. Q. Mussi, 'Bim and parametric design applications for buildings' energy efficiency: An analysis of practical applications', *Arquiteturarevista*, vol. 15, no. 2, pp. 238–255, 2019, doi: 10.4013/arq.2019.152.02.

[25] D. J. GERBER and S.-H. LIN, 'GEOMETRIC COMPLEXITY AND ENERGY SIMULATION', in *Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013),* Hong Kong, 2013, pp. 87–96.

[26] A. R. Felippe, R. W. da Fonseca, L. N. Moraes, and F. O. R. Pereira, 'Parametric modeling for the simulation of daylight and thermo-energetic performance of buildings', in *Blucher Design Proceedings*, 2015, pp. 398–404. Accessed: Aug. 08, 2023. [Online]. Available: https://www.proceedings.blucher.com.br/article-details/modelagem-paramtrica-para-simulao-do-desempenho-da-iluminao-natural-e-termo-energtico-da-edificao-22346

[27] A. R. Felippe, R. W. da Fonseca, L. N. Moraes, and F. O. R. Pereira, 'Parametric modeling for the simulation of daylight and thermo-energetic performance of buildings', no. 2009, pp. 398–404, 2015, doi: 10.5151/despro-sigradi2015-80289.

[28] W. Ma, X. Wang, J. Wang, X. Xiang, and J. Sun, 'Generative Design in Building Information Modelling (BIM): Approaches and Requirements', *Sensors*, vol. 21, no. 16, p. 5439, Aug. 2021, doi: 10.3390/s21165439.

[29] D. Popovic and J. Lindholm, 'APPLYING GENERATIVE DESIGN IN INDUSTRIALIZED HOUSE BUILDING ? – PREREQUISITES', in *2023 European Conference on Computing in Construction 40th International CIB W78 Conference Heraklion, Crete, Greece*, 2023.

[30] J. E. Harding and P. Shepherd, 'Meta-Parametric Design', *Design Studies*, vol. 52, pp. 73–95, Sep. 2017, doi: 10.1016/j.destud.2016.09.005.

[31] M. McKnight, 'Generative Design: What it is? How is it being used? Why it's a game changer', in *DesTech Conference Proceedings The International Conference on Design and Technology (2017)*, 2017, p. 176. doi: 10.18502/keg.v2i2.612.

[32] G. P. Monizza, E. Rauch, and D. T. Matt, 'Parametric and Generative Design Techniques for Mass-Customization in Building Industry: A Case Study for Glued-Laminated Timber', *Procedia CIRP*, vol. 60, pp. 392–397, 2017, doi: 10.1016/j.procir.2017.01.051.

[33] S. Macit İlal and H. M. Günaydın, 'Computer representation of building codes for automated compliance checking', *Automation in Construction*, vol. 82, no. May 2016, pp. 43–58, 2017, doi: 10.1016/j.autcon.2017.06.018.

[34] S. Zhang, J. Teizer, J.-K. Lee, C. M. Eastman, and M. Venugopal, 'Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules', *Automation in Construction*, vol. 29, pp. 183–195, Jan. 2013, doi: 10.1016/j.autcon.2012.05.006.

[35] C. Eastman, J. Lee, Y. Jeong, and J. Lee, 'Automatic rule-based checking of building designs', *Automation in Construction*, vol. 18, no. 8, pp. 1011–1033, Dec. 2009, doi: 10.1016/j.autcon.2009.07.002.

[36] L. Ding, R. Drogemuller, M. Rosenman, and D. Marchant, 'Automating code checking for building designs - DesignCheck', *Cooperative Research Centre (CRC) for Construction Innovation*, pp. 1–16, 2006.

[37] S. Zhang, J. Teizer, J. K. Lee, C. M. Eastman, and M. Venugopal, 'Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules', *Automation in Construction*, vol. 29, pp. 183–195, 2013, doi: 10.1016/j.autcon.2012.05.006.

[38] J. P. Carvalho, L. Bragança, and R. Mateus, 'Optimising building sustainability assessment using BIM', *Automation in Construction*, vol. 102, no. September 2018, pp. 170–182, 2019, doi: 10.1016/j.autcon.2019.02.021.

[39] B. Succar, 'Building information modelling framework: A research and delivery foundation for industry stakeholders', *Automation in Construction*, vol. 18, no. 3, pp. 357–375, 2009, doi: 10.1016/j.autcon.2008.10.003.

[40] T. Tan, G. Mills, E. Papadonikolaki, and Z. Liu, 'Combining multi-criteria decision making (MCDM) methods with building information modelling (BIM): A review', *Automation in Construction*, vol. 121, no. November 2020, p. 103451, 2021, doi: 10.1016/j.autcon.2020.103451.

[41] F. Bazzocchi, N. Banti, C. Biagini, C. Ciacci, and V. Di Naso, 'Design optioneering for the definition of technological solution of envelope using BIM', *Building Simulation Conference Proceedings*, pp. 1451–1458, 2022, doi: 10.26868/25222708.2021.30352.

[42] B. Abbasnejad, M. P. Nepal, A. Ahankoob, A. Nasirian, and R. Drogemuller, 'Building Information Modelling (BIM) adoption and implementation enablers in AEC firms: a systematic literature review', *Architectural Engineering and Design Management*, pp. 1–23, 2020, doi: 10.1080/17452007.2020.1793721.

[43] M. Demianenko and C. I. De Gaetani, 'A Procedure for Automating Energy Analyses in the BIM Context Exploiting Artificial Neural Networks and Transfer Learning Technique', *Energies*, vol. 14, no. 10, p. 2956, 2021, doi: 10.3390/en14102956.

[44] J. P. Carvalho, L. Bragança, and R. Mateus, 'Guidelines for analysing the building energy efficiency using BIM', in *IOP Conference Series: Earth and Environmental Science*, 2020, pp. 1–8. doi: 10.1088/1755-1315/588/2/022058.

[45] M. Z. Rahmani Asl, 'Towards BIM-based Parametric Building Energy Performance Optimization', in *ACADIA 13: Adaptive Architecture [Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA) ISBN 978-1-926724-22-5] Cambridge 24-26 October, 2013), pp. 101-108*, CUMINCAD, 2013. Accessed: Jun. 30, 2023. [Online]. Available: https://papers.cumincad.org/cgi-bin/works/paper/acadia13_101

[46] M. Rahmani Asl, M. Bergin, A. Menter, and W. Yan, 'BIM-based Parametric Building Energy Performance Multi-Objective Optimization', presented at the eCAADe 2014: Fusion, Newcastle upon Tyne, UK, 2014, pp. 455–464. doi: 10.52842/conf.ecaade.2014.2.455.

[47] B. Hardin and D. McCool, *BIM and Construction Management: Proven Tools, Methods, and Workflows*, Second Edtion. John Wiley & Sons, 2015. [Online]. Available: books.google.si/books?hl=en&lr=&id=1FB_BwAAQBAJ&oi=fnd&pg=PP18&ots=F9VX66yVdE&sig=6kE2vRuDmzHwY5xzpNwIE6BNkxQ&redir_esc=y#v=onepage&q&f=false

[48] G. Stegnar and T. Cerovšek, 'Information needs for progressive BIM methodology supporting the holistic energy renovation of office buildings', *Energy*, vol. 173, pp. 317–331, Apr. 2019, doi: 10.1016/j.energy.2019.02.087.

[49] K. Deepa, B. Suryarajan, V. Nagaraj, K. Srinath, and K. Vasanth, 'ENERGY ANALYSIS OF BUILDINGS', vol. 06, no. 01, 2019.

[50] S. Azhar and J. Brown, 'BIM for Sustainability Analyses', *International Journal of Construction Education and Research*, vol. 5, no. 4, pp. 276–292, Nov. 2009, doi: 10.1080/15578770903355657.

[51] G. Chaudhary, J. New, J. Sanyal, P. Im, Z. O'Neill, and V. Garg, 'Evaluation of "Autotune" calibration against manual calibration of building energy models', *Applied Energy*, vol. 182, pp. 115–134, Nov. 2016, doi: 10.1016/j.apenergy.2016.08.073.

[52] Z. Pezeshki, A. Soleimani, and A. Darabi, 'Application of BEM and using BIM database for BEM: A review', *Journal of Building Engineering*, vol. 23, pp. 1–17, May 2019, doi: 10.1016/j.jobe.2019.01.021.

[53] M. H. Elnabawi, ‘Building Information Modeling-Based Building Energy Modeling: Investigation of Interoperability and Simulation Results’, *Front. Built Environ.*, vol. 6, p. 573971, Dec. 2020, doi: 10.3389/fbuil.2020.573971.

[54] E. Kamel and A. M. Memari, ‘Review of BIM’s application in energy simulation: Tools, issues, and solutions’, *Automation in Construction*, vol. 97, pp. 164–180, Jan. 2019, doi: 10.1016/j.autcon.2018.11.008.

[55] T. Maile, M. Fischer, and V. Bazjanac, ‘Building Energy Performance Simulation Tools - a Life-Cycle and Interoperable Perspective’, Stanford University, 2007.

[56] A. S. Solmaz, ‘A CRITICAL REVIEW ON BUILDING PERFORMANCE SIMULATION TOOLS’, vol. 12, no. 2, 2019.

[57] T. J. Reeves, S. Olbina, and R. R. A. Issa, ‘Guidelines for Using Building Information Modeling (BIM) for Environmental Analysis of High-Performance Buildings’, in *Computing in Civil Engineering (2012)*, Clearwater Beach, Florida, United States: American Society of Civil Engineers, Jun. 2012, pp. 277–284. doi: 10.1061/9780784412343.0035.

[58] B. Dong, K. P. Lam, and Y. C. Huang, ‘A comparative study of the IFC and gbXML informational infrastructures for data exchange in computational design support environments’, *Building Simulation*, 2007.

[59] M. K. Najjar, V. W. Y. Tam, L. T. Di Gregorio, A. C. J. Evangelista, A. W. A. Hammad, and A. Haddad, ‘Integrating Parametric Analysis with Building Information Modeling to Improve Energy Performance of Construction Projects’, *Energies*, vol. 12, no. 8, p. 1515, Jan. 2019, doi: 10.3390/en12081515.

[60] S. Boeykens and H. Neuckermans, ‘Content Management Systems Versus Learning Environments’, presented at the CAADRIA 2009: Between Man and Machine? Integration, Intuition, Intelligence, Yunlin, Taiwan, 2009, pp. 285–294. doi: 10.52842/conf.caadria.2009.285.

[61] L. Zhao, W. Zhang, and W. Wang, ‘BIM-Based Multi-Objective Optimization of Low-Carbon and Energy-Saving Buildings’, *Sustainability*, vol. 14, no. 20, p. 13064, Oct. 2022, doi: 10.3390/su142013064.

[62] F. Goia, ‘Search for the optimal window-to-wall ratio in office buildings in different European climates and the implications on total energy saving potential’, *Solar Energy*, vol. 132, pp. 467–492, Jul. 2016, doi: 10.1016/j.solener.2016.03.031.