# PARAMETRIC ANALYSIS OF BIM-BASED BUILDING ENERGY PERFORMANCE FOR SUPPORTING MULTI-OBJECTIVE OPTIMIZATION

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# PARAMETRIC ANALYSIS OF BIM-BASED BUILDING ENERGY PERFORMANCE FOR SUPPORTING MULTI-OBJECTIVE OPTIMIZATION

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# ABSTRACT

## PARAMETRIC ANALYSIS OF BIM-BASED BUILDING ENERGY PERFORMANCE FOR SUPPORTING MULTI-OBJECTIVE OPTIMIZATION

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Building energy efficiency comes into prominence as buildings constitute a significant portion of world energy consumption and $CO_2$ emissions. To achieve energy-efficient buildings, energy performance assessments should be conducted meticulously, yet it is difficult to comprehensively estimate the buildings' energy consumption since energy performance assessments are complex multi-criteria problems that are affected by many factors such as building orientation, envelope design, climatic conditions, daylight levels, and HVAC system usage. Building Information Modeling (BIM) is frequently used in building energy analysis, as in many areas of the construction industry. BIM has the ability to both predict energy performance and provide the data needed to optimize the energy usage of buildings through changing design parameters that affect energy use. This study aims to analyze parameters that are affecting energy performance of a multi-storey residential building through BIM-based energy performance calculation, thus meeting the demand in literature for a comprehensive evaluation of majority of parameters comparatively. In this study, energy analysis is performed for each factor affecting building energy performance by keeping all other parameters constant, and then an evaluation of these parameters that will support optimization of the building energy performance is carried out. As a result, an understanding of the parameters that have the most significant impact on the energy performance of the building is achieved by using sensitivity analysis. Based on this analysis, it has been identified that the roof and wall insulation material thicknesses, building shape, and window material are the most effective parameters, respectively.

Keywords: Building Energy Performance, Building Information Modeling, Energy Analysis, Energy Optimization, BIM

# ÖZ

## ÇOK AMAÇLI OPTİMİZASYONU DESTEKLEMEK İÇİN BIM TABANLI BİNA ENERJİ PERFORMANSININ PARAMETRİK ANALİZİ

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Dünya enerji tüketimi ve $CO_2$ emisyonunun büyük bir bölümünü binalar oluşturduğu için binalardaki enerji verimliliği önem kazanmaktadır. Enerji verimli binalar elde etmek için enerji performans değerlendirmeleri titizlikle yapılmalıdır, ancak enerji performans değerlendirmeleri bina yönelimi, zarf tasarımı, iklim koşulları, gün ışığı seviyeleri ve HVAC sistemi kullanımı gibi birçok faktörden etkilenen karmaşık çok kriterli problemler olduğundan binanın enerji tüketimini kapsamlı bir şekilde tahmin etmek zordur. Yapı Bilgi Modellemesi (YBM), inşaat sektörünün birçok alanında olduğu gibi bina enerji analizlerinde de sıklıkla kullanılmaktadır. YBM, hem enerji performansını tahmin edebilmekte hem de enerji kullanımını etkileyen parametreleri değiştirerek binaların enerji kullanımını optimize etmek için gereken verileri sağlayabilmektedir. Bu çalışma, çok katlı bir konut binasının enerji performansını etkileyen parametreleri BIM tabanlı enerji performans hesaplaması yoluyla analiz etmeyi amaçlamaktadır ve böylelikle literatürdeki parametrelerin büyük bölümünün karşılaştırmalı olarak değelerndirilmesine olan ihtiyacı karşılamayı hedeflemektedir. Bu çalışmada, bina enerji performansını etkileyen her bir faktör için diğer tüm parametreler sabit tutularak enerji analizi yapılmış ve ardından bu parametrelerin bina enerji performansının optimizasyonunu destekleyecek bir değerlendirmesi yapılmıştır. Sonuç olarak, duyarlılık analizi kullanılarak bina enerji performansı üzerinde en önemli etkiye sahip olan parametrelerin anlaşılması sağlanmıştır. Bu analize dayalı olarak, sırasıyla çatı ve duvar yalıtım malzemesi kalınlıklarının, bina şeklinin ve pencere malzemesinin en etkili parametreler olduğu tespit edilmiştir.

Anahtar Kelimeler: Bina Enerji Performansı, Yapı Bilgi Modellemesi, Enerji Analizi, Bina Enerji Optimizasyonu, BIM

Dedicated to my beloved family…

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ABBREVIATIONS

| | |
|---|---|
| AAC | Aerated Autoclaved Concrete |
| AEC | Architecture, Engineering and Construction |
| ANN | Artificial Neural Network |
| ASHRAE | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| B.E.S.T | Ecological and Sustainable Design in Buildings |
| BEM | Building Energy Modeling |
| BIM | Building Information Modeling |
| BREEAM | British Research Establishment Environmental Assessment Method |
| ÇEDBİK | Turkish Green Building Council |
| EPS | Expanded Polystyrene |
| EUI | Energy Use Intensity |
| GA | Genetic Algorithm |
| GBCSs | Green Building Certification Systems |
| HVAC | Heating, Ventilating and Air Conditioning |
| IEA | International Energy Agency |
| IFC | Industry Foundation Classes |
| LEED | Leadership in Energy and Environmental Design |
| MOGA | Multi-Objective Genetic Algorithm |
| MOPSO | Multi-Objective Particle Swarm Optimization |
| NSGA-II | Non-dominated Sorted Genetic Algorithm |
| NURBS | Non-Uniform Rational B-Splines |
| SA | Sensitivity Analysis |
| SHGC | Solar Heat Gain Coefficient |
| USGBC | U.S. Green Building Council |
| VT | Visible Transmittance |
| WWR | Window to Wall Ratio |
| XPS | Extruded Polystyrene |

# CHAPTER 1

# INTRODUCTION

Energy, which means the ability to do work, forms the basis of human life, and it is an essential factor in all areas of life from the execution of vital activities to heating, transportation, the operation of factories. While the energy necessary for the continuation of human life is provided by food, the energy need for production in factories is met through resources such as electricity or fossil fuels. Population growth, urbanization, economic and technological developments lead to a rapid increase in energy demand on a global basis. As it can be seen in Figure 1.1, which is created according to the data received from the International Energy Agency (IEA), the rate of increase in the world's energy consumption has accelerated over the years between 1990 and 2019 (IEA, 2021a).

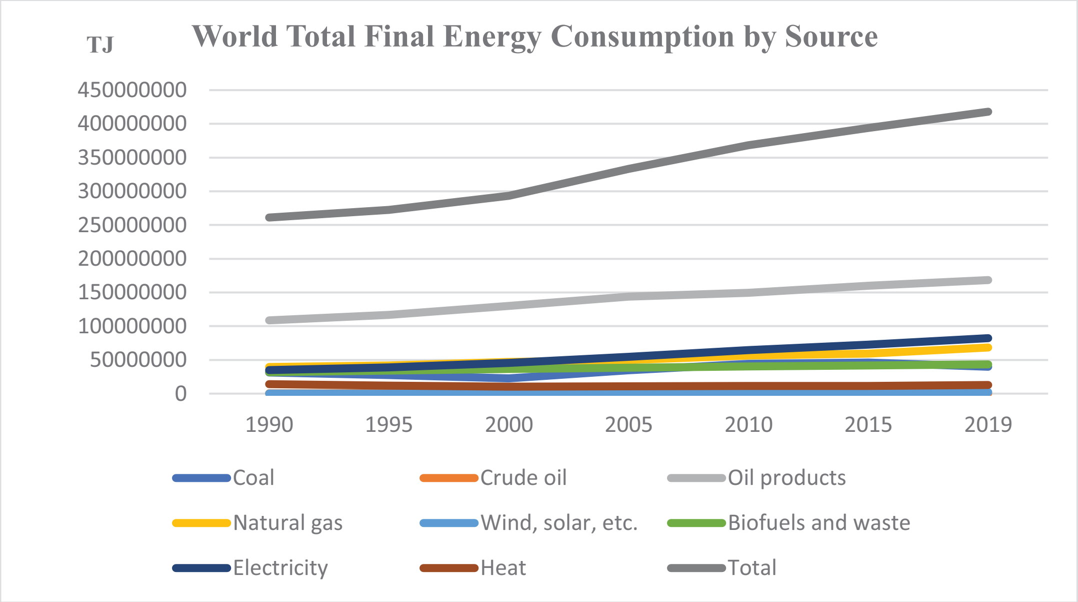


Figure 1.1. World Total Final Energy Consumption by Source 1990-2019 (IEA,2021a)

Energy is classified under two main headings as renewable and non-renewable according to the type of resource. Renewable energy, often called as clean energy, is derived from natural resources or processes that are constantly regenerated. The renewable energy sources renew themselves at the same rate as the energy drawn from the source or quicker than the source's depletion rate. Examples of renewable energy sources can be listed as solar, hydro, wind, geothermal, tide, wave, biofuels, and the renewable fraction of municipal waste. On the other hand, non-renewable energy sources, including fossils (hydrocarbon-based energies such as coal, natural gas, and oil) and nuclear energy, are depleted because they can renew themselves much slower than the depletion rate of the source. Table 1.1 is generated using IEA data to show the percentage distribution of resources that meet this energy need. It is seen that around 85% of the world's energy is supplied by non-renewable energy sources, and fossil fuel sources meet approximately 80% of the world's energy consumption. Besides the high cost and limited amount of fossil fuel resources, they cause serious damage to the world due to the greenhouse gas emissions they generate (Ellabban et al., 2014). This ever-increasing need for energy has led to a potential energy crisis, as well as serious environmental problems that endanger people's health and property, such as global warming and air pollution due to emissions (Lu & Lai, 2019). In the current situation, based on the use of conventional non-renewable energy sources, is not a long-term sustainable option. Thus, it is crucial to use existing energy resources most efficiently and turn to renewable energy resources to reduce the damage to the world and the survival of future generations.

Table 1.1 shows that the shares of renewable energy resources have increased over the years, but their percentages have reached only around 14% in total. The unfavorable part of renewable energy is that it depends on nature; although it is available worldwide, most of these resources are not available continuously throughout the year. For example, if the wind is insufficient, the wind turbines will not work and will not produce energy. Likewise, some days are cloudier than others, and droughts can occur from time to time. These changing weather events and climate may prevent the desired yield. Fossil fuels are not discrete and can be and climate may prevent the desired yield. Fossil fuels are not discrete and can be accessed and used at any time. Therefore, in addition to reducing the environmental impact by trying to obtain the world's energy from cleaner sources, its main focus is to increase energy efficiency because it is an indisputable fact that energy needs will increase day by day. Improving existing systems is one of the most significant steps to be taken in this way. Thus, it would be a good starting point to examine energy consumption on a sectoral basis, as can be seen in Figure 1.2.

Table 1.1 World Total Energy Supply by Source (IEA, 2021b)

| **Years** | **Non-renewable** | | | | | **Renewable** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Coal % | Natural gas % | Nuclear % | Oil % | Total % | Hydro % | Wind, solar etc. % | Biofuels and waste % | Total % |
| 1990 | 25.41 | 19.03 | 6.01 | 36.99 | 87.45 | 2.11 | 0.42 | 10.03 | 12.55 |
| 1995 | 24.02 | 19.63 | 6.62 | 36.70 | 86.97 | 2.32 | 0.46 | 10.25 | 13.03 |
| 2000 | 23.14 | 20.67 | 6.75 | 36.68 | 87.24 | 2.25 | 0.60 | 9.91 | 12.76 |
| 2005 | 26.08 | 20.54 | 6.29 | 34.98 | 87.89 | 2.20 | 0.61 | 9.30 | 12.11 |
| 2010 | 28.52 | 21.34 | 5.61 | 32.20 | 87.67 | 2.31 | 0.86 | 9.16 | 12.33 |
| 2015 | 28.33 | 21.56 | 4.94 | 31.90 | 86.74 | 2.47 | 1.50 | 9.30 | 13.26 |
| 2019 | 26.78 | 23.22 | 5.02 | 30.90 | 85.91 | 2.51 | 2.21 | 9.37 | 14.09 |

Figure 1.2 shows the world's total final energy consumption by sector; it can be said that the leading sectors are industry, transportation, and residential, respectively. As industry and commercial and public services are also located within a building, this energy consumption should be examined separately as the construction industry, which includes the construction phase and operation of the residential and non-residential buildings. Figure 1.3 shows the global share of buildings and construction industry final energy and emissions. It is seen that the construction industry has a significant share of final energy usage. Furthermore, considering the final energy usage and the sum of direct and indirect emissions from all components of the sector, the construction sector's leading position is a significant measure of the environmental damage it causes.

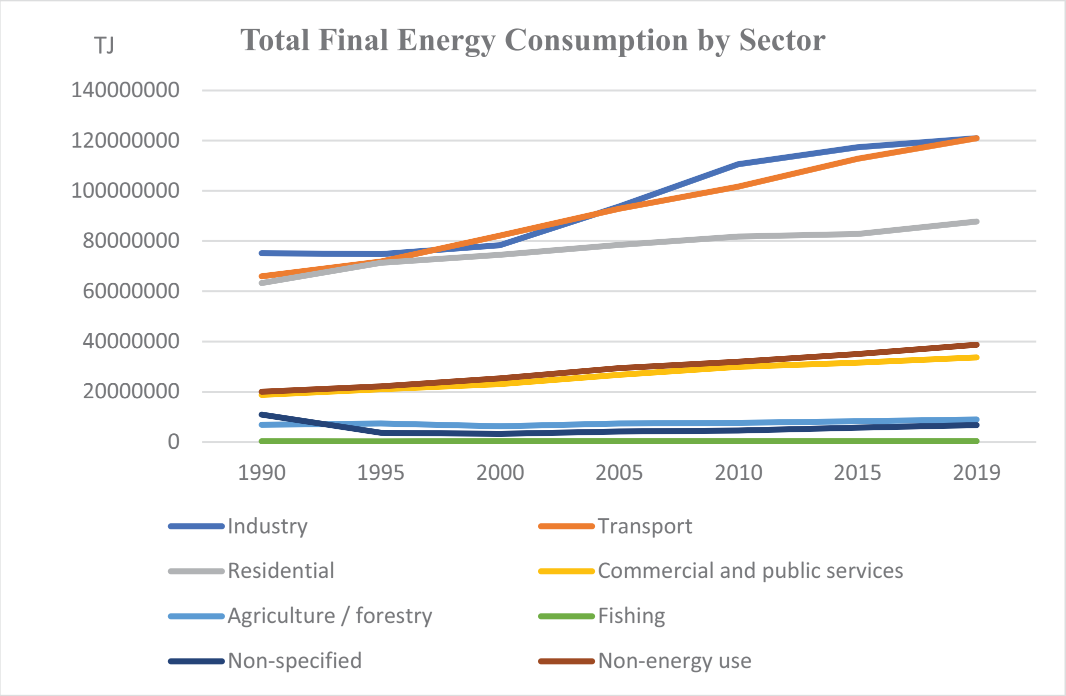


Figure 1.2. Total Final Energy Consumption by Sector (IEA, 2021c)

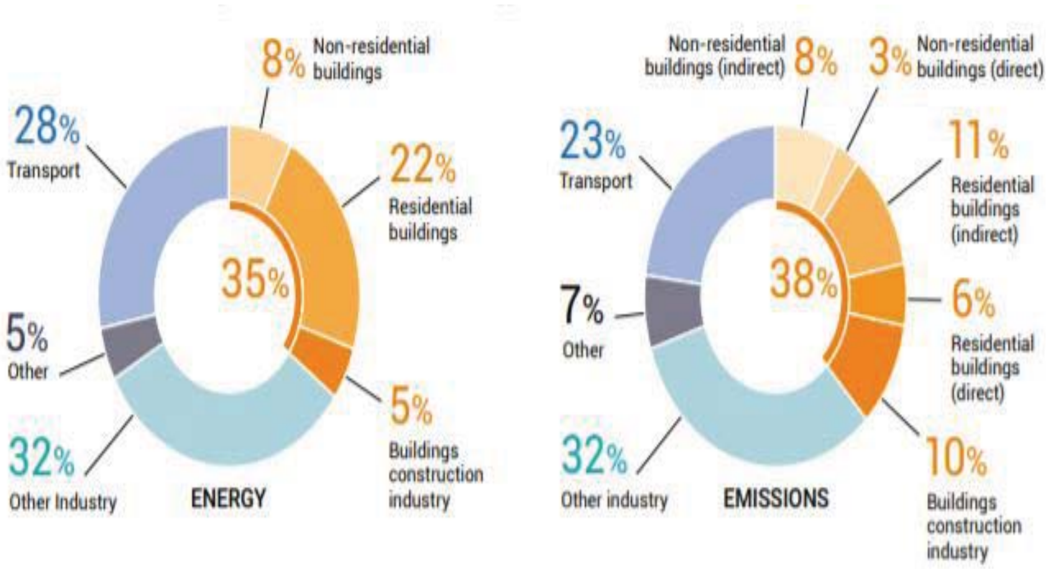
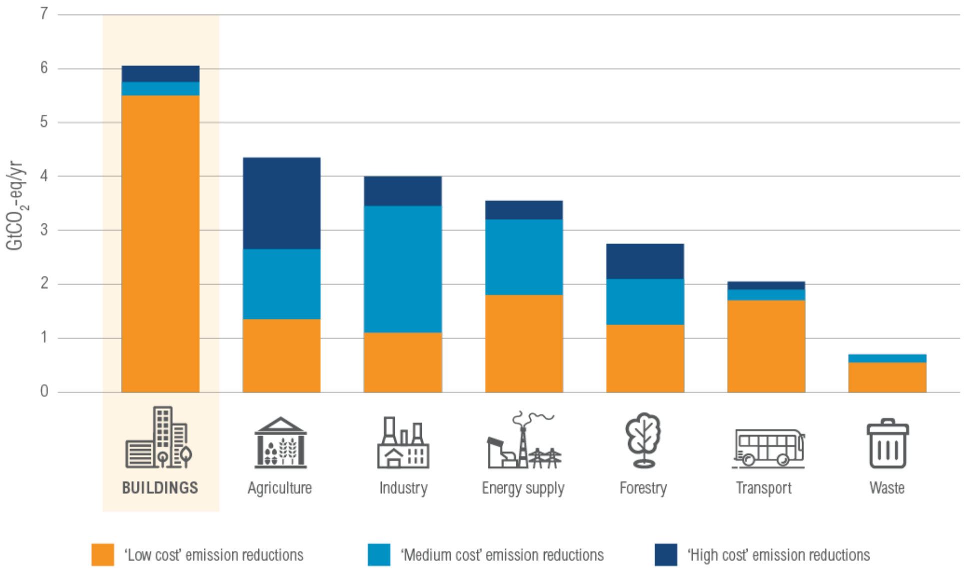


Figure 1.3. Global Share of Buildings and Construction Final Energy and Emissions (United Nations Environment Programme, 2020)

According to Global Status Report for Buildings and Construction 2019 report, building construction and operations had the largest share of both global final energy use (36%) and energy-related $CO_2$ emissions (39%) in 2018 (IEA, 2019). In the 2020 report, which is prepared by United Nations Environment Programme (United Nations Environment Programme, 2020), the construction industry retained its leading position in 2019 with the same energy consumption level as 2018. On the other hand, building emission of 38% in 2019 was slightly lower than in 2018, compared to 39%, due to increases in transport and other industrial emissions relative to buildings. In brief, the construction industry accounts for more than a third of all primary energy consumption and greenhouse gas emissions worldwide.

On the other hand, efficiency improvements in buildings generally have no or low marginal cost, or they cover the cost with a return on investment in the form of energy cost savings in as little as six months to 1 year (Mackres, 2016). As it can be seen in Figure 1.4, which shows the costs of emissions-saving investments on a sectoral basis, the investment cost required for unit emissions reduction in the construction industry is very low when compared to other sectors such as agriculture or transportation, where comparatively more expensive investments are required for similar emission reductions or much fewer emission reductions are achieved with the same investment amount.

The negative environmental effects of the construction industry, as well as the costs of emissions-saving investments, have raised the issue of increasing building energy efficiency. Building energy efficiency refers to reducing energy consumption and minimizing energy loss. In order to obtain energy-efficient buildings, the amount of energy consumption must first be calculated since it is not possible to make improvements without measuring the current situation. Thus, the determination of building energy usage has a crucial role in improving energy performance to reduce energy use and environmental impacts.



*Note:* 'Low cost' emission reductions = carbon price <20 US$/tCO$_2$-eq. 'Medium cost' emission reductions = carbon price <50 US$/tCO$^2$-eq.
'High cost' emission reductions = carbon price <100 US$/tCO$_2$-eq.
*Source:* IPCC. 2007. IPCC Fourth Assessment Report: Climate Change 2007: Synthesis Report. "4.3 Mitigation options." https://www.ipcc.ch/publications_and_data/ar4/syr/en/mains4-3.html

Figure 1.4. Costs of Emissions-Saving Investments on Sectoral Basis (Mackres, 2016)

## 1.1 Building Energy Performance Assessment

Buildings need energy at every stage of their life cycle. Although this usage amount varies according to building usage purposes (office, residential, etc.), energy used in the operation and maintenance phase can account for 80-90% of the total energy (Ramesh et al., 2010). This situation is related to a relatively long life of the operational phase compared to other phases. The energy used in the operation and maintenance phase, also called operational energy, refers to the energy needed by a building during its entire service life, including lighting, heating, cooling, and ventilation systems, and building appliances (Tuladhar & Yin, 2019). These energy consumptions are essential for the indoor environment to be comfortable and livable. Although the basic needs of energy use in buildings are almost the same, their amount of consumption varies significantly between buildings or periodically in the same building because many factors have an impact on it, such as building type, building size (surface, opening), building orientation, HVAC (heating, ventilating, and air-conditioning) system type and its operating characteristics, building construction details (including the thermal properties of all construction elements like walls, floors, roofs, ceilings, windows, doors, shading devices), building usage (functional use), weather conditions as well as the behavior patterns of the residents (Egwunatum et al., 2016; Moon et al., 2011).

Building energy performance refers to how efficiently a building consumes energy to perform its functions. Building energy performance analysis is used to evaluate the building's energy usage profile and energy consumption cost in order to quantify performance. Building energy systems are quite complex and comprise some contextual analyses such as solar and thermal energy, daylighting, ventilation, building massing, site orientation, and HVAC systems (U.S. General Service Administration, 2009). Therefore, it is necessary to model the building energy analysis in detail in the early design process. Since building energy performance depends on several factors and requires multiple analyses, its assessment is a time-consuming and complicated process; it is also hard to predict consumption amount accurately. Some technical advancements, such as building information modeling, are used to improve this challenging process.

## 1.2 Building Information Modeling (BIM)

Building Information Modeling, or BIM, has recently gained widespread acceptance in the architecture, engineering and construction (AEC) industry, and its usage is increasing day by day. BIM is considered as the most promising development in the construction industry (Azhar, 2011). BIM is the generation and management of digital representations of the physical and functional characteristics of a facility. It serves as a shared source of information for collaboration throughout the life cycle of a facility and provides a reliable basis for decisions from initial design to demolition (Sacks et al., 2018). The key feature of BIM is that it provides an environment that enables the collaboration of different parties involved in the project at different stages of a facility throughout its lifecycle to play with information in BIM by adding, removing, updating, or modifying it to support and reflect the roles of stakeholders (Sacks et al., 2018). All 3D models in the computer environment are not BIM models. To define a model as a BIM, it should be data-rich, object-oriented, intelligent, and it should parametrically represent the facility. In other words, BIM models are made up of objects rather than just lines, and these objects have the capability to store information, which makes them intelligent. BIM is based on parametric design, which provides great time and resource savings compared to classical design methods. When a change needs to be made in traditional design, it is necessary to go back to the beginning and remodel it all over again. However, when similar problems arise in parametric modeling, the process works differently. As appropriate adjustments are made, all other parameters that are influenced by the change are automatically updated, and this change is reflected in the final design simultaneously since all objects are modeled by defining their relations with each other parametrically. For example, if you change the dimension of any object in one view, it is automatically updating the other views according to it.

BIM is widely utilized in the construction industry. Individuals, companies, and government agencies involved in all stages of the building lifecycle use BIM in the different types of physical infrastructures, like highways, railways, communication services. In international construction projects, BIM technology has become a world standard. Contractors and designers must use BIM in contracts for building projects in countries like the United Kingdom, the United States, Norway, Finland, and Singapore (Smith, 2014). Other countries have also started to emphasize the BIM requirement by supporting the industry with various BIM solutions. In Turkey, individuals and companies have been widely using BIM; and government agencies have started to impose some obligations on the use of BIM for efficiency in information management areas. Turkey Ministry of Transportation and Infrastructure has prepared a 'BIM Technical Specifications and Tender Documents' to be used in the tenders for the construction works of transportation projects, and the obligation to apply these documents in construction tenders was imposed (TC Ulaştırma ve Altyapı Bakanlığı, 2021).

BIM has been adapted to almost every application in the construction industry and serves many different purposes. It is widely used for design coordination and visualization as it provides more precise representations of the facility even if in the early design processes, which also allows construction coordination, like clash detection, which helps analyze the constructability of the facility. The generation of automatic design documentation is a remarkable feature of BIM. It produces accurate and consistent 2D drawings at any stage of the design that can be used for construction management, quantity take-off, and scheduling purposes. Furthermore, the most striking feature of BIM is that it allows the collaboration of multiple disciplines, which makes it possible to work on what-if scenarios to get the best design option. In addition, BIM-based software is compatible with data exchange formats like IFC (Industry Foundation Classes), which provides the exchange of information between different programs without data loss. This feature can be considered as life-saving in building energy modeling applications because building energy performance evaluation includes multiple different analyzes and requires different disciplines to work together, as mentioned in the previous section. Considering all of these factors, it is reasonable to conclude that BIM is an excellent setting in which to conduct these analyses. Furthermore, BIM helps to solve the drawbacks of traditional building energy modeling, such as the tedious model preparation process, model inconsistency, and costly implementation (Gao, Zhang, et al., 2019).

## 1.3 BIM-based Building Energy Performance Estimation

The building energy modeling process consists of multi-participants, which is aided by various software solutions. This technical and social complexity necessitates the deployment of collaborative conversation management with users of software solutions or process participants, in addition to more extensive system coordination and communication (Maskil-Leitan & Reychav, 2019). In such projects, using BIM facilitates stakeholder management by creating collaborative working platforms to transfer and process information.

Conventional building energy modeling has some drawbacks, such as time-consuming model preparation, model inconsistencies, and high implementation costs (Gao, Koch, et al., 2019). BIM allows to overcome these limitations, and also it promotes building energy modeling as part of the digital building design process. While BIM enables performance evaluation at the early stages of construction, such as location, orientation, material properties, and glazing ratio, BEM (Building Energy Modeling) software tools allows building performance professionally at later stages (Elnabawi, 2020). As a result of linking the two models, the work and time spent developing model geometry may be reduced (Elnabawi, 2020). Moreover, BIM enables designers to improve the sustainability of buildings by comparing the energy savings resulting from the execution of various design scenarios, starting at the early design phases and with fewer resources (Carvalho et al., 2019). Another remarkable benefits of the usage of BIM in energy analysis are that it makes data entry into energy analysis more efficient and that existing data can be reused more. Additionally, BIM enables the use of dynamic thermal simulation instead of traditionally used static calculation methods, as well as the use of whole-building spatial simulation rather than the conventional zone-based approach (Laine et al., 2007).

## 1.4 Aim and Objectives

The aim of this study is to determine and analyze parameters that are affecting energy performance of a multi-storey residential building through BIM-based energy performance calculation. In addition, it has been seen that the studies in the literature mainly focus on several parameters at the same time, however a comprehensive evaluation of majority of parameters comparatively is needed in order to support multi-objective optimization of building energy performance.

Therefore, this study attempts to address this demand. The main objectives of this study are listed below:

- To determine the parameters affecting the building energy performance through a literature review,
- To evaluate these parameters that will support optimization of the building energy performance,
- To determine the parameters which have the most significant impact on the energy performance of the buildings by using the sensitivity analysis.

## 1.5 Disposition

The study is composed of five chapters:

The first chapter introduces the basic concepts of the study, building energy analysis and building energy performance estimation as well as the aim, objectives, disposition of the study.

The second chapter is a literature review to determine the main parameters that affect the building energy performance and methods used for optimization.

The third chapter explains the methodology that is used for this study. It is composed of building energy simulation and sensitivity analysis for the determination of the most effective parameters.

The fourth chapter includes the result of the assessment studies and the interpretation of the results.

The fifth chapter concludes the study.

# CHAPTER 2

# LITERATURE REVIEW

In this chapter, the literature is reviewed to identify the parameters affecting the building energy performance and optimization methods used for optimizing the building energy consumption. The information obtained from the literature has been gathered under two main headings: parameters affecting the building energy performance and multi-objective optimization methods in building energy performance assessment. In the first part, Green Building Certification Systems and their criteria are presented as well as the academic studies conducted in this area were examined to determine the parameters that have an impact on building energy consumption. In the second part, commonly used optimization techniques in the studies are investigated.

To reach the related materials such as standards or technical manuals, as well as journals, conference papers, and thesis, the initial search was conducted using Google Scholar and Google search engine. During the research process, the METU online library was used as it provides free access to resources in several databases. Then, advanced search options were used in Scopus, Web of Science databases by using keyword combinations in the following tables, and searches were carried out for resources published until January 2022.

In Table 2.1, the studies obtained from search results related to Green Building Certification Systems are listed. After the examination of the review articles on Green Building Certificates, it is seen that LEED (Leadership in Energy and Environmental Design) and BREEAM (British Research Establishment Environmental Assessment Method) are among the most widely used certificates in the world. As this study was carried out in Turkey, the country's unique building certification system, B.E.S.T (Ecological and Sustainable Design in Buildings), has been incorporated. After determining these certifications, the year type and language were set to "all" and the relevant keywords searched in the title, abstract and keywords of the paper. As a result of these searches, the results in Table 2.1 were obtained in the relevant databases.

Table 2.1 Literature Review for Green Building Certification Systems

| Keyword | *Document Type* | *Number of Studies in Scopus* | *Number of Studies in Web of Science* |
|---|---|---|---|
| Green Building Certification Systems | review | 38 | 20 |
| Leadership in Energy and Environmental Design | all | 555 | 569 |
| BREEAM | all | 516 | 328 |
| B.E.S.T- Residential Certificate | all | 0 | 0 |

Table 2.2 presents the searching results of the literature review for obtaining parameters. To get the results in the table; year, document type, and language were set to "all", and keywords were searched between article title, abstract, and keywords. First, searches were conducted using keyword groups of building energy optimization and building energy performance parameters. After reviewing the related studies that emerged as a result of these, the most repetitive parameters were identified. Factors that affect indoor environmental comfort or consume energy for purposes other than heating - such as refrigerators, televisions, etc.- are not taken into consideration in this study since it only considers the thermal part of the building's energy usage. Considering all these circumstances, searches were conducted using the other keyword combinations in Table 2.2 to reach more related studies.

Table 2.2 Literature Review for Parameters

| Keyword | *Number of Studies in Scopus* | *Number of Studies in Web of Science* |
|---|---|---|
| Building energy optimization | 15246 | 11666 |
| Building energy performance parameters | 7263 | 63 |
| Building Energy and location | 7585 | 5858 |
| Building energy and building shape | 4826 | 6253 |
| Building energy and building form | 10452 | 13408 |
| Building energy and building orientation | 3533 | 3004 |
| Building energy and building insulation | 9314 | 5318 |
| Building energy and wall | 13151 | 8712 |
| Building energy and window | 7656 | 5314 |
| Building energy and HVAC | 6617 | 3567 |
| Building energy and building envelope | 8660 | 5713 |
| Building energy and floor | 5982 | 3474 |
| Building energy and basement | 625 | 217 |
| Building energy and ground floor | 727 | 419 |
| Building energy and interior floor | 313 | 174 |
| Building energy and ceiling | 1583 | 876 |
| Building energy and roof | 6896 | 4106 |
| Building energy and surrounding | 2676 | 2538 |
| Building energy and shading | 3029 | 2125 |

To obtain Table 2.3, which displays the literature review for optimization methods, the year and document type were set to "all" the language to "English," and the search was done within the article title, abstract, and keywords during the research process.

Table 2.3 Literature Review for Optimization Methods

| Keyword | *Number of Studies in Scopus* | *Number of Studies in Web of Science* |
|---|---|---|
| Building energy performance and BIM | 754 | 605 |
| BIM-based energy performance assessments | 54 | 45 |
| Parametric analysis tools and building energy performance | 222 | 88 |
| Building energy optimization algorithms | 3842 | 3053 |
| Building energy optimization genetic algorithms | 1175 | 892 |
| Building energy optimization and NSGA-II | 162 | 138 |
| Building energy optimization and hybrid algorithms | 487 | 329 |
| Building energy optimization and direct search algorithms | 24 | 21 |
| Building energy optimization and pattern search algorithms | 42 | 18 |

Several documents, both related and unrelated to the selected topic, were obtained as a consequence of these searches, and some studies were repeated as a result of different keyword combinations. A pre-screening was carried out to exclude publications covering unrelated topics. After reaching an article highly relevant to the thesis subject, a retrospective literature search is done. Furthermore, a citation index search is performed that allows for the acquisition of more recent publications that are later criticized. In the following sections, these publications are presented under the relevant headings.

## 2.1 Parameters Affecting Building Energy Performance

Building energy performance evaluation includes several complex analyses. To obtain a high-performance building, one of the important aspects is generally solar energy assessment. Solar energy can be utilized in two ways: passive solar design and active solar systems.

Passive solar design, which has been used in building design for hundreds of years all over the world, uses solar energy for heating and cooling and works independently from external devices. It aims to optimize the design, placement, or materials for the use of heat or light directly from the sun. In winters, the temperature of the sun is used to heat a house, and in summers, it is tried to minimize the solar heat while taking advantage of natural evening ventilation for cooling. The passive design focuses primarily on the location of the building and site conditions such as the sun path during winter or summer, and the design specifics are shaped accordingly. Then, building's form (high and narrow, square or spherical), orientation (north-south or east-west), placement of windows, and ventilation strategy are respectively decided. On the other hand, active systems include devices that convert solar energy into a more useful form like hot water or electricity. The selection and placement of these devices are an important part of the active system. For example, if it is desired to generate electricity with photovoltaic panels, the panels should be placed on the roof to get more sunlight and generate more energy.

To determine the parameters which affect the building energy performance, Green Building Assessment Systems like LEED, BREEAM are analyzed, and then the academic studies conducted in this area were examined.

### 2.1.1 Green Building Certification Systems

Green Building Certification Systems (GBCSs) have been developed to promote sustainability in the construction industry. GBCSs aim to evaluate the building's performance and its environmental impact. They have a predefined set of criteria relating to the design, construction, and operations of the buildings. The building can be certified if it satisfies these requirements. When a building receives a certificate, it is understood that it uses less energy and water, avoids waste, saves maintenance costs, improves the indoor air quality, offers comfort to its occupants, and causes less environmental impacts.

The number of these certificates is increasing day by day; each country is trying to create its own certification system that is suitable for its own conditions. The British Research Establishment Environmental Assessment Method (BREEAM), the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) are the most widely used in the construction industry. In Turkey, ÇEDBİK (Turkey Green Building Council) developed the B.E.S.T (Ecological and Sustainable Design in Buildings) Residential Certification system for new residential projects.

In the following sections, general information about the aforementioned certification system will be given, and criteria compatible with this study will be included.

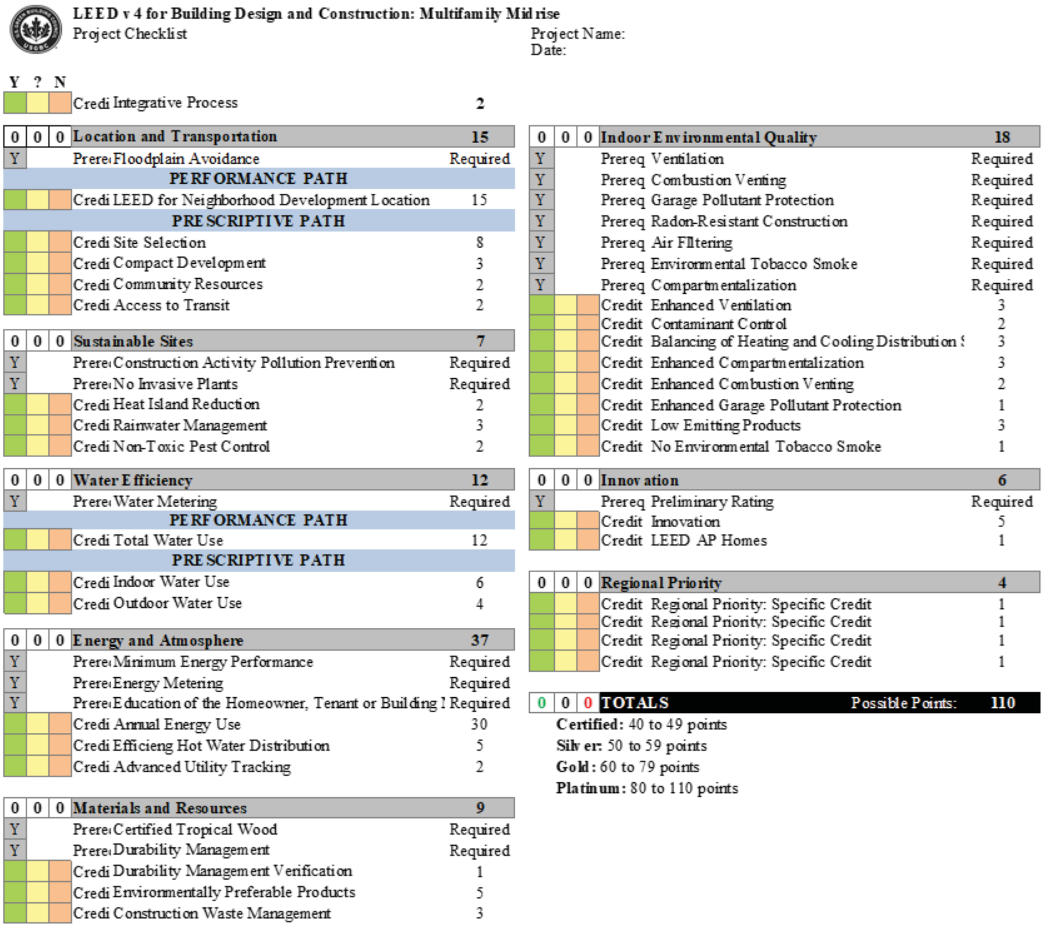
#### 2.1.1.1 LEED (Leadership in Energy and Environmental Design)

The USGBC created the LEED certification system in 1998 with the aim of improving the construction industry in terms of sustainability. It aims to improve a building's environmental performance in areas of energy savings, water efficiency, and $CO_2$ emissions reduction. LEED offers different rating systems for different building types and all building phases including design, construction, operation and maintenance of the buildings and the neighborhoods.

The criteria are expressed according to the related rating system, and each has a score. The structure reaches a certain point according to the conditions it presents and is eligible to obtain the certificate that corresponds to that score. LEED offers levels of certification as Certified (40–49 points), Silver (50–59 points), Gold (60–

79 points), Platinum (80+ points). Criteria required for new building design and construction are listed below since this study is interested in the design of a new building.

As it can be seen in Figure 2.1, Annual Energy Use under the Energy and Atmosphere has the largest share of all possible points. It requires to upload a set of documents such as minimum energy performance calculator, mechanical plan, and mechanical/plumbing schedule(s), energy model summary reports for the proposed and baseline 0-degree buildings (*Minimum energy performance calculator - ASHRAE 90.1 – 2010,* 2016).



**LEED v 4 for Building Design and Construction: Multifamily Midrise**
Project Checklist

Project Name:
Date:

| Y | ? | N |  |  |  |
|---|---|---|---|---|---|
| 🟩 | 🟨 | 🟧 | Credi | Integrative Process | **2** |
| **0** | **0** | **0** |  | **Location and Transportation** | **15** |
| Y |  |  | Prere | Floodplain Avoidance | Required |
|  |  |  |  | **PERFORMANCE PATH** |  |
| 🟩 | 🟨 | 🟧 | Credi | LEED for Neighborhood Development Location | 15 |
|  |  |  |  | **PRESCRIPTIVE PATH** |  |
| 🟩 | 🟨 | 🟧 | Credi | Site Selection | 8 |
| 🟩 | 🟨 | 🟧 | Credi | Compact Development | 3 |
| 🟩 | 🟨 | 🟧 | Credi | Community Resources | 2 |
| 🟩 | 🟨 | 🟧 | Credi | Access to Transit | 2 |
| **0** | **0** | **0** |  | **Sustainable Sites** | **7** |
| Y |  |  | Prere | Construction Activity Pollution Prevention | Required |
| Y |  |  | Prere | No Invasive Plants | Required |
| 🟩 | 🟨 | 🟧 | Credi | Heat Island Reduction | 2 |
| 🟩 | 🟨 | 🟧 | Credi | Rainwater Management | 3 |
| 🟩 | 🟨 | 🟧 | Credi | Non-Toxic Pest Control | 2 |
| **0** | **0** | **0** |  | **Water Efficiency** | **12** |
| Y |  |  | Prere | Water Metering | Required |
|  |  |  |  | **PERFORMANCE PATH** |  |
| 🟩 | 🟨 | 🟧 | Credi | Total Water Use | 12 |
|  |  |  |  | **PRESCRIPTIVE PATH** |  |
| 🟩 | 🟨 | 🟧 | Credi | Indoor Water Use | 6 |
| 🟩 | 🟨 | 🟧 | Credi | Outdoor Water Use | 4 |
| **0** | **0** | **0** |  | **Energy and Atmosphere** | **37** |
| Y |  |  | Prere | Minimum Energy Performance | Required |
| Y |  |  | Prere | Energy Metering | Required |
| Y |  |  | Prere | Education of the Homeowner, Tenant or Building I | Required |
| 🟩 | 🟨 | 🟧 | Credi | Annual Energy Use | 30 |
| 🟩 | 🟨 | 🟧 | Credi | Efficieng Hot Water Distribution | 5 |
| 🟩 | 🟨 | 🟧 | Credi | Advanced Utility Tracking | 2 |
| **0** | **0** | **0** |  | **Materials and Resources** | **9** |
| Y |  |  | Prere | Certified Tropical Wood | Required |
| Y |  |  | Prere | Durability Management | Required |
| 🟩 | 🟨 | 🟧 | Credi | Durability Management Verification | 1 |
| 🟩 | 🟨 | 🟧 | Credi | Environmentally Preferable Products | 5 |
| 🟩 | 🟨 | 🟧 | Credi | Construction Waste Management | 3 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| **0** | **0** | **0** |  | **Indoor Environmental Quality** | **18** |
| Y |  |  | Prereq | Ventilation | Required |
| Y |  |  | Prereq | Combustion Venting | Required |
| Y |  |  | Prereq | Garage Pollutant Protection | Required |
| Y |  |  | Prereq | Radon-Resistant Construction | Required |
| Y |  |  | Prereq | Air Filtering | Required |
| Y |  |  | Prereq | Environmental Tobacco Smoke | Required |
| Y |  |  | Prereq | Compartmentalization | Required |
| 🟩 | 🟨 | 🟧 | Credit | Enhanced Ventilation | 3 |
| 🟩 | 🟨 | 🟧 | Credit | Contaminant Control | 2 |
| 🟩 | 🟨 | 🟧 | Credit | Balancing of Heating and Cooling Distribution S | 3 |
| 🟩 | 🟨 | 🟧 | Credit | Enhanced Compartmentalization | 3 |
| 🟩 | 🟨 | 🟧 | Credit | Enhanced Combustion Venting | 2 |
| 🟩 | 🟨 | 🟧 | Credit | Enhanced Garage Pollutant Protection | 1 |
| 🟩 | 🟨 | 🟧 | Credit | Low Emitting Products | 3 |
| 🟩 | 🟨 | 🟧 | Credit | No Environmental Tobacco Smoke | 1 |
| **0** | **0** | **0** |  | **Innovation** | **6** |
| Y |  |  | Prereq | Preliminary Rating | Required |
| 🟩 | 🟨 | 🟧 | Credit | Innovation | 5 |
| 🟩 | 🟨 | 🟧 | Credit | LEED AP Homes | 1 |
| **0** | **0** | **0** |  | **Regional Priority** | **4** |
| 🟩 | 🟨 | 🟧 | Credit | Regional Priority: Specific Credit | 1 |
| 🟩 | 🟨 | 🟧 | Credit | Regional Priority: Specific Credit | 1 |
| 🟩 | 🟨 | 🟧 | Credit | Regional Priority: Specific Credit | 1 |
| 🟩 | 🟨 | 🟧 | Credit | Regional Priority: Specific Credit | 1 |
| 0 | 0 | 0 |  | **TOTALS** Possible Points: | **110** |

**Certified:** 40 to 49 points
**Silver:** 50 to 59 points
**Gold:** 60 to 79 points
**Platinum:** 80 to 110 points

Figure 2.1. Criteria of LEED v4 for Building Design and Construction: Multifamily Midrise (*LEED v4 homes and multifamily Midrise - current version,* 2019)

The energy model summary reports include a sample of the wall, roof, floor, and window assembly inputs with U-values and window SHGC (solar heat gain coefficient), and the infiltration for a few representative spaces. Besides, examples of lighting and HVAC load inputs for a few representative spaces also be in energy model summary reports (*LEED BD+C: Homes V4 LEED BD+C: Multifamily Midrise V4 Verification and submittal guidelines*, n.d).

#### 2.1.1.2 BREEAM (British Research Establishment Environmental Assessment Method)

BREEAM, the first certification system to evaluate the sustainability of buildings, was published by BRE (Building Research Establishment) in the UK in 1990. It was intended to be a countrywide system for office and residential buildings at first. The certification system is now utilized for a variety of building types all around the world (Rezaallah et al., 2012). BREEAM International New Construction 2016 includes 57 distinct assessment criteria covering the nine environmental categories (energy, materials, waste, pollution, health & well-being, water, transport, land use, and ecology management), plus a tenth category called "Innovation" (*BREEAM International New Construction 2016*, 2016). Calculation style is based on percentage, and it offers levels of certification as Unclassified (<30), Pass (≥30), Good (≥45), Very Good (≥55), Excellent (≥70), Outstanding (≥85). Figure 2.2 represents a BREEAM score and rating calculation example.

| BREEAM section | Credits achieved | Credits available | % of Credits achieved | Section weighting (fully fitted) | Section score |
|---|---|---|---|---|---|
| Management | 10 | 20 | 50.00% | 0.12 | 6.00% |
| Health and wellbeing | 17 | 21 | 80.95% | 0.14 | 11.33% |
| Hazards | 1 | 1 | 100.00% | 0.01 | 1.00% |
| Energy | 16 | 34 | 47.05% | 0.19 | 8.94% |
| Transport | 5 | 11 | 45.45% | 0.08 | 3.63% |
| Water | 5 | 9 | 55.56% | 0.06 | 3.33% |
| Materials | 10 | 14 | 71.43% | 0.125 | 8.92% |
| Waste | 3 | 13 | 23.07% | 0.075 | 1.73% |
| Land use and ecology | 5 | 5 | 100.00% | 0.10 | 10.00% |
| Pollution | 9 | 12 | 75.00% | 0.10 | 7.44% |
| Innovation | 2 | 10 | 20.00% | 0.10 | 2.00% |

Figure 2.2. Example BREEAM Score and Rating Calculation (*BREEAM International New Construction 2016*, 2016)

The criteria related to the energy category are listed in Table 2.4, which is prepared according to BREEAM International New Construction 2016. Reduction of energy usage is also an outstanding criterion for BREEAM. When the BREEAM International New Construction 2016 Technical Manuel is examined, it is seen that similar building components and their material properties should be listed in various sections (*BREEAM International New Construction 2016*, 2016).

Table 2.4 BREEAM International New Construction 2016 Energy Category Criteria

| Issue | Credits |
|---|---|
| Ene 01 Reduction of energy use and carbon emissions | 15 |
| Ene 02a Energy monitoring | 2 |
| Ene 02b Energy monitoring | 2 |
| Ene 03 External lighting | 1 |
| Ene 04 Low carbon design | 3 |
| Ene 05 Energy efficient cold storage | 3 |
| Ene 06 Energy efficient transport systems | 3 |
| Ene 07 Energy efficient laboratory systems | 5 |
| Ene 08 Energy efficient equipment | 2 |
| Ene 09 Drying space | 1 |

#### 2.1.1.3 B.E.S.T. (Ecological and Sustainable Design in Buildings)

ÇEDBİK (Turkish Green Building Council) established the B.E.S.T Residential Certification system, which can be used for new residential projects in Turkey in 2019. B.E.S.T evaluates new residential buildings in 9 categories: Integrated Green Project Management, Land Use, Water Efficiency, Energy Efficiency, Health and Comfort, Material and Resource, Living in Residence, Operation and Maintenance, and Innovation. Projects are evaluated over 110 points based on the strategies they implement in these categories and are certified with one of 4 different certification degrees: Certified (46-64 points), Good (65-79 points), Very Good (80-99 points), Excellent (100-110 points) (*B.E.S.T Residential Certificate,* n.d). Table 2.5 has been created in line with the information in the Scoring Table in the B.E.S.T - Residential Certificate Guide, which is prepared in Turkish, and the parts of the table related to this study are shown in detail (*B.E.S .T - Konut Sertifika Kılavuzu*, 2019).

Table 2.5 Criteria of B.E.S.T Residential Certification System

| **EVALUATION CRITERIA** | **Possible Points** | **Design** | **Construction** | **Total Points** |
|---|---|---|---|---|
| **1. Integrated Green Project Management** | | | | **9** |
| **2. Land Use** | | | | **13** |
| **3. Water Use** | | | | **12** |
| **4. Energy Use** | | | | **26** |
| Prerequisite 1 - Control, Commissioning and Acceptance | Required | Required | | |
| Prerequisite 2 - Energy Efficiency | Required | Required | | |
| 4.1 Energy Efficiency | 1-15 | 15 | - | |
| 4.2 Use of Renewable Energy | 1-7 | 2 | 5 | |
| 4.3 Exterior Lighting | 1 | 1 | - | |
| 4.4 Energy Efficient Household Appliances | 1 | - | 1 | |
| 4.5 Elevators | 2 | 1 | 1 | |
| **5. Health and Comfort** | | | | **14** |
| **6. Material and Resource** | | | | **14** |
| **7. Living in Residence** | | | | **14** |
| **8. Operation and Maintenance** | | | | **6** |
| **9. Innovation** | | | | **2** |
| **Total** | | **54** | **56** | **110** |

Table 2.5 shows that the energy efficiency criteria under the energy use category have the largest share of the overall points. It requires energy modeling in line with architectural, mechanical, and electrical/lighting designs and strategies in order to minimize energy consumption in residential buildings. It shows the effects of building orientation, form, shell, and passive air conditioning systems on the designed building's energy performance. It also requires detailing the material

properties of elements such as the framework, roof, exterior wall and/or curtain wall, interior partition wall, floors and coverings, doors, windows, and their profiles.

When these three certificates are examined, it is seen that energy usage has the highest impact in all of them. Furthermore, the materials utilized in the construction have a remarkable place in the scoring.

### 2.1.2 Parameters from Literature

In this section, academic studies were examined in order to have a better understanding of the parameters that have an influence on building energy consumption. The parameters were determined first in the review studies, and then the relevant papers were compiled under the appropriate titles for each parameter. In Table 2.6, parameters used in literature in building energy analysis are listed. As shown in Table 2.6, window material and WWR (window to wall ratio), building location and shape, HVAC, insulation material, and thickness are most commonly considered parameters in the literature, as well as roof, floor, orientation and shadings/surroundings are also mentioned. These parameters will be explained in the following subsections.

Table 2.6 Parameters Used in Literature in Building Energy Analysis

| **Parameters** | **Articles** |
|---|---|
| **Building Location** | Hancioğlu Kuzgunkaya et al., 2021; Ascione et al., 2019; Tuhus-dubrow & Krarti, 2010; Aksin & Selçuk, 2021; Konis et al., 2016; Salakij et al., 2016; W. Xu et al., 2021 |
| **Building Shape** | Menezo et al., 2001; Amani & Reza Soroush, 2020; Adamski, 2007; Pathirana et al., 2019; Mahan & Geyer, 2020; Tuhus-dubrow & Krarti, 2010; Pacheco et al., 2012 |
| **Building Orientation** | Pathirana et al., 2019; Abanda & Byers, 2016; Yarramsetty et al., 2020; Alothman et al., 2021 |
| **Insulation Materials** | Dodoo et al., 2019; Schlueter & Geyer, 2018; Cabeza et al., 2010; Evin & Ucar, 2019; Z. Chen et al., 2020 |
| **Insulation Thickness** | Hong et al., 2017; Z. Chen et al., 2020; Dodoo et al., 2019; Feng et al., 2017; Evin & Ucar, 2019; Aksin & Selçuk, 2021 |
| **Wall Material** | Alothman et al., 2021; Sadeghifam et al., 2019; Aksin & Selçuk, 2021; Marwan, 2020 |
| **Window material and/or WWR** | Mehndi & Chakraborty, 2020; Asl & Zarrinmehr, 2015; Sadeghifam et al., 2019; Najjar et al., 2019; Pathirana et al., 2019; Aksin & Selçuk, 2021; Tuhus-dubrow & Krarti, 2010; Ahn et al., 2016; Menzel & Shetty, 2019 |
| **Roof** | Sadeghifam et al., 2019; Alothman et al., 2021; Y. Li et al., 2021 |
| **Floor** | Sadeghifam et al., 2019; Najjar et al., 2019 |
| **HVAC** | Yuan et al., 2016; Pezeshki et al., 2020; Jaušovec & Sitar, 2019; Alothman et al., 2021; Salakij et al., 2016; Hancioğlu Kuzgunkaya et al., 2021 |
| **Shading/ Surroundings** | W. Xu et al., 2021; Quan et al., 2016; Han et al., 2017 |

S. Chen et al., (2020) reviewed studies on determining the factors affecting building energy performance and categorized the findings into three categories: building characteristics, equipment and technologies, and occupant's behaviors. Building characteristics have a crucial impact in assessing a building's energy performance since they include a variety of building and construction-related technologies and activities, and the most popular factors in this group are building shape and orientation, wall insulation, window glazing, window to wall ratio (WWR), insulation materials, and optimum insulation thickness (S. Chen et al., 2020). Pacheco et al., (2012) performed a review study that includes building orientation, shape, envelope system, passive heating and cooling mechanisms, shading, and glazing. Sadineni et al., (2011) presented a review paper that collects some building components and respective improvements from an energy efficiency perspective taking into account walls, fenestration (windows and doors), roofs, and floors.

#### 2.1.2.1 Building Location

The building location has a notable impact on the building's energy consumption since all climatic data such as solar radiation, humidity, air temperature, and circulation are based on it. In order to observe how the location affects the energy consumption of the building, energy analyzes were performed at different locations representing various climate zones, yielding valuable results that could be applied on a large scale. Hancioğlu Kuzgunkaya et al., (2021) adjusted the temperature values of the building, the energy use values of the designed single-storey detached house. While some studies have tried to find minimum energy consumption by optimizing parameters for buildings in locations in various climates (Ascione et al., 2019; Tuhus-dubrow & Krarti, 2010; Aksin & Selçuk, 2021; Konis et al., 2016), some have demonstrated the impact of location on energy usage (Salakij et al., 2016) or energy demand of building (W. Xu et al., 2021).

#### 2.1.2.2 Building Shape

Shape factor, compactness factor, and relative compactness are the commonly used parameters to show the impacts of building shape on building energy consumption (S. Chen et al., 2020). The shape factor is the ratio of the building surface area to the conditioned floor area (S. Chen et al., 2020). The compactness factor refers to the ratio between building's thermal envelope area and its volume. If the building has a higher shape factor, it means that it has a bigger surface area in relation to its volume, which results in larger heat losses in cold climates (Danielski et al., 2012). Relative compactness evaluates the effects of shape and geometric dimensions on building energy performance (S. Chen et al., 2020).

In order to observe the correlation between building shape and energy consumption, there are studies comparing different building forms which are obtained by making some minor changes in the shape of the building (Menezo et al., 2001; Amani & Reza Soroush, 2020). Several studies have investigated the impact of different building shapes on energy consumption. In addition to the studies trying to optimize a particular shape-oval shape (Adamski, 2007), others attempted to discover the optimal form by comparing different shapes. Square, rectangle, L-shape (Pathirana et al., 2019), and Plus-shape, U-shape, H-shape, T-shape (Singh & Geyer, 2020), and trapezoidal (Tuhus-dubrow & Krarti, 2010). Pacheco et al., (2012) optimized the curved-shaped building and a polygonal-shaped building by using shape factors.

The height of the building is also an important factor affecting the shape of the building, as it can be directly related to the shape factor. There are studies on building height or floor height/ceiling height in the literature. Ghafari et al., (2018) investigated the influence of ceiling height on heating energy consumption through an educational building case study in Tabriz, Iran and concluded that heating energy consumption is reduced by 1% for every 10 cm of ceiling height reduction. On the other hand, Guimarães et al., (2013) examined the impact of ceiling height in thermal comfort of buildings in Brazil by varying the ceiling height of 2.4m, 2.8m, and 3m and the result of study shows that temperature increases 1°C for every 20 cm height reduction.

#### 2.1.2.3 Building Orientation

The position of the building in respect to the path of the sun and the prevailing wind in the region is referred to as orientation. The building should be positioned to take advantage of the sun's heat and radiation. For instance, southern orientation is generally recommended for a building located in the northern hemisphere.

There are several studies in the literature that analyze the building orientation; they usually change the position of the building with certain degree intervals and try to find the best orientation by repeating the analysis in terms of thermal comfort, lighting electricity (Pathirana et al., 2019), or the total energy consumption of the building (Abanda & Byers, 2016; Yarramsetty et al., 2020; Alothman et al., 2021).

#### 2.1.2.4 Building Envelope

The building envelope refers to the components that separate a structure's indoor and exterior environments, protecting the interior space from environmental factors such as rain, wind, temperature, humidity. It is generally made up of a number of components like walls, roof, fenestration, foundation, thermal insulation, thermal mass, external shading devices (Khidmat et al., 2022). In the following sections, these studies related to these components are listed.

##### 2.1.2.4.1 Building Insulation

Insulation refers to all the critical processes to extend the buildings' life, make them more comfortable from the inside, and protect the building against external factors. Although there are varieties such as water, heat, and sound insulation (Schiavoni et al., 2016), only thermal insulation has been considered within the scope of this study. The insulation materials can be used on the wall, roof, ceiling, floor and basement of the building for thermal insulation purposes. In general, wall insulation was considered to be the most effective insulation application because of its extensive surface area (S. Chen et al., 2020). The thickness and thermal conductivity of applied materials have a remarkable effect on the functionality of the thermal insulation (S. Chen et al., 2020).

There are two basic concepts regarding the thermal conductivity of materials, U-value and R-value. The R-Value is a measurement of thermal resistance, or the ability of the material to resist heat flow, whereas the U-Value (or sometimes called as U-Factor) represents thermal transmittance or the heat loss through a component. Generally, U-Value indicates the insulating properties of windows, while the R-values represent the insulating properties of walls, floors, and roofs (Akcay & Arditi, 2017).

Dodoo et al., (2019) investigated cost-effective, energy-efficient building envelope measures in a newly constructed Swedish high-rise building by changing the thickness of the selected insulation materials for the roof, ground floor, and exterior walls as well as using different U-values for windows and doors. In addition to the studies that try to optimize energy by changing the U values of thermal insulation (Schlueter & Geyer, 2018), there are also those who analyze the materials commonly used in the construction industry. Polyurethane, polystyrene, mineral wool (Cabeza et al., 2010), rock wool, expanded polystyrene (EPS), extruded polystyrene (XPS), polyurethane (Evin & Ucar, 2019) are frequently used. In addition to all these materials, cellulose, fiberglass, wood-wool, recycled wool are also used for the thermal insulation of buildings (Z. Chen et al., 2020).

#### 2.1.2.4.2 Building Insulation Thickness

As the thickness of the insulation material increases, the amount of insulation it provides increases, which reduces cooling and heating costs while material cost increases. The optimum insulation thickness is the one that provides the lowest total cost during the heating and cooling periods over the life of the building (Evin & Ucar, 2019). There are several studies that compare different insulation thicknesses to achieve the lowest energy consumption (Hong et al., 2017; Z. Chen et al., 2020; Dodoo et al., 2019; Feng et al., 2017; Evin & Ucar, 2019; Aksin & Selçuk, 2021).

#### 2.1.2.4.3 Wall Material

Walls have a remarkable impact on building energy usage, the selection of suitable materials for the walls can significantly reduce energy consumption. There are several studies that compare different wall materials: the eight different types of wall construction components in the green building studio database (Alothman et al., 2021) or ten types of wall materials (Sadeghifam et al., 2019). Moreover, some studies compare two different materials, such as brick and aerated concrete (Aksin & Selçuk, 2021), traditional CLC (Cellular Lightweight Concrete) brick and innovative CLC brick (Marwan, 2020).

#### 2.1.2.4.4 Window

Windows have a crucial role in providing daylight and a view, as well as influencing a building's overall energy usage (Mangkuto et al., 2016). While using large windows to maximize daylighting and view, it is often necessary to reduce windows' size to minimize energy consumption. The heating and cooling loads of a building are related to its U-value, solar heat gain coefficient (SHGC) or G-Value (G-value is the coefficient commonly used in Europe and SHGC in the United States) (Seeboth et al., 2010), and window to wall ratio (WWR). In the previous sections, it was mentioned what U-value means. Solar heat gain generally refers to the rise in the heat of a structure (or object) in space due to absorbed solar radiation (Leftheriotis & Yianoulis, 2012). Solar heat gain coefficient (SHGC) is a measurement of how efficiently a window controls solar radiation. When sunlight strikes a window, some of the sunlight is transmitted, some is reflected back, and some is absorbed (Paulus, 2014). The heat that has been absorbed might flow into or out of the house. The ratio of solar energy delivered as heat gain is known as SHGC (Paulus, 2014). Another parameters related to windows are Visible

Transmittance (VT) which can be mostly associated with daylight that represent the ratio of visible light that makes it through a window. The amount of aperture filled by non-transparent components like as the frame and sash, as well as the type of glass used, influence the VT (Paulus, 2014). The larger the VT, the better the daylight potential.

Building thermal energy consumption can be optimized by changing window size (Mehndi & Chakraborty, 2020; Asl & Zarrinmehr, 2015), or evaluating the several glazing materials (Sadeghifam et al., 2019; Najjar et al., 2019), or just changing WWR values (Pathirana et al., 2019). Furthermore, the lowest energy consumption can be obtained by combining several of these parameters and making changes to each parameter, for instance; windows glazing type, WWR, (Banihashemi et al., 2017) (Aksin & Selçuk, 2021), WWR, window type, and size (Tuhus-dubrow & Krarti, 2010), different U-value, SHGC and WWR values (Ahn et al., 2016). On the other hand, there are also studies that optimize the facade – the exterior of a building, i.e., windows and walls – to obtain the optimum daylight performance (Menzel & Shetty, 2019).

#### 2.1.2.4.5 Roof

A roof is the top covering of the building that protects it from external conditions like rain, snow, sunlight, extreme temperatures, wind. Roofs can also provide insulation by keeping the heat in the winter or cool air in the summer. In this way, it is possible to make remarkable improvements in building energy consumption with an effective roof design.

It has been seen that the roof material is analyzed in the studies related to the roof and building energy consumption. Sadeghifam et al., (2019) tested five different roof materials in addition to the base case and compared them in terms of cooling loads, and determined the material with the highest energy efficiency, while Alothman et al., (2021) used roof materials recommended from green building studios to find the optimum option for selecting an alternative roof. Other factors analyzed regarding the roof and energy analysis are the shape and angle of the roof.

Y. Li et al., (2021) examined the effect of roof forms and roof gradients on annual energy consumption through a case study that aims to flat-to-slope roof retrofitting. For this purpose, two common slope roof retrofitting types (long slope and four-side slope) and five slope roof retrofitting gradients (21.8°, 26.57°, 30°, 35°, 40°), a total of ten flat-to-slope roof retrofitting models were used to generate ten flat-to-slope roof retrofitting models, which were then evaluated in terms of annual energy consumption.

#### 2.1.2.4.6 Floor

The thermal performance of the floor is essential to the building's overall energy efficiency. Interior floors, ceilings (excluding the roof), and foundations are covered under this category. In interior floors, the ceiling of the lower floor and the floor of the upper floor can be considered together since the slab part is common for both parts.

In order to determine the energy-efficient floor materials, Sadeghifam et al., (2019) generated four more alternatives besides the base case, tested all of them separately, and chose the option that provides the least cooling load through a selected one-storey terrace house in Malaysia.

Najjar et al., (2019) compared the alternative materials for floors and ceilings in terms of life cycle energy and annual energy use intensity considering the ground floor and eight floors of the selected building. In this context, concrete floor with wooden friezes and ceramic tiles, suspended concrete floor, and precast concrete platform slab materials were taken into account (Najjar et al., 2019).

#### 2.1.2.5 HVAC (Heating, Ventilation and Air Conditioning)

Building service systems (e.g., HVAC system, hot water supply, lighting system, electrical appliances, and control management) are the most energy consumers in a building (S. Chen et al., 2020). The energy use of HVAC systems accounts for 50% of the building consumption and 20% of the total energy consumption in the USA (Pérez-Lombard et al., 2008). Yuan et al., (2016) conducted a study to analyze the factors affecting energy consumption of government office buildings in Qingdao, China and it was found that occupancy density and type of cooling system were the main factors affecting energy consumption. Pezeshki et al. (2020) examined the impact of HVAC systems by developing a new methodology. There are some studies that investigate to reduce HVAC energy usage. For instance, evaluating the energy consumption of different heating systems (Jaušovec & Sitar, 2019; Alothman et al., 2021), adjusting the optimal setpoint schedule on HVAC system (Salakij et al., 2016; Hancioğlu Kuzgunkaya et al., 2021).

#### 2.1.2.6 Shading and Surrounding

The building surrounding is another critical parameter in terms of building energy usage as it affects solar energy utilization as well as the direction and speed of the wind in the environment. The distance between the building and the surrounding structures, as well as the height and position of the nearby structure, are all significant contributing elements. When a building remains within the shade region of neighboring buildings, the usage of sun rays is affected, and the energy consumption is increased (Yüksek & Karadayi, 2017). The speed and direction of the wind on the building are also affected by the location and distance of neighboring structures, which has an impact on the building's energy performance (Yüksek & Karadayi, 2017).

W. Xu et al., (2021) investigated the impact of surrounding on energy consumption by changing the quantity, position, and height of the neighboring buildings through a residential building. Quan et al., (2016) investigate the relationship between urban form and building energy performance through a case study of nine Shanghai neighborhoods. Han et al., (2017) explored mutual shading and mutual reflection inter-building effects on building energy performance and conducted interregional simulations under different climatic contexts by constructing a network of urban structures and examining only mutual shadowing and only mutual reflection, respectively, and then studied two realistic urban contexts in Perugia, Italy.

#### 2.1.2.7 Multi-criteria

There are several studies in the literature that make energy analysis by evaluating several parameters together. Table 2.7 lists parameters that are included in studies dealing with multiple parameters.

Table 2.7 Multi-parameter Studies in the Literature

| | Location | Shape | Orientation | Material | | | Insulation | Window | | HVAC systems | Lighting | Roof | Shading Surrounding |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Wall | Roof | Floor | | WWR | Glazing material | | | | |
| **Aksin & Selçuk (2021)** | ✓ | - | - | ✓ | - | - | ✓ | ✓ | ✓ | - | - | - | - |
| **Alothman et al. (2021)** | - | - | ✓ | ✓ | ✓ | - | - | - | - | ✓ | - | - | - |
| **Elbeltagi et al. (2017)** | - | ✓ | ✓ | ✓ | ✓ | ✓ | - | ✓ | ✓ | ✓ | - | - | - |
| **Banihashemi et al. (2017)** | - | - | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | - | - | - |
| **Khidmat et al. (2022)** | - | ✓ | ✓ | - | - | - | - | - | - | - | - | ✓ | - |
| **Morsali et al. (2021)** | ✓ | - | - | - | - | - | - | - | - | - | - | ✓ | - |
| **Stumpf et al. (2009)** | - | ✓ | ✓ | ✓ | ✓ | ✓ | - | - | ✓ | ✓ | ✓ | - | - |
| **Won et al., (2019)** | ✓ | ✓ | - | - | - | - | - | ✓ | - | - | - | - | - |
| **Singh et al., (2020)** | - | ✓ | - | ✓ | ✓ | ✓ | - | - | ✓ | - | ✓ | - | - |
| **Chardon et al., (2016)** | - | - | - | ✓ | ✓ | ✓ | ✓ | - | ✓ | - | - | - | - |
| **Puˇcko et al., (2020)** | - | - | - | ✓ | - | - | - | - | - | - | - | ✓ | - |
| **Akcay & Arditi, (2017)** | - | - | - | ✓ | ✓ | ✓ | - | - | ✓ | - | - | ✓ | - |
| **Elhadad & Orban (2021)** | - | - | - | ✓ | ✓ | ✓ | - | - | ✓ | - | - | - | - |
| **Delgarm et al., (2016)** | ✓ | ✓ | ✓ | ✓ | - | - | - | ✓ | ✓ | - | - | - | ✓ |
| **Ibrahim et al., (2022)** | - | ✓ | - | ✓ | ✓ | - | - | ✓ | ✓ | - | - | - | - |
| **Singh & Geyer (2020)** | - | ✓ | ✓ | ✓ | ✓ | ✓ | - | ✓ | ✓ | ✓ | ✓ | - | - |

Aksin & Selçuk, (2021) carried out a single-objective optimization process to minimize the energy use intensity for Turkey's two different climatic zones, İstanbul and Ankara, by considering the wall materials and insulation thickness, WWR, glazing type. Alothman et al., (2021) conducted a case study covering life cycle electricity, fuel use, and life cycle energy cost, as well as annual energy use intensity and annual peak demand through an education building, taking into account four-building parameters (orientation, wall, roof, HVAC) and changed the parameters each time and compared them with the first building. Elbeltagi et al., (2017) considered the parameters of different building envelope alternatives for wall type, roof type, basement type by changing values in a certain range for building dimensions, orientation, WWR, glazing properties (changing windows U-Value, SGHC, VT), heating and cooling set points in the study where the parametric analysis and energy modeling was combined based on thermal comfort analysis. To determine the optimum energy consumption, a total of more than 12,000 simulations was performed with parametric energy simulation to complete the thermal analysis for a generalized residential building model (Elbeltagi et al., 2017). Banihashemi et al., (2017) optimized energy consumption of residential buildings by considering both continuous (building orientation, WWR, ceiling height, meter square of rooms heated and cooled and lighting) and discrete (wall, roof and insulation materials, floor ground system, glazing type and the types of main space heating and cooling systems) parameters of energy simultaneously. Khidmat et al., (2022) optimized the building orientation, base radius, twisting and scaling factor, and the angle of the roof slope parameters to find optimum design solution of free-form loft-twisted structure to minimize the solar radiation both for the site and the building surface affected by the geometry. Morsali et al., (2021) evaluated three different roof shapes in 24 directions and showed the effect of these parameters on annual energy consumption. Stumpf et al., (2009) conducted an energy analysis study using BIM in which different options for several parameters were created (three distinct building configurations, 15 degrees rotation for building orientation, 10 different alternatives in HVAC, 17 in glazing, 20 in roof, 15 in walls, 4 in lighting, and 3 in lighting control) and the option with the least consumption for each parameter was specified based on the energy analysis results. Won et al., (2019) identified the key factors affecting energy use intensity (EUI) of large-scale office buildings located in New York and Chicago by performing Spearman's correlation analysis and multiple variate regression tests. The results showed the number of floors, construction year, window-to-wall ratio (WWR), and source-to-site ratio have a significant impact on EUI, whereas morphological characteristics like the relative compactness and surface-to-volume ratio have a limited impact on EUI (Won et al., 2019). Singh et al., (2020) used four different approaches to test for an office building with five design possibilities (box-shaped, L-shaped, T-shaped, S-shaped, and square) under high and low uncertainty. Several undecided design parameters (u-values of walls, ground floor, roof and windows, g-value of windows, airtightness, internal mass) and scenario parameters (light and equipment heat gain, operating hours, occupant load, heat pump coefficients of performance, boiler efficiency) defined by a probability distribution function are considered in the study (Singh et al., 2020). Chardon et al., (2016) conducted a case study for a single-family house by optimizing building envelope design by considering different materials for walls, floors, windows and insulation materials and thicknesses for walls and floors. Puˇcko et al., (2020) conducted energy and cost analysis through a case study that yielded a total of 24 different scenarios by examining the four different alternatives of external wall components and two systems of flat roof taking into account three different U-values. Akcay & Arditi, (2017) examined ten-story office building in Illinois as a case study and compared energy use intensities by creating a total of 81 combinations, taking into account three alternative R-values for wall, floor, roof and three alternative U-values for window glazing.

Elhadad & Orban (2021) assessed thickness, materials, density, specific heat and thermal conductivity of the basement, exterior floor, interior floor, exterior wall, interior wall, roof, ground slab, glazing type, and infiltration rate to see how these parameters affect energy consumption and carbon dioxide concentrations. The study found that the exterior flooring materials have the greatest impact on the annual energy delivered for heating and cooling, whereas the density of all structural elements and the thickness of the basement, exterior floors, interior floors, and walls have the minimum effect on energy consumption (Elhadad & Orban, 2021).

Delgarm et al., (2016) conducted a case study in four major climatic regions of Iran to optimize the annual cooling, heating, and lighting electricity consumption of a single room model by considering building orientation, shading overhang specifications, window size, glazing, and wall material properties.

Ibrahim et al., (2022) investigated the impact of eight parameters (building size, floor height, glazing area, wall area, window to wall ratio (WWR), window glazing u-value, roof u-value, and external wall u-value on the heating cooling load values.

Singh & Geyer, (2020) conducted a study to rank the design parameters in order of their influence on the energy prediction, for this reason five parameter groups are identified as geometrical (length, width, height, the ratio for lengtha, the ratio for widtha and orientation), technical specification (wall u-value, ground floor u-value, roof u-value and infiltration), window construction (window u-value, window g-value and window-to-wall for each direction), operational design and system efficiency parameters (operating hours, lighting and electrical heat gain, boiler efficiency and chiller coefficient of performance). All these parameters were evaluated using six different shapes (rectangular, plus-shape, L-shape, U-shape, H-shape and T-shape) and it was concluded that designers should focus on geometric parameters, technical specifications and operational design parameters, and window structure and system efficiency parameters, respectively (Singh & Geyer, 2020).

Considering the GBCSs and the literature review results, the parameters that are decided to be included in this thesis can be listed as follows: Location, Building shape, floor height and number of stories, building orientation, glazing materials, glazing ratio (also called as a WWR) for each side, roof angle, materials and insulation materials and thickness for the building envelopes (wall, floor, roof), HVAC schedules, cooling and heating set points and surroundings. These parameters are selected since the building energy analysis is conducted in thermal standpoints in this study, the lighting parameter mentioned in the literature was therefore not taken into account. The values given to the determined parameters and the intervals at which these values change will be explained in detail under the title of "Building Energy Simulations".

## 2.2 Multi-objective Optimization in Building Energy Performance Analysis

Optimization is the process of finding the best available solutions that maximize or minimize a particular objective function while satisfying a set of constraints (Ong & Kohshelan, 2016). Building energy performance optimization aims to identify the design that minimizes energy use and costs while increasing the occupants' comfort and quality. As building energy performance depends on several parameters, its optimization is a compelling task. BIM-based building energy performance optimization is becoming an increasingly popular technique for achieving increased energy efficiency and overall performance in buildings. BIM-based building energy performance assessment overcomes some of the disadvantages of traditional building energy modeling, such as time-consuming model preparation, model inconsistencies, and high implementation costs, while providing many advantages such as using dynamic thermal simulation and working with what-if scenarios. Besides all these benefits, there are some technical limitations arising from simulation and optimization tools, such as the seamless implementation of BIM-BEM is still challenging and lacks a high level of interoperability (Farzaneh et al., 2019), automatic comparisons between different conditions are not enough (Yi & Malkawi, 2009), bidirectional BIM is not possible which means that building performance simulation or optimization information cannot be returned to the original model, for this reason, it necessitates remodeling activities accompanied by well-documented change management (Gourlis & Kovacic, 2017). As a result, there are significant efforts to improve BIM-based building energy efficiency assessments. In this study, energy optimization studies utilizing integrated parametric analysis tools or optimization algorithms are taken into account. Relevant studies are gathered under these main headings in the following sections.

### 2.2.1 Parametric Analysis Tools

Parametric modeling is the development of a digital model based on a set of predefined rules or algorithms known as parameters. In other words, the model or its components are automatically modified in response to changing situations instead of being manually edited (Aish & Woodbury, 2005; Qian, 2007). There are different parametric design software developed by several companies and software developers, including Catia, 3D MAX, 3D Maya, Revit, Grasshopper based on Rhino 3D, Dynamo, GenerativeComponents, Marionette and Modelur (Eltaweel & SU, 2017). Grasshopper is the most commonly used program in this field, and it offers a variety of plug-ins for many disciplines, including architecture, urban planning, structural analysis, environmental analysis, mechanical engineering, sound analysis, medical, fashion, and decoration (Eltaweel & SU, 2017).

In the building energy performance, parametric design tools enable to explore all possible alternative solutions and make decisions based on the performance of the building (Lara et al., 2017; Dautremont et al., 2019). As stated in the previous sections, the smooth implementation of BIM-BEM is challenging and lacks a high level of interoperability, so the energy performance data obtained with BIM is not sufficient to provide direct building optimization. However, performing this optimization in a BIM context using parametric modeling capabilities or additional tools is easier. This section collects studies that employ a parametric analysis method to optimize building energy performance.

Parametric simulations based on BIM are a widely utilized technique for different optimization purposes in the field of building energy performance. One of the common uses is the optimization of the parameter or parameters that affect the building energy performance. For instance; optimization of the building orientation (Abanda & Byers, 2016), building-envelope components (Sadeghifam et al., 2019), the facade of the building (Menzel & Shetty, 2019; Baker, 2018), parameters affect the building energy performance (Amani & Reza Soroush, 2020).

Another common usage of parametric analysis is the automation of workflow. The studies optimize the simulation process by parametric analysis tools. Konis et al., (2016) developed a simulation-based design workflow in Grasshopper that can evaluate the performance of multiple passive design alternatives. Welle et al., (2011) developed a methodology for integrating and automating the workflow from a parametric BIM model to an energy simulation engine and a daylight simulation engine using Industry Foundation Classes (IFC) called ThermalOpt for thermal simulation and optimization. Asl and Zarrinmehr (2015) created the Revit2GBSOpt (Revit to Green Building Studio Optimization) tool, which integrates parametric BIM and building energy performance simulation allowing designers to automatically explore energy performance simulation alternatives. Schlueter and Geyer (2018) developed a bi-directional design workflow combining BIM and the Design Performance Viewer toolset.

### 2.2.2 Optimization Algorithms

Another extensively utilized method for improving building energy performance is optimization algorithms. Algorithms, which mean a way designed to solve a specific problem or achieve a particular goal, are essential for generating new designs and driving the design optimization process. In BIM-based energy assessment, algorithms are commonly used to optimize the data collected from BIM. Algorithms can be simply implemented since BIM is interoperable with a wide range of data exchange formats and tools. Optimization algorithms can be classified into three main categories as direct search algorithms, intelligent optimization algorithms, and hybrid algorithms (Si et al., 2019).

Direct search, also known as pattern search, is a method for addressing optimization issues that do not require any knowledge of the objective function's gradient (Baeyens et al., 2016). It can be applied to non-continuous and nondifferentiable functions. One of the most popular direct search algorithm employed in building optimization is the Hooke-Jeeves algorithm (Si et al., 2016). Hooke and Jeeves' method consists of a series of exploratory moves from the base point, which are followed by pattern motions if they are successful (Baeyens et al., 2016).

Intelligent optimization algorithms are widely used in building energy performance optimization. An intelligent optimization algorithm, also called as, a modern heuristic algorithm, is an algorithm suitable for parallel processing, with global optimization performance and strong versatility (W. Li et al., 2021). There are many intelligent optimization algorithms, and one of the well-known them is the Genetic Algorithm (GA), which is used to solve nonlinear optimization problems (Ooka & Komamura, 2009).

GA is used for overall building energy performance optimization (Hong et al., 2017; Arida et al., 2016) or particular parameters like building form (Yi & Malkawi, 2009). Nagpal et al., (2019) estimated several unknown building parameters by using GA. Non-sorting genetic algorithm (NSGA-II) is one of the commonly used genetic algorithms. There are several studies in the literature that use NSGA-II algorithms for different purposes: energy performance optimization (Weili Xu et al., 2016; Petri et al., 2017), daylighting and energy usage optimization (Rahmani Asl et al., 2015), energy performance, and the cost of the building envelope (Chardon et al., 2016),

Hybrid algorithms combine two or more other algorithms that solve the same problem. Artificial intelligence algorithms are frequently preferred in hybrid algorithms used for the estimation and optimization of the energy consumption of buildings. Banihashemi et al., (2017) integrated two well-known Artificial Neural Network (ANN) and Decision Tree algorithms for energy optimization and enhancing the accuracy of data-driven energy modeling and prediction. Chegari et al., (2021) combined the ANNs in particular Multilayer Feedforward Neural Networks, coupled with NSGA-II, Multi-Objective Particle Swarm Optimization (MOPSO), and Multi-Objective Genetic Algorithm (MOGA) for multi-objective optimization of building energy performance and indoor thermal comfort.

According to the result of the study, MOPSO achieved the greatest desired performance, followed by the NSGA-II and finally the MOGA.

Si et al., (2016) evaluated HookeeJeeves, MOGA-II, and MOPSO algorithms in terms of stability, robustness, validity, speed, and coverage indices with a case study that optimizes different design variables such as window positions, orientation, thermal conductivity. The conclusion of the study is that no algorithm is superior in all areas; so, the algorithm must be carefully chosen based on the nature of the problem and design variables (Si et al., 2016).

# CHAPTER 3

# METHODOLOGY

The parameters affecting building energy performance were determined by literature review. Each of these parameters is analyzed using a BIM-based energy performance assessment in a hypothetical case study, by keeping all other parameters constant. Then, the parameter that has the most significant impact on the building energy performance is determined through sensitivity analysis, which is used to measure the effect of a particular input on an output. Moreover, an evaluation of these parameters is made to support the optimization of building energy performance. Periodic and initial cost values are required to calculate the life cycle cost assessment, and the annual energy consumption cost can be calculated through the consumption amount obtained as a result of these analyzes, and thus the most optimum case can be determined.

This chapter is composed of two main parts as Building Energy Simulations and Sensitivity Analysis. In the first part, the software used and parameters considered in the case study are defined, and the base case and test case scenarios are explained. The second section defines and explains how sensitivity analysis is conducted in this study.

## 3.1 Building Energy Simulations

In order to represent all the parameters determined in the literature, a multi-storey residential building was created as a hypothetical case study to conduct a building energy performance assessment. This study aims to examine the effects of the parameters determined in the light of the literature on building energy performance. Building energy performance is a complex problem that depends on many parameters and each parameter is in relationship with other parameters. The energy analysis was conducted multiple times in this study, with only one parameter changed at a time. This approach is preferred as the goal of this study is to see how the parameters affect energy usage rather than to get all conceivable combinations of parameters in order to achieve the best results. The results obtained through these analyzes were used to determine the most effective parameter by local sensitivity analysis.

This part has been compiled under three main headings: the program used, the parameters selected, and the base case and other scenarios.

### 3.1.1 Software

In this section, the software and plug-ins used in energy analysis and the interaction between them are explained. Figure 3.1 shows this system through a chart.

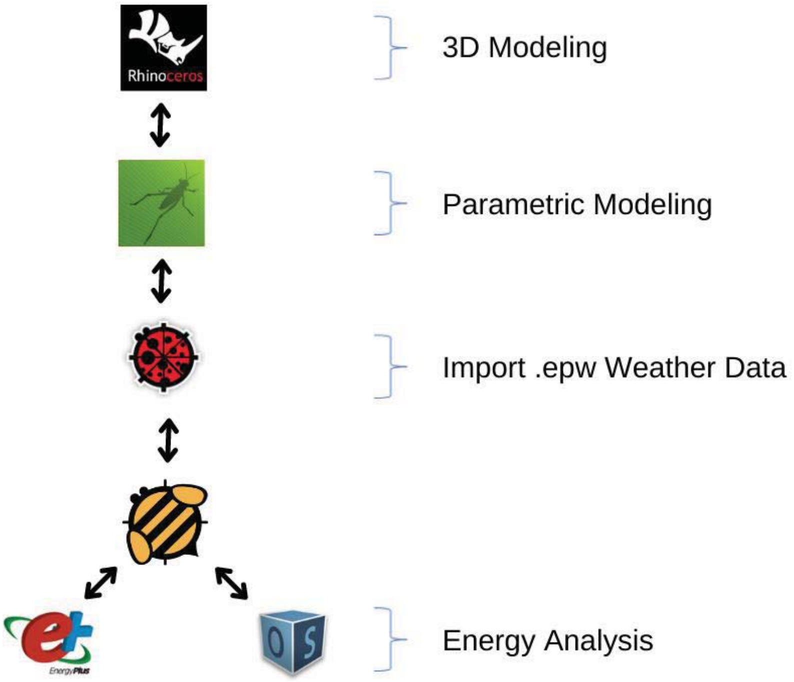


Figure 3.1. A Diagram That Represents the Interaction of Software Used for Energy Analysis

3D model is generated in Rhinoceros, which is a CAD (Computer Aided Design) software specifically designed for 3D modeling and prototyping for the industry. Instead of mesh modeling, Rhino uses NURBS (Non-Uniform Rational B-Splines) modeling, which can accurately describe any shape from a simple 2D line, circle, arc, or curve to the most complex 3D organic freeform surface. It is one of the commonly used software by architectures owing to its flexibility and accuracy. For these reasons, Rhino 6 was preferred to be used in this study.

Grasshopper enables the parametric modeling in the Rhino, and it is a visual programming tool for architectural design. Visual programming is a type of programming language that allows to create computer programs by describing processes graphically rather than textually (Asl et al., 2014). With Rhino 6 and 7, Grasshopper is already included; for earlier versions, it must be installed manually.

The functionality of Grasshopper is continuing to expand due to the development of third-party plug-ins, including environmental simulation components that allow solar studies, input to energy engines, and optimization  (Kensek, 2015). External developers have created a number of components for a variety of purposes; for example, many have been created to automate environmental calculations: visualization of weather data, daylight and energy simulation, optimization, or other tasks related to energy simulation (Kensek, 2015). Grasshopper has been chosen since it has many plugins (Elbeltagi et al., 2017), and is advanced for energy studies.

Ladybug and Honeybee are environmental plug-ins for Grasshopper. Ladybug 0.0.69 and Honeybee 0.0.66 are used in this study. Ladybug allows to import standard EnergyPlus Weather files (*epw) into Grasshopper, and it provides a variety of 2D and 3D interactive diagrams for weather data (sun path, wind rose, psychrometric chart etc.) and geometry studies such as radiation analysis, shadow studies, and view analysis (Wintour, 2016). These graphs support the decision-making process during the early stages of design.

Honeybee connects Grasshopper to building energy analysis (EnergyPlus/OpenStudio) and daylighting simulation tools (Radiance, Daysim). The Honeybee does not actually run simulations, it is an interface that creates instructions for other software programs to run simulations (Wintour, 2016). The honeybee is a free and open-source plug-in. Open-source products' copyright holders offer individuals the ability to study, change, and distribute the software for any purpose, and these products are often the concerted efforts of people around the world (Corbly, 2014).

Ladybug may be sufficient if the only geometric analysis is concerned. For example, Ladybug can determine the direction of the sun at any given time, as well as the number of hours of direct sunlight shining on a certain piece of geometry over the course of a year. On the other hand, the Honeybee is required for any material computations, such as diffuse daylight ray-tracing calculations, calculating consequent heat gains, simulating temperatures, or estimating overall energy usage. For the purpose of this study, these tools will be used together.

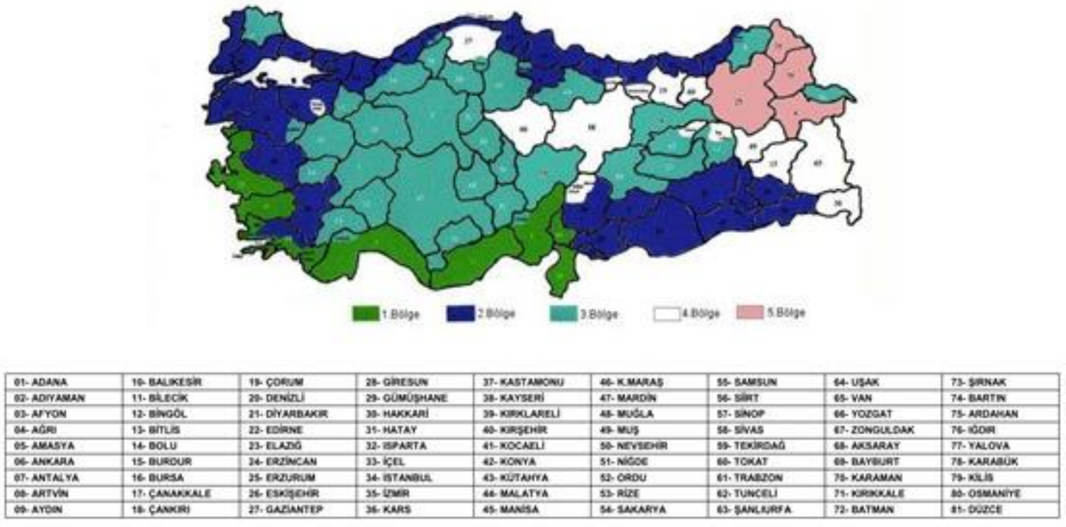
EnergyPlus is a complete building energy simulation program for modeling both energy consumption for heating, cooling, ventilation, lighting, and plug and process loads, as well as water use in buildings (U.S. Department of Energy, 2021). In this study, EnergyPlus 8.1.0 is used. EnergyPlus is mostly used energy dynamic simulation tools an among the practitioners (Hashempour et al., 2020). OpenStudio is a cross-platform software suite that enables whole-building energy modeling with EnergyPlus and comprehensive daylight analysis with Radiance. OpenStudio 1.12.0 is used in this study.

### 3.1.2 Parameters

The parameters used in this study and their values are explained in the following subtitles.

### 3.1.2.1 Location

To investigate the effect of different locations on building energy consumption, cities with different climatic characteristics in Turkey were selected. The reason why it is limited to Turkish provinces is that this study was conducted in Turkey. TS 825 thermal insulation requirements for buildings, was used for the selection of these cities. TS 825 is a standard for energy estimation method in Turkey, and it divides Turkey into five main climatic regions, as seen in Figure 3.2. The cities of Ankara, İstanbul, İzmir, Kayseri, and Erzurum were chosen to represent each region, these cities have the highest population density of their region.



| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 01- ADANA | 10- BALIKESİR | 19- ÇORUM | 28- GİRESUN | 37- KASTAMONU | 46- K.MARAŞ | 55- SAMSUN | 64- UŞAK | 73- ŞIRNAK |
| 02- ADIYAMAN | 11- BİLECİK | 20- DENİZLİ | 29- GÜMÜŞHANE | 38- KAYSERİ | 47- MARDİN | 56- SİİRT | 65- VAN | 74- BARTIN |
| 03- AFYON | 12- BİNGÖL | 21- DİYARBAKIR | 30- HAKKARİ | 39- KIRKLARELİ | 48- MUĞLA | 57- SİNOP | 66- YOZGAT | 75- ARDAHAN |
| 04- AĞRI | 13- BİTLİS | 22- EDİRNE | 31- HATAY | 40- KIRŞEHİR | 49- MUŞ | 58- SİVAS | 67- ZONGULDAK | 76- IĞDIR |
| 05- AMASYA | 14- BOLU | 23- ELAZIĞ | 32- ISPARTA | 41- KOCAELİ | 50- NEVSEHİR | 59- TEKİRDAĞ | 68- AKSARAY | 77- YALOVA |
| 06- ANKARA | 15- BURDUR | 24- ERZİNCAN | 33- İÇEL | 42- KONYA | 51- NİĞDE | 60- TOKAT | 69- BAYBURT | 78- KARABÜK |
| 07- ANTALYA | 16- BURSA | 25- ERZURUM | 34- İSTANBUL | 43- KÜTAHYA | 52- ORDU | 61- TRABZON | 70- KARAMAN | 79- KİLİS |
| 08- ARTVİN | 17- ÇANAKKALE | 26- ESKİŞEHİR | 35- İZMİR | 44- MALATYA | 53- RİZE | 62- TUNCELİ | 71- KIRIKKALE | 80- OSMANİYE |
| 09- AYDIN | 18- ÇANKIRI | 27- GAZİANTEP | 36- KARS | 45- MANİSA | 54- SAKARYA | 63- ŞANLIURFA | 72- BATMAN | 81- DÜZCE |

Figure 3.2. Regions of TS 825 Code for Thermal Insulation Requirements for Buildings (Turkish Standard Institute, 2013)

### 3.1.2.2 Shape

Considering the building forms frequently encountered in the literature, the building forms in Figure 3.3 were selected. The shape factor, compactness factor, and relative compactness parameters mentioned in the literature were not considered separately in the model, but they were taken into account while creating the building shapes. The model generates a total of twelve different building forms. The decagon and octagon shapes were chosen to observe what changes might occur when the shape of the building approaches an oval. The volume of the building is kept constant as 64000 m$^3$, while creating different building forms. The selected forms and their surface areas providing the selected volume are listed in Figure 3.3.

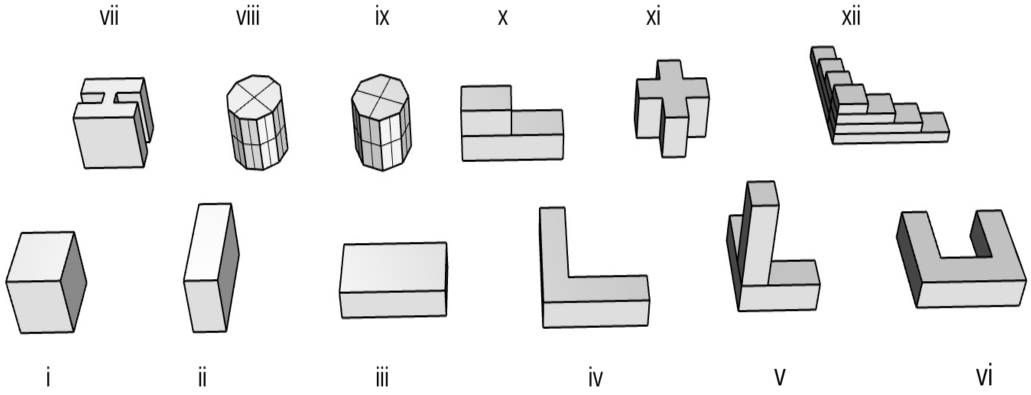


Figure 3.3. Forms of Buildings

Another parameter related to building shape is height, since the building volume was kept constant within the scope of this study, only the floor height was changed. If the building height was changed, the floor area would change as well, which would not be an accurate comparison since it would affect many parameters. The base case is a 10-storey building with a height of 4 m and a total building height of 40 m. In the Table 3.2, the floor heights used in the model and the corresponding number of floors and total building heights are shown.

Table 3.1 Surface Area of the Selected Building Forms

| ID | *Form* | *Total Floor Area ($m^2$)* | *Volume ($m^3$)* | *Height (m)* |
|---|---|---|---|---|
| i | Square | 9600 | 64000 | 40 |
| ii | LongRectangle | 10320 | 64000 | 40 |
| iii | ShortRectangle | 11200 | 64000 | 20 |
| iv | Lshaped | 13600 | 64000 | 20 |
| v | L+Ishaped | 14400 | 64000 | 80 |
| vi | Ushaped | 13600 | 64000 | 20 |
| vii | Hshaped | 13600 | 64000 | 40 |
| viii | Decagon | 8968 | 64000 | 40 |
| ix | Octagon | 9025 | 64000 | 40 |
| x | Lvertical | 13520 | 64000 | 40 |
| xi | PlusShaped | 11680 | 64000 | 32 |
| xii | Lladdered | 24640 | 64000 | 32 |

Table 3.2 Floor Height

| Floor Height | *Number of Floors* | *Total Building Height* |
|---|---|---|
| 4 m | 10 | 40 |
| 2.5 m | 16 | 40 |
| 3.33 m | 12 | 40 |
| 5 m | 8 | 40 |

#### 3.1.2.3 Orientation

The rotation angle was selected as 15°, and a total of 24 different cases (including the base case) were obtained for this parameter. The positions of the forms seen in Figure 3.3 show their base case, that is, their unturned state. Although analyses were performed by changing only one parameter throughout this study, a combination of these two parameters was also done to investigate the effect of position on the shape.

In this context, each shape has been rotated with an angle of 15°, but there is no need to make 24 different analyzes in some symmetrical shapes; for example, a square shape comes to the same position at 90°, rectangles come to the same place at 180°, since parameters like WWR are the same for each facade, the same results are obtained in the rotation angle corresponding to the same position.

#### 3.1.2.4 Wall

Under this heading, only the external walls are taken into consideration, since there are not enough studies on the internal walls in the literature.

The related parameters for external wall construction are wall materials and insulation materials and their thickness. Wall materials and their thermal properties used in the model are listed in Table 3.3. Whereas Table 3.4 exhibits the wall insulation materials and their thicknesses.

Table 3.3 Exterior Wall Materials and R-values

| Material Name | *R-value ($m^2 \cdot K/W$)* |
|---|---|
| Brick | 0.114157 |
| Aerated Autoclaved Concrete (AAC) | 0.75 |
| Double-Brick | 0.228315 |
| Dry Wall | 3.6 |

Table 3.4 Exterior Wall Insulation Materials and Thickness

| Material Name | *Min (mm)* | *Max (mm)* | *Interval (mm)* | *R-value ($m^2 \cdot K/W$)* |
|---|---|---|---|---|
| Rock Wool | 10 | 120 | 10 | 0.238 |
| Glass Wool | 10 | 120 | 10 | 0.263 |
| XPS | 10 | 120 | 10 | 0.345 |
| EPS | 10 | 120 | 10 | 0.302 |

#### 3.1.2.5 Window

As seen in the studies in the literature, essential factors related to window design are windows glazing type, window-to-wall ratio and window size. In Table 3.5, considered window materials are listed with U-Value, SHGC, and VT values. Table 3.6 shows the names of the cases that were generated for the window-to-wall ratios as well as the percentage ratio of windows to walls on each facade of these cases.

Table 3.5 Window Material Properties

| Material Name | *Short Name* | *U-Value* | *SHGC* | *VT* |
|---|---|---|---|---|
| Standard Double Glazing 4+12+4 | sdg4 | 2.9 | 0.75 | 0.8 |
| Standard Double Glazing 6+12+6 | sdg6 | 2.8 | 0.71 | 0.78 |
| Sinergy 4+12+4 | sinergy4 | 1.6 | 0.56 | 0.79 |
| Sinergy 6+12+6 | sinergy6 | 1.6 | 0.54 | 0.77 |
| Comfort 4+12+4 | comfort4 | 1.6 | 0.44 | 0.71 |
| Comfort 6+12+6 | comfort6 | 1.6 | 0.43 | 0.69 |

The minimum and maximum glazing ratios are taken as 20% and 80%, respectively, because it is not very common usage to have no windows on the façades or to have all the façades covered with windows. As only one parameter was changed in each case throughout the study, each façade was set to 20% while calculating the WWR and the ratio of the specified façade was changed, and a total of 25 different cases were obtained by including the base case.

Table 3.6 Window to Wall Ratio

| Case Name | *North Glazing* | *South Glazing* | *West Glazing* | *East Glazing* |
|---|---|---|---|---|
| nsew2 | 20% | 20% | 20% | 20% |
| n3sew2 | 30% | 20% | 20% | 20% |
| n4sew2 | 40% | 20% | 20% | 20% |
| n5sew2 | 50% | 20% | 20% | 20% |
| n6sew2 | 60% | 20% | 20% | 20% |
| n7sew2 | 70% | 20% | 20% | 20% |
| n8sew2 | 80% | 20% | 20% | 20% |
| s3new2 | 20% | 30% | 20% | 20% |
| s4new2 | 20% | 40% | 20% | 20% |
| s5new2 | 20% | 50% | 20% | 20% |
| s6new2 | 20% | 60% | 20% | 20% |
| s7new2 | 20% | 70% | 20% | 20% |
| s8new2 | 20% | 80% | 20% | 20% |
| w3nse2 | 20% | 20% | 30% | 20% |
| w4nse2 | 20% | 20% | 40% | 20% |
| w5nse2 | 20% | 20% | 50% | 20% |
| w6nse2 | 20% | 20% | 60% | 20% |
| w7nse2 | 20% | 20% | 70% | 20% |
| w8nse2 | 20% | 20% | 80% | 20% |
| e3nsw2 | 20% | 20% | 20% | 30% |
| e4nsw2 | 20% | 20% | 20% | 40% |
| e5nsw2 | 20% | 20% | 20% | 50% |
| e6nsw2 | 20% | 20% | 20% | 60% |
| e7nsw2 | 20% | 20% | 20% | 70% |
| e8nsw2 | 20% | 20% | 20% | 80% |

### 3.1.2.6 Roof

Roof shape, angle, materials, insulation materials, and thicknesses are the main parameters related to roof construction. In order to see the effect of the angle parameter on the energy of the roof, analyses were conducted using a chamfer-shaped roof, which is formed as a flat roof in the base case. In this shape, the extrusion height is kept constant, and the angle is changed. The roof angle is selected 10°, and it is changed between 10° and 60°. In Figure 3.4, the shapes formed as a result of the relevant angle are seen. Apart from the ones shown in Figure 3.4, another case with an angle of 0° was created to examine this situation without any angle, because a 4 m extrusion height was created to generate a roof slope.

If the roof shape had been created like sharp, the extrusion height would fluctuate when the angle was modified since the base part of the roof would be constant which would not provide a suitable environment for comparison.

Roof materials and their thermal properties used in the model are listed in Table 3.7 and Table 3.8 exhibits the roof insulation materials and their thicknesses.

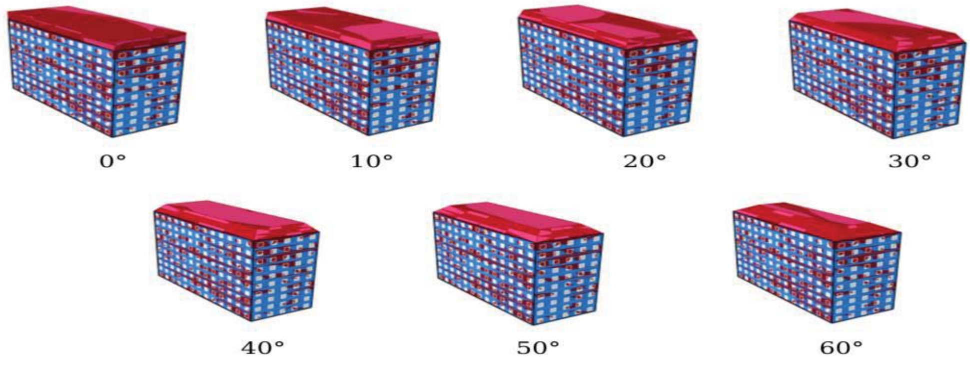


Figure 3.4. Roof Angle

Table 3.7 Roof Materials

| Material Name | *R-value ($m^2 \cdot K/W$)* |
|---|---|
| Metal | 0.000033 |
| Asphalt Shingles | 0.44 |
| Tile | 2.95 |

Table 3.8 Roof Insulation Materials

| Material Name | *Min (mm)* | *Max (mm)* | *Interval (mm)* |
|---|---|---|---|
| Glass Wool | 10 | 200 | 10 |
| Rock Wool | 10 | 200 | 10 |
| EPS | 10 | 200 | 10 |
| XPS | 10 | 200 | 10 |

#### 3.1.2.7 Interior Floor Construction

In the interior floor construction, the structural element is shared with the lower floor's ceiling, hence the interior floor is evaluated as a whole with the ceiling. The parameters related to the interior floor have been decided as the floor covering material and the insulation material applied to the ceiling of the lower floor. Floor materials and their thermal properties used in the model are listed in Table 3.9, and insulation materials and their thicknesses are tabulated in Table 3.10.

Table 3.9 Interior Floor Materials and R-values

| Material Name | *R-value($m^2 \cdot K/W$)* |
|---|---|
| Ceramic Tiles | 0.2 |
| Laminate | 0.3 |
| Marble | 0.4 |

Table 3.10 Interior Floor Insulation Materials and Thickness

| Material Name | *Min(mm)* | *Max(mm)* | *Interval (mm)* |
|---|---|---|---|
| Rock Wool | 10 | 120 | 10 |
| Glass Wool | 10 | 120 | 10 |

#### 3.1.2.8 Underground Floor Construction

In underground floor, or basement, construction, insulation materials are employed in addition to structural element concrete. In Table 3.11, a list of insulation materials used in the foundation and their thicknesses can be seen.

Table 3.11 Basement Insulation Materials and Thickness

| Material Name | *Min (mm)* | *Max (mm)* | *Interval (mm)* |
|---|---|---|---|
| XPS | 10 | 120 | 10 |
| EPS | 10 | 120 | 10 |

#### 3.1.2.9 HVAC

Under this title, cooling setpoint, heating setpoint, and schedule parts are discussed, rather than materials or different types of HVAC systems. In this study, the heating and cooling setpoints were chosen as 20°C and 24°C, respectively, taking into account the studies in the literature (Griego et al., 2012; Hoyt et al., 2015). ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standard's recommendations were also taken into account while determining these set values. Table 3.12 exhibits the maximum and minimum values of set points, their change interval, and the total number of analyses for the related parameters. Furthermore, to avoid confusion when expressing heating and cooling setpoints together, H was written in front of heating setpoints, C was written in front of cooling setpoints, and then the setpoint value was written. For example, H25 indicates that the heating setpoint is 25°C.

Table 3.12 Setpoints

| Settings | *Min* | *Max* | *Interval* | *Numbers* |
|---|---|---|---|---|
| Cooling Setpoint | 21 | 30 | 1 | 10 |
| Heating Setpoint | 14 | 23 | 1 | 10 |

For the schedule parameter, “MidriseApartment::Apartment” building program in the Honeybee library was chosen instead of creating a new schedule. To observe the effect of the schedule, “MidriseApartment::Office” program was also analyzed.

In “MidriseApartment::Apartment” schedule program, every day of the year is taken into account, with the same assumptions for each day, and in this study, the default values of this schedule have not been changed. There is an occupancy value for each hour of the day, and it is assumed that all of the people in the house are at home for 9 hours a day, with a portion of the people in the house present for other hours. In “MidriseApartment::Office” program every day of the year is taken into account, but there is no occupancy on weekends and outside working hours, and it is considered full occupancy during working hours (8 hours) and half occupancy at noon.

#### 3.1.2.10 Shading

In the base case of this study, the building is analyzed on a flat land and assuming that there are no buildings etc. around it. However, considering that this is not possible in today's urbanization, it is tried to simulate the effect of the surroundings on the model by placing a certain shading ratio on each façade to observe the shading caused by the effects of the surrounding structures. In Table 3.13, the name of cases created for shading and the shading rate of each case on the relevant facade were indicated. Since it was seen that the effect of shading on energy consumption did not make a significant difference, it was not necessary to prefer smaller change intervals.

Table 3.13 Shading

| Case Name | *North Facade* | *South Facade* | *East Facade* | *West Facade* |
|---|---|---|---|---|
| No shading | 0 | 0 | 0 | 0 |
| 50 % on north facade | 0.5 | 0 | 0 | 0 |
| 100 % on north facade | 1 | 0 | 0 | 0 |
| 50 % on south facade | 0 | 0.5 | 0 | 0 |
| 100 % on south facade | 0 | 1 | 0 | 0 |
| 50 % on west facade | 0 | 0 | 0.5 | 0 |
| 100 % on west facade | 0 | 0 | 1 | 0 |
| 50 % on east facade | 0 | 0 | 0 | 0.5 |
| 100 % on east facade | 0 | 0 | 0 | 1 |
| 100 % all facades | 1 | 1 | 1 | 1 |

### 3.1.3 Base Case and Scenarios

To compare the energy analysis result, a base case should be created primarily. In Table 3.14, base case parameters and their values are tabulated. The analysis was conducted using annual climate data rather than evaluating a few days to represent the year. Analyzes were performed for every hour of the year as the default setting of the program and calculated for 8760 values over 365 days x 24 hours for each scenario.

Table 3.14 Parameters of Base Case

| Parameters | *Value* |
|---|---|
| City | Ankara |
| Shape | LongRectangle |
| Rotation | 0 |
| Exterior wall construction | 50 mm-rock wool insulated AAC wall |
| Exterior window construction | COMFORT 4+12+4 |
| Exterior roof construction | 120 mm-glass wool insulated roof |
| Interior ceiling construction | 200mm heavyweight concrete |
| Interior floor construction | 200mm heavyweight concrete |
| Underground floor construction | 50 mm-XPS insulated basement |
| North Glazing | 20% |
| West Glazing | 20% |
| South Glazing | 20% |
| East Glazing | 20% |
| Cooling set point | 24°C |
| Heating set point | 20°C |
| Schedule | MidriseApartment::Apartment |
| Context | - |

During the creation of the model, instead of generating each item in the model one by one, it is left to the program to create the model by providing specified parameter values. For instance, windows were created by giving certain WWR values to the program, rather than modeling the windows one by one according to their location. In the simulation, the windows are divided into multiple groups that are split over the walls, rather than simply one window per rectangular wall surface. The distance between individual windows on surfaces was set at 5 m, but this input will be overridden by the program at high glass ratios or window heights.

## 3.2 Sensitivity Analysis

Sensitivity analysis (SA) is used to measure the impact of a given set of inputs on a particular output (Saltelli et al., 2004). SA can be used in a variety of disciplines, including business analysis, investment, environmental studies, engineering, physics, and chemistry, as well as building energy performance analysis. SA is usually performed in conjunction with energy simulations to understand buildings energy performance (Attia et al., 2012; Calleja Rodríguez et al., 2013). SA of energy models is performed to prioritize the design parameters in order of their influence on energy consumption (Mahan & Geyer, 2020). Once the relationships and relative importance of the design parameters are understood, the important design parameters can easily be selected to improve building performance (Nguyen & Reiter, 2015). In this study, sensitivity analysis was performed using the data obtained from the energy simulations to determine the most effective parameter on building energy consumption.

Sensitivity analysis methods used in building performance can be categorized into two main groups local and global sensitivity analysis (Tian, 2013). In this study, local sensitivity analysis, which is also known as differential sensitivity analysis, was used; it is a one-factor-at-a-time method. Sensitivity measures in this method are typically calculated when one factor is changed while all other factors remain constant (Tian, 2013), so it was determined that this method was appropriate for this study.

In this study, the sensitivity analysis was performed by listing the annual total heating and cooling consumption values of each analysis. A total of 185 analyzes were obtained from 22 different parameters by changing only one variable on the main model, Table 4.1 exhibits these analyses and results. Since the objective of this study is to examine the effect of parameters on energy consumption, it is focused on how much change each case causes rather than these consumption values. For this reason, the sensitivity analysis was made over the changes in the total energy consumption and for this, the base case analysis results were extracted from each analysis.

A total of 185 analyzes were produced by changing only one variable on the main model. As presenting such a large number of analyses in a single graphic would be difficult and complex, the parameters were first evaluated within themselves, so that the changes within them could be observed more clearly. Then, 30% of the cases that caused the highest change among all cases were determined and a sensitivity analysis was made among them. As a result of this elimination, 55 out of 185 analyzes were evaluated, so it was possible to express them in a single figure.

In addition, a spider diagram was created for the energy analysis of two parameters for two cases: building shape and orientation, wall materials, wall insulation material, and thicknesses. The shape and orientation were evaluated together to see how much the total energy consumption would change when a different shape was chosen at a different angle than the base case. In addition, since it is seen in the literature that the walls are effective in terms of energy consumption due to their large area (S. Chen et al., 2020), the parameters related to the wall (wall material, wall insulation material, and thickness) were evaluated together.

# CHAPTER 4

# RESULTS AND DISCUSSION

In Chapter 3, the case study developed to evaluate building energy performance is described. This chapter presents the results of energy simulations and sensitivity analysis results for one parameter and two parameters. Furthermore, the most effective parameters on the building energy consumption is determined by using sensitivity analysis.

## 4.1 Results of Energy Simulations

In the Table 4.1, where the results of the energy simulations are tabulated, the calculated energy consumption values represent the annual total consumption values. The base case's relevant parameters and their values are highlighted in bold in the table.

Table 4.1 Result of Energy Simulations

| ID | | Parameter | Heating Energy (kWh) | Cooling Energy (kWh) | Total Energy (kWh) |
|---|---|---|---|---|---|
| A1 | Location | **Ankara** | **94136.84** | **222116.07** | **316252.91** |
| A2 | | İstanbul | 16771.45 | 406623.19 | 423394.64 |
| A3 | | İzmir | 393.47 | 522910.77 | 523304.24 |
| A4 | | Kayseri | 111704.92 | 276043.06 | 387747.98 |
| A5 | | Erzurum | 368806.31 | 149973.06 | 518779.38 |
| B1 | Shape | Square | 82811.15 | 225044.77 | 307855.92 |
| B2 | | **LongRectangle** | **94136.84** | **222116.07** | **316252.91** |
| B3 | | ShortRectangle | 76281.73 | 213329.68 | 289611.41 |
| B4 | | Lshaped | 115605.00 | 201538.33 | 317143.32 |
| B5 | | L+Ishaped | 148473.50 | 250032.15 | 398505.65 |
| B6 | | Ushaped | 130254.56 | 223893.13 | 354147.68 |
| B7 | | Lladdered | 83212.66 | 214943.45 | 298156.11 |
| B8 | | Lvertical | 97879.36 | 238358.96 | 336238.32 |

Table 4.1 Result of Energy Simulations (continued)

| ID | | Parameter | Heating Energy (kWh) | Cooling Energy (kWh) | Total Energy (kWh) |
|---|---|---|---|---|---|
| B9 | | Octagon | 71126.53 | 220986.05 | 292112.58 |
| B10 | | Decagon | 69904.53 | 220607.74 | 290512.28 |
| B11 | | Hshaped | 107100.60 | 235414.63 | 342515.24 |
| B12 | | PlusShaped | 126378.97 | 227751.93 | 354130.91 |
| C1 | Floor Height | 2.5m | 55610.73 | 322851.86 | 378462.59 |
| C2 | | 3.33m | 78437.10 | 255480.46 | 333917.56 |
| C3 | | **4m** | **94136.84** | **222116.07** | **316252.91** |
| C4 | | 5m | 113715.91 | 189001.60 | 302717.52 |
| D1 | Orientation | **0** | **94136.84** | **222116.07** | **316252.91** |
| D2 | | 15 | 95232.00 | 223915.98 | 319147.98 |
| D3 | | 30 | 97952.27 | 229046.98 | 326999.25 |
| D4 | | 45 | 100884.39 | 235118.39 | 336002.78 |
| D5 | | 60 | 103023.63 | 238985.16 | 342008.78 |
| D6 | | 75 | 103883.32 | 240949.78 | 344833.10 |
| D7 | | 90 | 103789.49 | 241562.27 | 345351.76 |
| D8 | | 105 | 103188.99 | 240734.39 | 343923.38 |
| D9 | | 120 | 101939.55 | 238721.83 | 340661.38 |
| D10 | | 135 | 99945.99 | 234743.01 | 334689.00 |
| D11 | | 150 | 97377.28 | 228811.46 | 326188.74 |
| D12 | | 165 | 95072.02 | 223903.93 | 318975.95 |
| E1 | Wall Material | **AAC wall** | **94136.84** | **222116.07** | **316252.91** |
| E2 | | brick | 137877.46 | 217610.72 | 355488.19 |
| E3 | | doublebrick | 114789.36 | 213042.81 | 327832.16 |
| E4 | | drywall | 39562.55 | 220303.63 | 259866.18 |
| F1 | Wall Insulation Material | **Rockwool** | **94136.84** | **222116.07** | **316252.91** |
| F2 | | XPS | 73393.07 | 221367.69 | 294760.76 |
| F3 | | EPS | 80486.71 | 221616.55 | 302103.26 |
| F4 | | GlassWool | 88235.75 | 221896.18 | 310131.93 |
| G1 | Wall Insulation Material Thickness | 10 mm | 184750.04 | 226085.61 | 410835.65 |
| G2 | | 20 mm | 150227.41 | 224464.37 | 374691.78 |
| G3 | | 30 mm | 125838.60 | 223392.36 | 349230.97 |
| G4 | | 40 mm | 107824.86 | 222647.37 | 330472.23 |
| G5 | | **50 mm** | **94136.84** | **222116.07** | **316252.91** |
| G6 | | 60 mm | 83516.82 | 221724.95 | 305241.77 |
| G7 | | 70 mm | 75155.70 | 221428.50 | 296584.19 |
| G8 | | 80 mm | 68339.21 | 221197.90 | 289537.11 |
| G9 | | 90 mm | 62739.12 | 221014.45 | 283753.57 |
| G10 | | 100 mm | 58135.97 | 220865.06 | 279001.04 |
| G11 | | 110 mm | 54175.57 | 220742.10 | 274917.67 |
| G12 | | 120 mm | 50834.39 | 220638.93 | 271473.32 |

Table 4.1 Result of Energy Simulations (continued)

| ID | | Parameter | Heating Energy (kWh) | Cooling Energy (kWh) | Total Energy (kWh) |
|---|---|---|---|---|---|
| H1 | Window Material | sdg4 | 105841.68 | 286714.23 | 392555.91 |
| H2 | | sdg6 | 108524.28 | 275571.97 | 384096.25 |
| H3 | | sinergy4 | 77338.08 | 244882.51 | 322220.59 |
| H4 | | sinergy6 | 80107.14 | 240623.20 | 320730.33 |
| H5 | | **comfort4** | **94136.84** | **222116.07** | **316252.91** |
| H6 | | comfort6 | 95546.37 | 220440.82 | 315987.19 |
| I1 | WWR | **nsew2** | **94136.84** | **222116.07** | **316252.91** |
| I2 | | n3sew2 | 101812.32 | 227153.91 | 328966.24 |
| I3 | | n4sew2 | 109603.22 | 232171.72 | 341774.94 |
| I4 | | n5sew2 | 117490.11 | 237029.95 | 354520.05 |
| I5 | | n6sew2 | 124960.49 | 241922.30 | 366882.79 |
| I6 | | n7sew2 | 132445.48 | 246804.41 | 379249.89 |
| I7 | | n8sew2 | 139921.09 | 251617.10 | 391538.19 |
| I8 | | s3new2 | 90323.98 | 232094.36 | 322418.34 |
| I9 | | s4new2 | 87081.16 | 242152.41 | 329233.57 |
| I10 | | s5new2 | 84366.17 | 252228.54 | 336594.71 |
| I11 | | s6new2 | 81819.14 | 262317.26 | 344136.40 |
| I12 | | s7new2 | 79646.90 | 272423.94 | 352070.84 |
| I13 | | s8new2 | 77757.34 | 282517.89 | 360275.23 |
| I14 | | w3nse2 | 95929.75 | 227222.23 | 323151.98 |
| I15 | | w4nse2 | 97725.04 | 232324.68 | 330049.73 |
| I16 | | w5nse2 | 99530.40 | 237412.31 | 336942.71 |
| I17 | | w6nse2 | 101122.23 | 242427.59 | 343549.82 |
| I18 | | w7nse2 | 102786.59 | 247403.13 | 350189.72 |
| I19 | | w8nse2 | 104429.41 | 252361.75 | 356791.17 |
| I20 | | e3nsw2 | 96031.61 | 227850.75 | 323882.36 |
| I21 | | e4nsw2 | 97844.44 | 233610.65 | 331455.09 |
| I22 | | e5nsw2 | 99848.23 | 239381.83 | 339230.06 |
| I23 | | e6nsw2 | 101628.26 | 245164.95 | 346793.21 |
| I24 | | e7nsw2 | 103381.15 | 250966.69 | 354347.85 |
| I25 | | e8nsw2 | 105137.21 | 256779.25 | 361916.46 |
| J1 | Roof Material | **metal** | **94136.84** | **222116.07** | **316252.91** |
| J2 | | asphalt | 91193.10 | 221796.21 | 312989.31 |
| J3 | | tile | 82389.83 | 220876.23 | 303266.06 |
| K1 | Roof Insulation Material | **GlassWool** | **94136.84** | **222116.07** | **316252.91** |
| K2 | | RockWool | 96656.19 | 222385.26 | 319041.44 |
| K3 | | XPS | 88456.20 | 221506.08 | 309962.28 |
| K4 | | EPS | 91075.22 | 221787.99 | 312863.21 |
| L1 | Roof Insulation Material Thickness | 10 mm | 254532.15 | 237483.23 | 492015.38 |
| L2 | | 20 mm | 189395.23 | 230849.30 | 420244.54 |
| L3 | | 30 mm | 157291.34 | 228048.65 | 385339.98 |

Table 4.1 Result of Energy Simulations (continued)

| ID | | Parameter | Heating Energy (kWh) | Cooling Energy (kWh) | Total Energy (kWh) |
|---|---|---|---|---|---|
| L4 | | 40 mm | 138376.90 | 226497.74 | 364874.64 |
| L5 | | 50 mm | 125973.87 | 225343.59 | 351317.46 |
| L6 | | 60 mm | 117246.26 | 224506.97 | 341753.23 |
| L7 | | 70 mm | 110806.18 | 223847.88 | 334654.06 |
| L8 | | 80 mm | 105896.99 | 223343.91 | 329240.89 |
| L9 | | 90 mm | 102040.59 | 222947.00 | 324987.59 |
| L10 | | 100 mm | 98903.69 | 222626.02 | 321529.72 |
| L11 | | 110 mm | 96315.62 | 222348.52 | 318664.14 |
| L12 | | **120 mm** | **94136.84** | **222116.07** | **316252.91** |
| L13 | | 130 mm | 92295.71 | 221918.40 | 314214.11 |
| L14 | | 140 mm | 90720.97 | 221748.84 | 312469.81 |
| L15 | | 150 mm | 89341.40 | 221601.14 | 310942.55 |
| L16 | | 160 mm | 88140.30 | 221472.18 | 309612.48 |
| L17 | | 170 mm | 87063.91 | 221358.66 | 308422.57 |
| L18 | | 180 mm | 86098.63 | 221257.57 | 307356.19 |
| L19 | | 190 mm | 85231.59 | 221167.34 | 306398.93 |
| L20 | | 200 mm | 84453.33 | 221085.60 | 305538.93 |
| M1 | Roof Angle | **flat** | **94136.84** | **222116.07** | **316252.91** |
| M2 | | 0 | 94425.49 | 237809.84 | 332235.33 |
| M3 | | 10 | 92631.34 | 237717.76 | 330349.10 |
| M4 | | 20 | 91292.22 | 237531.06 | 328823.28 |
| M5 | | 30 | 90186.22 | 237373.92 | 327560.14 |
| M6 | | 40 | 89137.57 | 237171.56 | 326309.14 |
| M7 | | 50 | 88134.25 | 236966.49 | 325100.74 |
| M8 | | 60 | 87553.81 | 236805.99 | 324359.80 |
| N1 | Basement Insulation Material | **XPS** | **94136.84** | **222116.07** | **316252.91** |
| N2 | | EPS | 94441.71 | 221494.69 | 315936.39 |
| O1 | Basement Insulation Material Thickness | 10 mm | 98354.01 | 214099.69 | 312453.70 |
| O2 | | 20 mm | 96491.43 | 217605.92 | 314097.35 |
| O3 | | 30 mm | 95386.60 | 219663.95 | 315050.55 |
| O4 | | 40 mm | 94655.29 | 221065.82 | 315721.11 |
| O5 | | **50 mm** | **94136.84** | **222116.07** | **316252.91** |
| O6 | | 60 mm | 93750.08 | 222910.61 | 316660.69 |
| O7 | | 70 mm | 93450.49 | 223528.43 | 316978.92 |
| O8 | | 80 mm | 93211.90 | 224021.67 | 317233.57 |
| O9 | | 90 mm | 93017.10 | 224424.45 | 317441.55 |
| O10 | | 100 mm | 92855.22 | 224759.75 | 317614.97 |
| O11 | | 110 mm | 92718.42 | 225043.31 | 317761.73 |
| O12 | | 120 mm | 92601.28 | 225285.98 | 317887.26 |

Table 4.1 Result of Energy Simulations (continued)

| ID | | Parameter | Heating Energy (kWh) | Cooling Energy (kWh) | Total Energy (kWh) |
|---|---|---|---|---|---|
| P1 | Interior Floor Material | **200mm heavyweight concrete** | **94136.84** | **222116.07** | **316252.91** |
| P2 | | Ceramic Tile | 95599.85 | 218677.49 | 314277.34 |
| P3 | | Laminate | 92747.63 | 220817.50 | 313565.12 |
| P4 | | Marble | 92697.41 | 220884.47 | 313581.88 |
| R1 | Interior Floor Insulation Material | **No Insulation** | **94136.84** | **222116.07** | **316252.91** |
| R2 | | GlassWool | 92747.63 | 220817.50 | 313565.12 |
| R3 | | RockWool | 92789.13 | 220751.87 | 313541.00 |
| S1 | Interior Floor Insulation Material Thickness | **No Insulation** | **94136.84** | **222116.07** | **316252.91** |
| S2 | | 10 mm | 93803.34 | 219529.14 | 313332.48 |
| S3 | | 20 mm | 93287.81 | 220130.17 | 313417.98 |
| S4 | | 30 mm | 92987.96 | 220464.27 | 313452.23 |
| S5 | | 40 mm | 92840.24 | 220666.68 | 313506.92 |
| S6 | | 50 mm | 92747.63 | 220817.50 | 313565.12 |
| S7 | | 60 mm | 92700.80 | 220928.48 | 313629.29 |
| S8 | | 70 mm | 92660.17 | 221024.21 | 313684.38 |
| S9 | | 80 mm | 92638.36 | 221097.52 | 313735.87 |
| S10 | | 90 mm | 92609.10 | 221171.61 | 313780.70 |
| S11 | | 100 mm | 92608.07 | 221218.45 | 313826.51 |
| S12 | | 110 mm | 92602.86 | 221259.05 | 313861.91 |
| S13 | | 120 mm | 93937.68 | 220284.27 | 314221.95 |
| T1 | Heating Set Points | H14 | 4535.87 | 222115.43 | 226651.30 |
| T2 | | H15 | 9165.60 | 222115.43 | 231281.03 |
| T3 | | H16 | 17657.74 | 222115.44 | 239773.18 |
| T4 | | H17 | 29854.39 | 222115.45 | 251969.84 |
| T5 | | H18 | 46455.13 | 222115.50 | 268570.63 |
| T6 | | H19 | 67705.93 | 222115.63 | 289821.55 |
| T7 | | **H20** | **94136.84** | **222116.07** | **316252.91** |
| T8 | | H21 | 126062.24 | 222122.25 | 348184.49 |
| T9 | | H22 | 165344.50 | 222160.55 | 387505.05 |
| T10 | | H23 | 219814.78 | 222416.10 | 442230.88 |
| U1 | Cooling Set points | C21 | 124741.36 | 343605.34 | 468346.70 |
| U2 | | C22 | 104952.20 | 299366.00 | 404318.20 |
| U3 | | C23 | 96756.67 | 259052.63 | 355809.31 |
| U4 | | **C24** | **94136.84** | **222116.07** | **316252.91** |
| U5 | | C25 | 93261.17 | 188622.25 | 281883.43 |
| U6 | | C26 | 92978.64 | 157917.21 | 250895.84 |
| U7 | | C27 | 92841.89 | 130325.37 | 223167.26 |
| U8 | | C28 | 92768.52 | 106429.75 | 199198.27 |
| U9 | | C29 | 92717.20 | 84875.47 | 177592.66 |

Table 4.1 Result of Energy Simulations (continued)

| ID | | Parameter | Heating Energy (kWh) | Cooling Energy (kWh) | Total Energy (kWh) |
|---|---|---|---|---|---|
| U10 | | C30 | 92679.14 | 66552.81 | 159231.95 |
| V1 | Schedule | **apartment** | **94136.84** | **222116.07** | **316252.91** |
| V2 | | office | 319181.82 | 307605.44 | 626787.3 |
| Y1 | Shading | **No shading** | **94136.84** | **222116.07** | **316252.91** |
| Y2 | | 50% north facade | 95140.82 | 220706.12 | 315846.94 |
| Y3 | | 100% north facade | 95772.32 | 219742.57 | 315514.88 |
| Y4 | | 50% south facade | 98768.29 | 216168.97 | 314937.26 |
| Y5 | | 100% south facade | 102680.17 | 212500.14 | 315180.32 |
| Y6 | | 50% west facade | 94874.16 | 220069.35 | 314943.51 |
| Y7 | | 100% west facade | 95336.57 | 218451.51 | 313788.08 |
| Y8 | | 50% east facade | 94849.17 | 219847.83 | 314697.00 |
| Y9 | | 100% east facade | 95306.09 | 218036.44 | 313342.52 |
| Y10 | | 100% all facades | 107088.90 | 202609.93 | 309698.83 |

## 4.2 Results of Sensitivity Analysis for One Parameter

A total of 185 analyzes were generated for 22 different parameters by changing only one variable at a time on the main model, as seen in Table 4.1. Since presenting such a large number of analyses in a visual would be difficult and complicated, the parameters were first analyzed within themselves, and then the ones that caused a noticeable difference in the energy consumption were determined and analyzed separately.

### 4.2.1 Location

The change in the heating, cooling and total energy consumption values according to the base location, Ankara, can be seen in Figure 4.1. When the provinces are sorted according to change in total energy consumption, it is seen that İzmir, which has a milder climate when compared to Ankara, needs much more cooling energy and less heating energy, and its total annual energy consumption is approximately

207 000 kWh more than Ankara. Erzurum ranks second in the list with an annual consumption difference of approximately 202 000 kWh. However, Erzurum, which has colder climatic conditions, needs more heating and less cooling energy than Ankara, unlike İzmir.

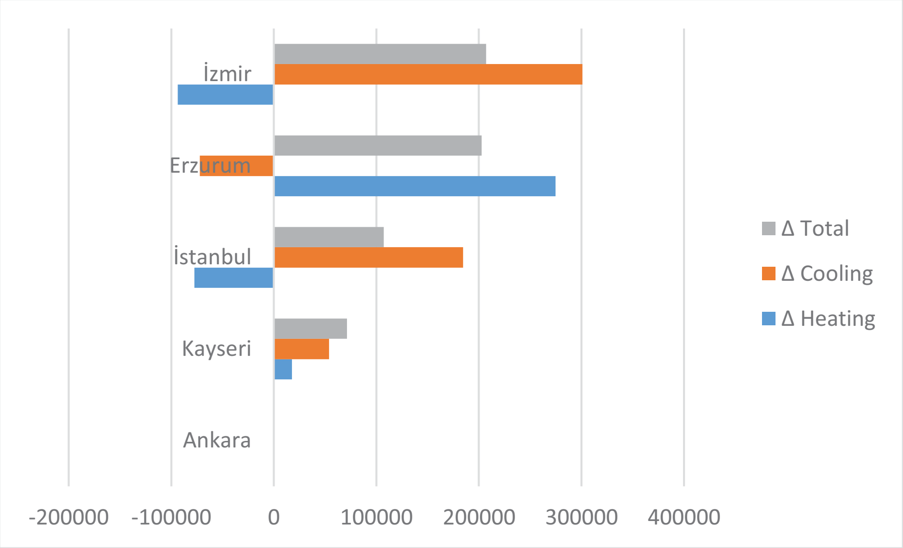


Figure 4.1. Location Parameter Effect on Energy Consumption

### 4.2.2 Shape

Figure 4.2 shows the differences in the energy consumption of the selected building forms and floor heights according to the base case, and the values in the graph are in kWh. The total energy consumption increased as the floor height decreased. Depending on the floor height, the fluctuation ranged from -13 535 kWh (for 5m height) to 62 210 kWh (for 2.5m height). On the other hand, while the ShortRectangle, Decagon, and Octagon shapes have the lowest consumption in building shapes (from least to most), the L+Ishaped have the highest consumption.

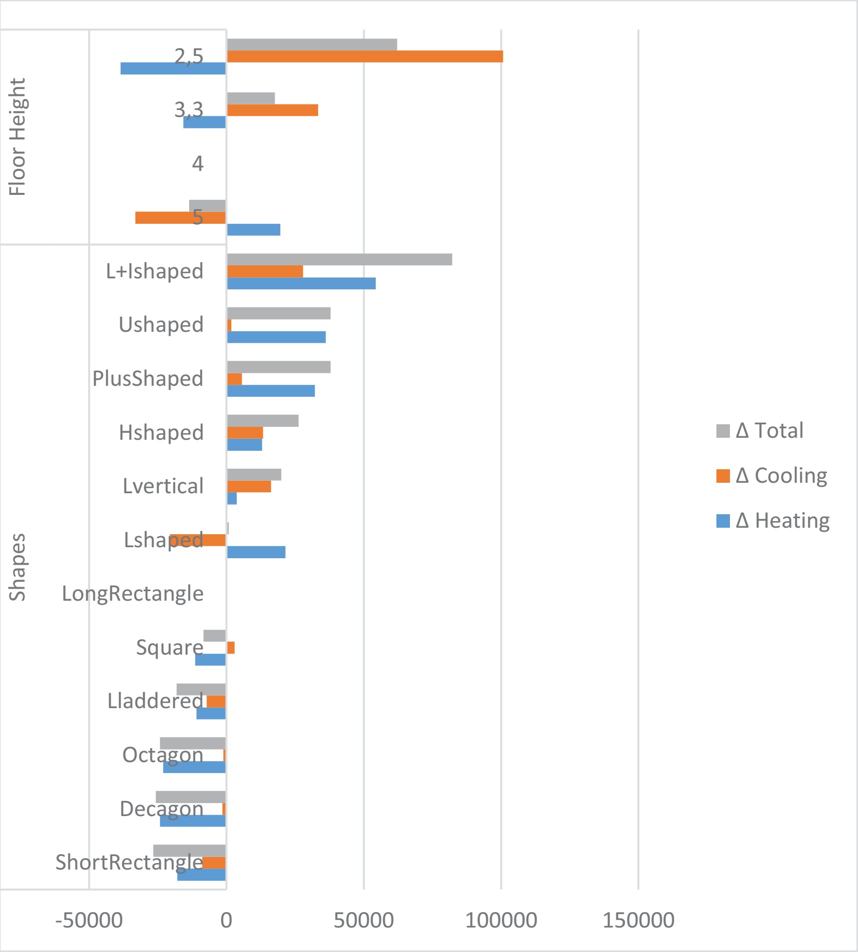


Figure 4.2. Shape Parameters' Effect on Energy Consumption

### 4.2.3 Orientation

The highest change in energy consumption values owing to orientation can be seen in Figure 4.3, which illustrates the change in energy consumption values due to orientation. It can be said that the base case gives the minimum annual total energy consumption.

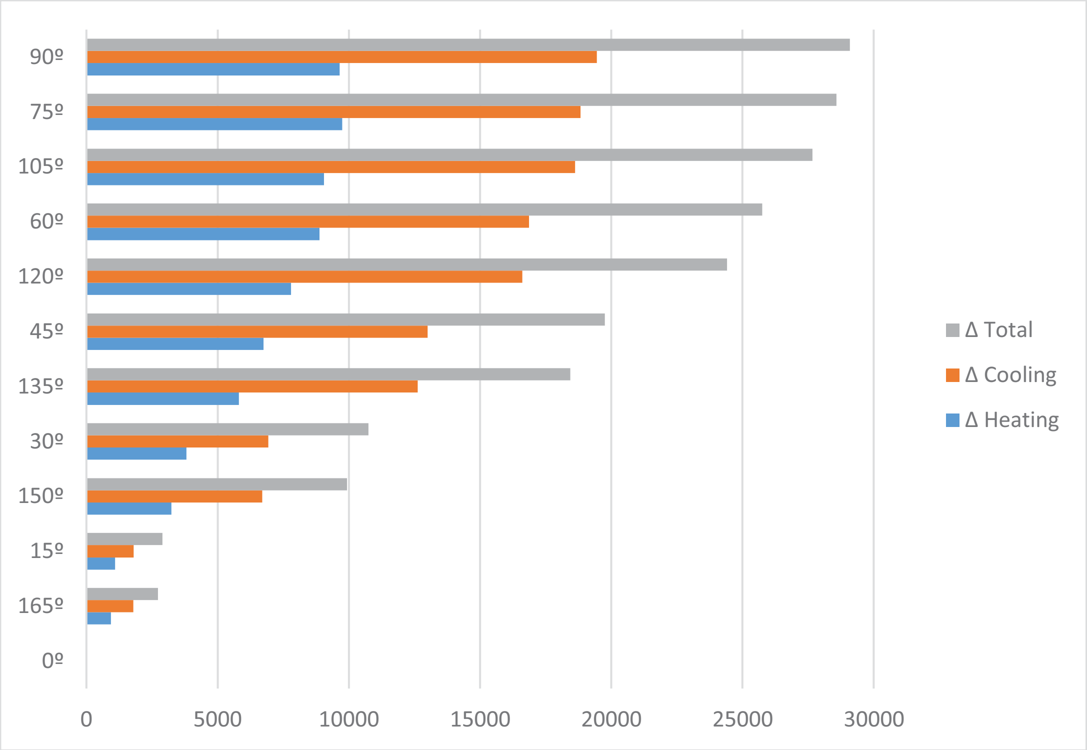


Figure 4.3. Orientation Parameter Effect on Energy Consumption

### 4.2.4 Wall

Figure 4.4 displays the energy analysis result of parameters related to the wall (wall material, wall insulation material, and thickness of insulation material). The total energy consumption change due to the wall material varies between -56 387 kWh (drywall) and 39 235 kWh (brick) per year. According to Figure 4.4, if XPS had been used as the insulation material, the annual energy consumption could have been reduced by 21 492 kWh. In addition, the thickness of the insulation material and the energy consumption are inversely proportional. While 94 583 kWh is consumed more in 10 mm thickness, 44 780 kWh is consumed less in 120 mm thickness.

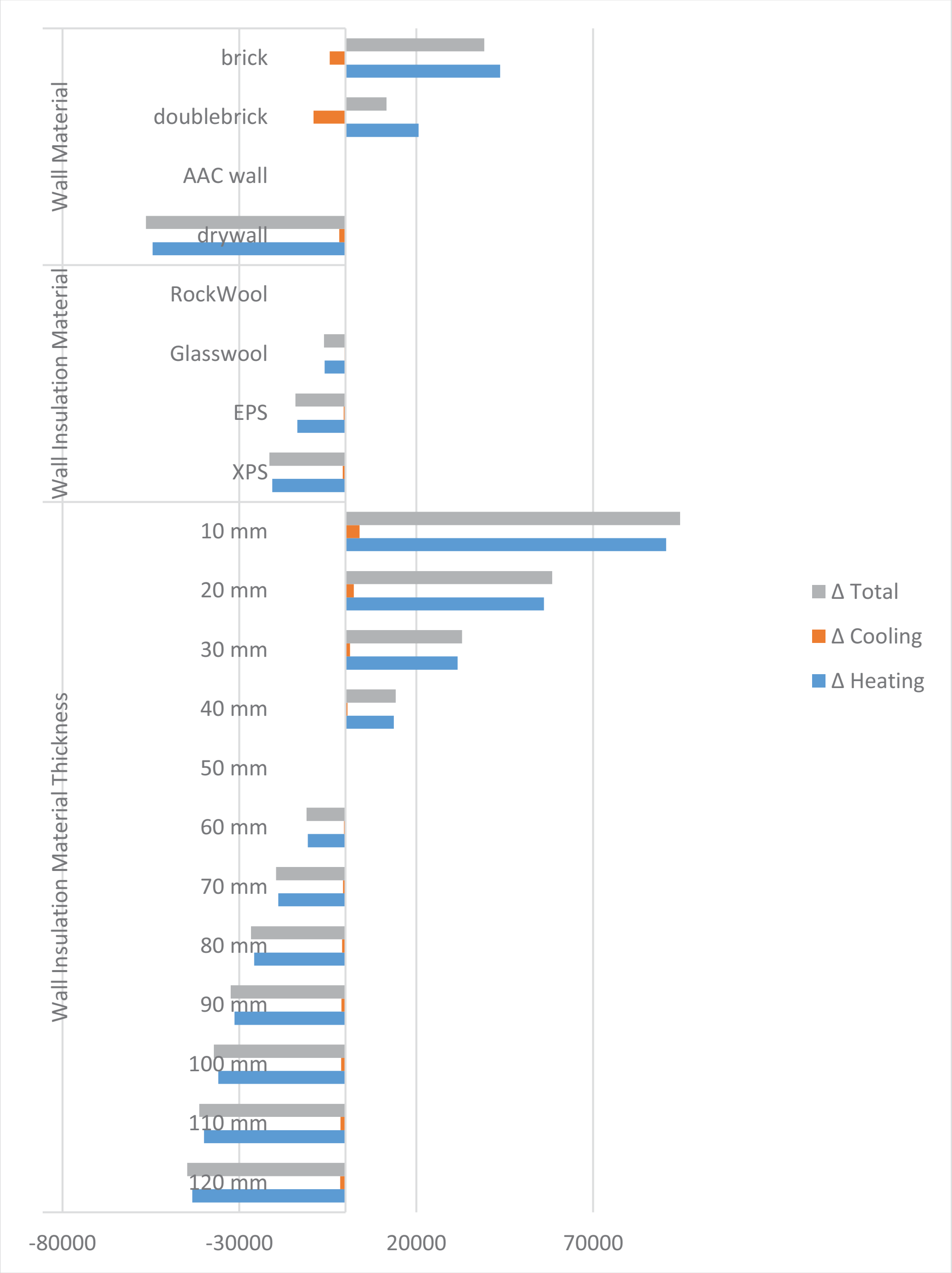


Figure 4.4. Wall Parameters' Effect on Energy Consumption

### 4.2.5 Window

Figure 4.5 exhibits the analysis results of window related parameters: window material and WWR. Based on Figure 4.5, it can be concluded that in general, as WWR increases, energy consumption increases. The increase in WWR in the south direction leads to a decrease in heating energy, while it causes an increase in the energy required for cooling, which causes an increase in total consumption. In addition, the change caused by the window material varies between -266 kWh (comfort6) and 11 705 kWh (sdg4).

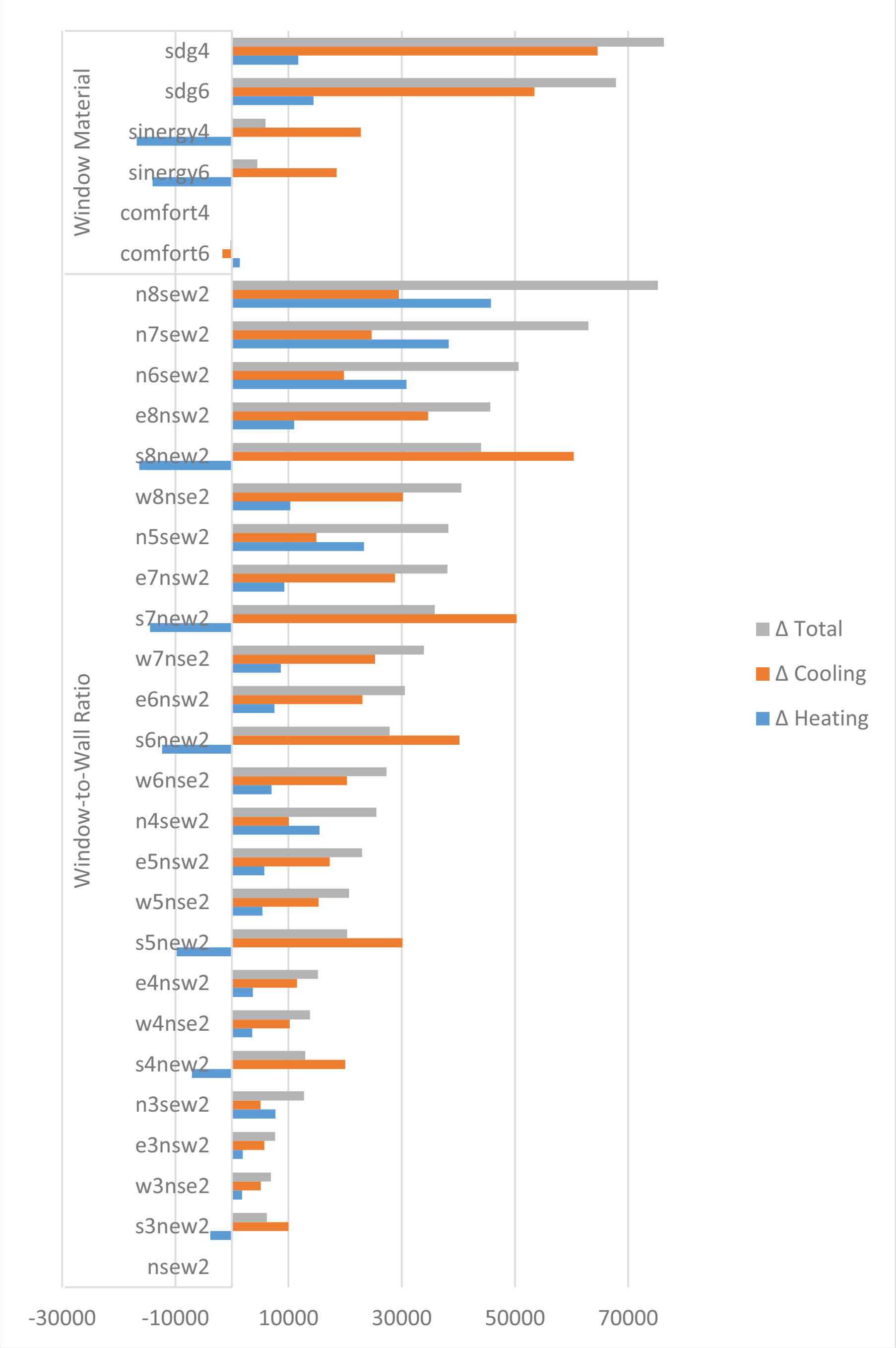


Figure 4.5. Window Parameters' Effect on Energy Consumption

### 4.2.6 Roof

When the parameters related to the roof (roof material, insulation material, insulation material thickness and roof angle) are evaluated together, it is seen that a remarkable change is in the thickness of the insulation material. Figure 4.6 shows the total annual energy consumption change with respect to the base case and the values in the graph are in kWh.

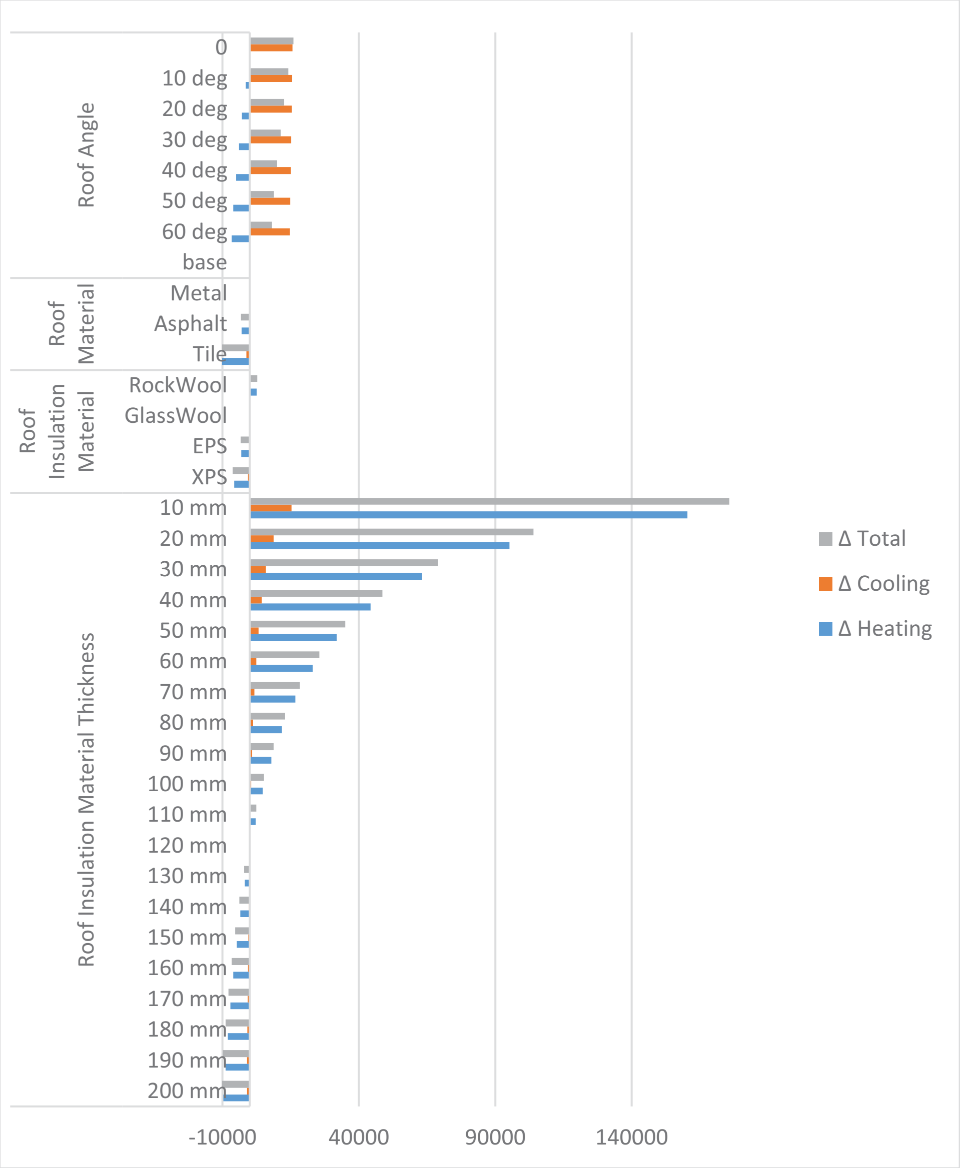


Figure 4.6. Roof Parameters’ Effect on Energy Consumption

### 4.2.7 Interior Floor

Figure 4.7 displays the relationship between the coating material, insulation material, and thickness of the insulation material of the interior floor and annual energy consumption values. The values in the graph are obtained by subtracting the base case value, that have only structural concrete, from each case, and the values shown are in kwh units. As seen in Figure 4.7, change values provided by all cases are around -2 000 kWh annually, there is no remarkable difference between these cases.

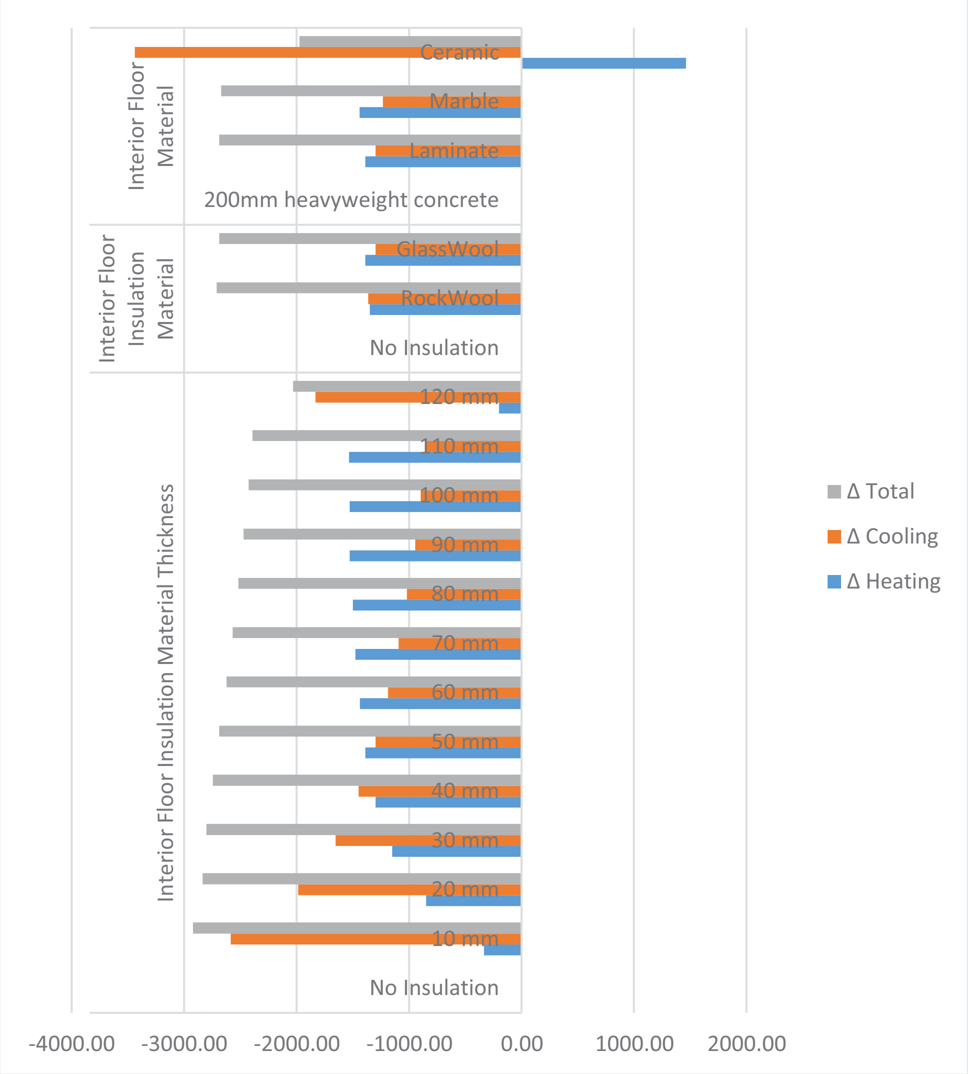


Figure 4.7. Interior Floor Parameters' Effect on Energy Consumption

### 4.2.8 Basement

In Figure 4.8, where the parameters related to basement were displayed, the thickness of the insulation material is the most striking parameter, and this parameter has resulted in an annual energy consumption reduction of only 4 000 kWh from the base case.

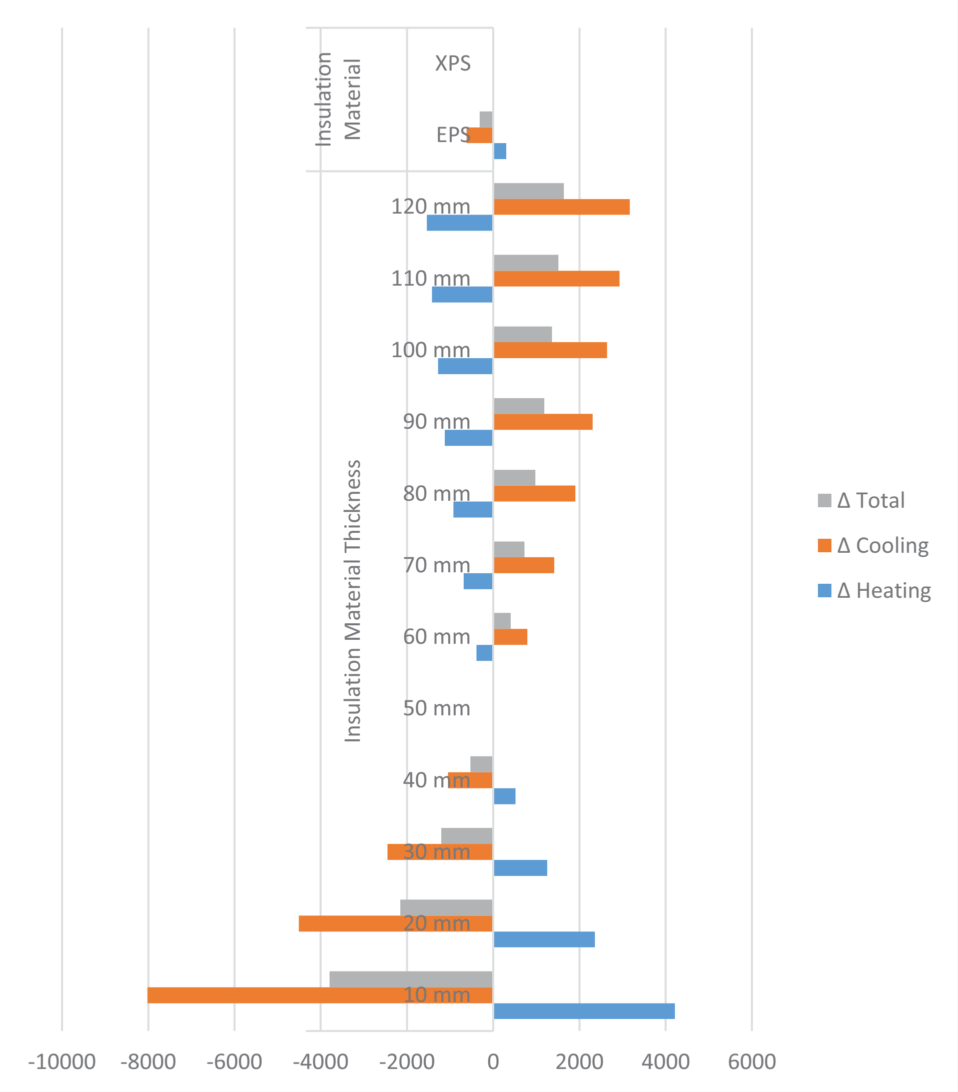


Figure 4.8. Basement Parameters' Effect on Energy Consumption

### 4.2.9 HVAC

Figure 4.9 displays the parameters related to HVAC system. When the parameters of the HVAC system are evaluated, it is seen that they have a noticeable effect on the total energy consumption.

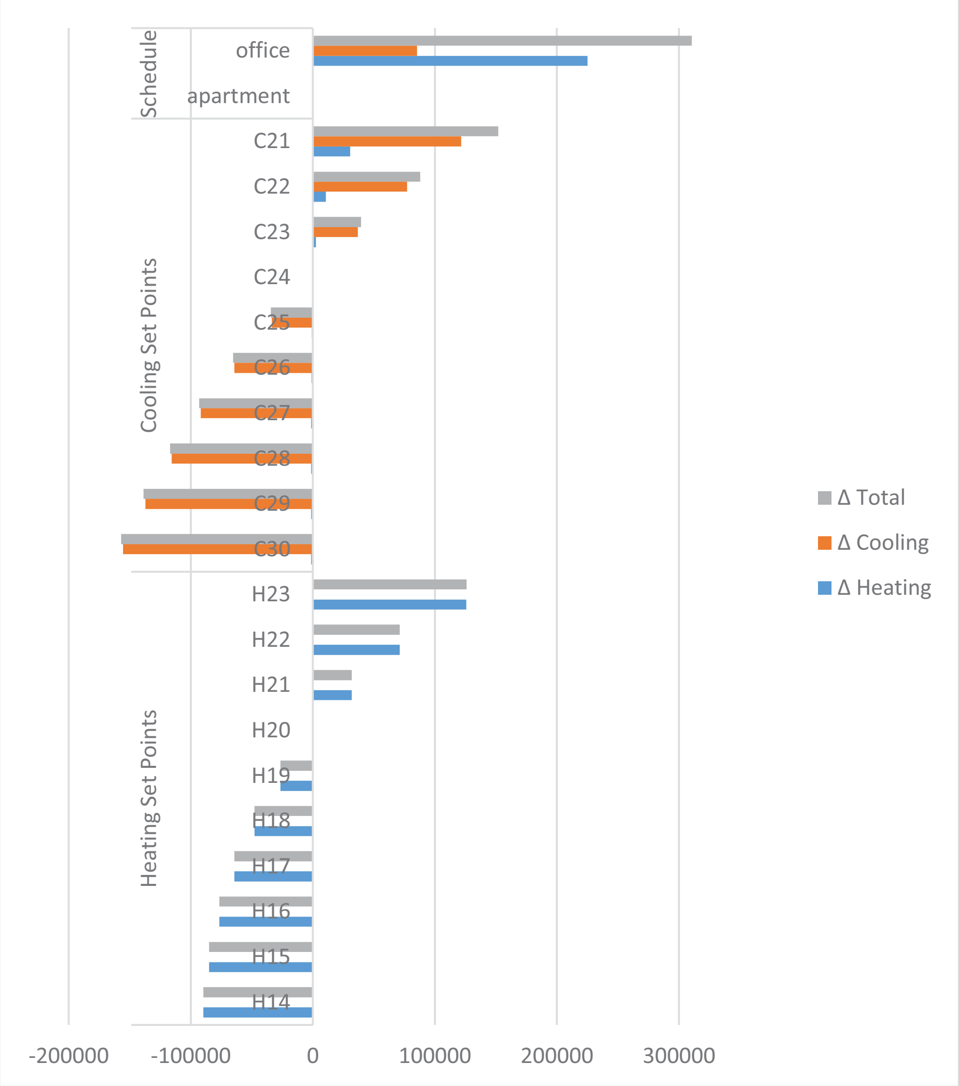


Figure 4.9. HVAC Parameters' Effect on Energy Consumption

When the parameters of the HVAC system are evaluated, it is seen that they have a noticeable effect on the total energy consumption. As it seen in Figure 4.9, total energy consumption value increases as the heating set point value increases, and the consumption values range from -89 602 kWh to 125 978 kWh. Conversely, as the cooling set point increases, the consumption value falls, and the consumption values fluctuate between -157 021 kWh and 152 094 kWh. Besides, HVAC schedules have a considerably greater effect causing a 310 534 kWh energy consumption change in the office program.

### 4.2.10 Shading

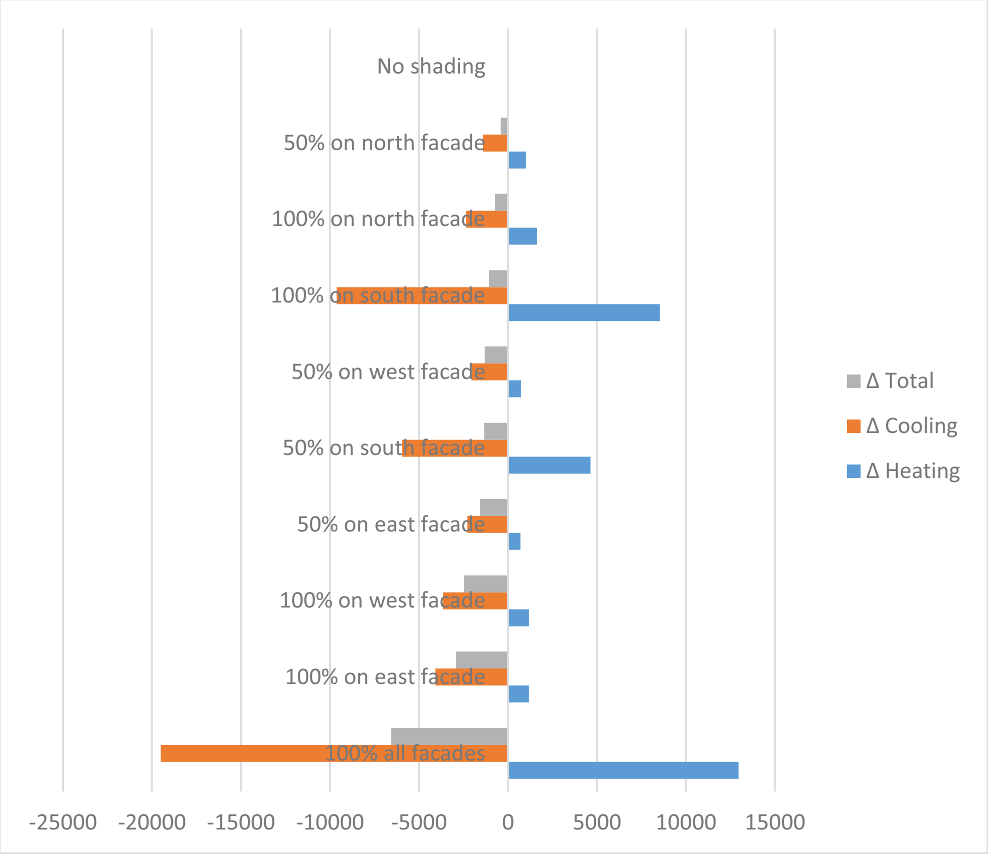


Figure 4.10. Shading Parameter’s Effect on Energy Consumption

Figure 4.10 shows shading and its effect on annual energy consumption. As the part of the building exposed to the shade increased, the energy required for heating increased, while the amount of cooling and total energy consumption decreased. When all facades are shaded, the decrease in total energy consumption is the most, with a value of -6 554 kWh.

## 4.3 Results of Sensitivity Analysis for Two Parameters

As mentioned in the previous sections, the model based energy consumption analyses were carried out by changing only one parameter at a time throughout this study. However, in this section, more than one parameter was evaluated together for two different situations. The first of these situations is shape and rotation which was created to see how much the total energy consumption would change if both a different shape and rotation was chosen from the base case. The other one is wall material, insulation material, and thickness of the insulation material. In general, wall insulation is regarded as the most effective insulation placement due to its large area (S. Chen et al., 2020). For this reason, it was decided to perform a sensitivity analysis with these parameters to observe the effect of the material, insulation, and thickness used in the walls on energy consumption.

### 4.3.1 Shapes and Rotation

In order to observe the effect of shape and rotation on total energy consumption, 12 different shapes listed in Figure 3.3 were rotated at 15º angles, and a total of 186 different states were obtained. Subsequently, a sensitivity analysis was performed using these energy analysis results. Figure 4.11 shows changes in the total energy consumption of the each case according to base case which is the Longrectangle shape with no rotation, and the values are shown in kWh.

As stated under the heading 3.1.2.3, there is no need to perform 24 different analyses for each shape because symmetrical shapes come to the same point from a certain angle and the same results are obtained. The values in Figure 4.11 represent the change in annual total energy consumption that is calculated by subtracting the energy consumption in the base case from the total annual energy consumption of each case.

According to Figure 4.11, when the building forms are listed according to energy consumption from least to most, it is seen that ShortRectangle, Decagon and

Octagon shapes provide the least amount of consumption, and L+Ishaped causes the highest consumption. In addition, it can be deduced that the consumption values of ShortRectangle, Decagon, Octagon, Lladdered and Square forms at all angles, as well as the consumption values of Lvertical in some angles, are less than the total annual energy consumption of the base case.

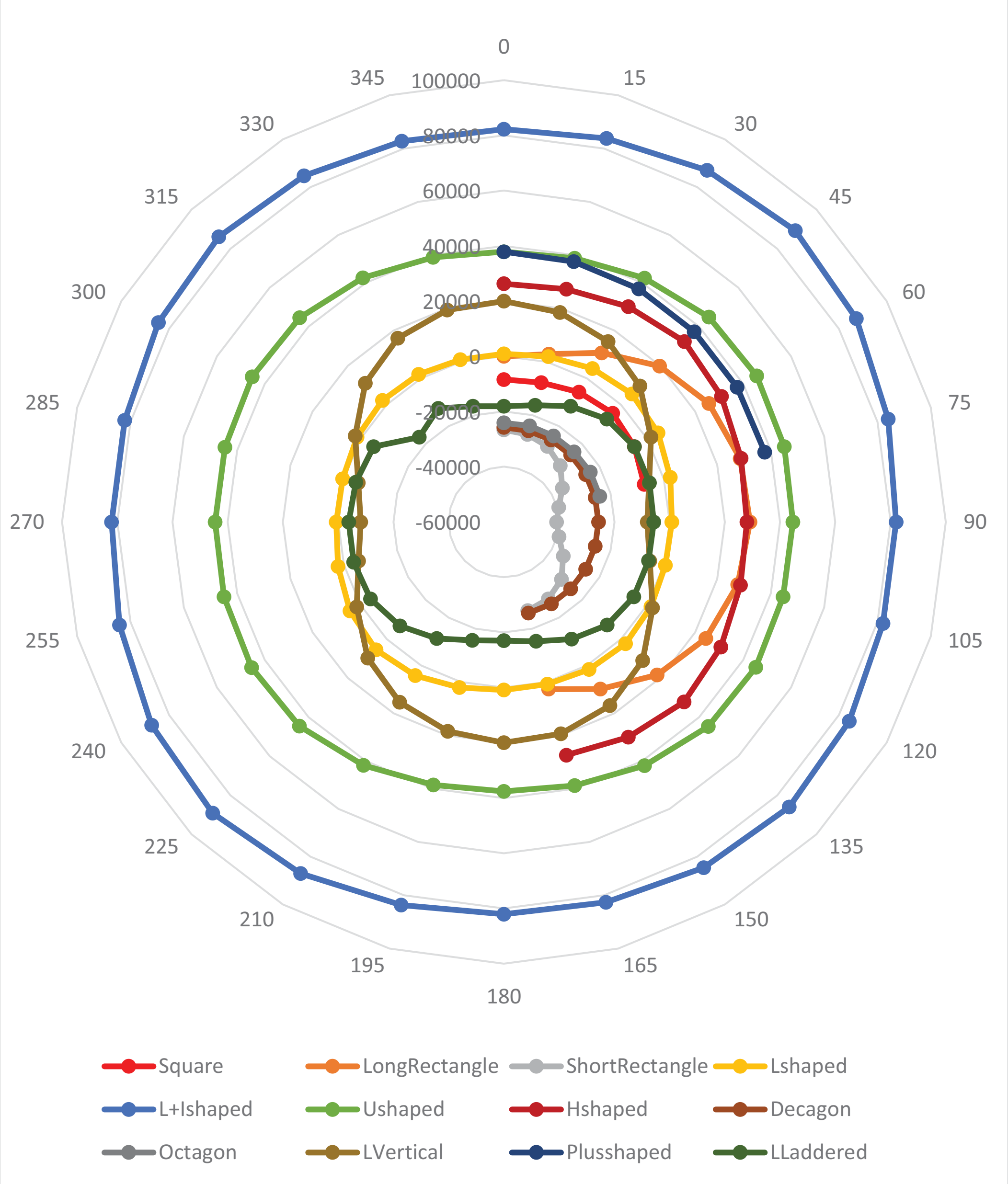


Figure 4.11. Differences of Energy Consumption due to Different Building Shapes and Orientations

Table 4.2 was created to see how much of a change in total annual energy consumption could have been made if different building shapes and rotations were selected from the base case. Table 4.2 displays the floor area of each shape, the maximum and minimum energy change values relative to the base case, and the total change value to show the total difference between the maximum and the minimum. It is seen that the forms that give the least variation between the max and min energy change values are Decagon, Octagon and PlusShaped, respectively. In Decagon and Octagon shapes, no matter how much the rotation angle changes, the change in total energy is quite low, which can be associated with the fact that these shapes are close to oval shape. In addition, the small change in PlusShaped can be associated with the fact that these shapes are compact and quite symmetrical compared to the others. Nevertheless, by looking at Table 4.2, a straight correlation between floor area and energy use cannot be drawn.

Table 4.2 Total Energy Consumption Difference of Each Building Form

| Shape Name | Floor Area ($m^2$) | Max kWh Change | Min kWh Change | Total Change Difference |
|---|---|---|---|---|
| Square | 9600 | -4322.9 | -7713.4 | 3390.5 |
| LongRectangle | 10320 | 28580.2 | 2895.1 | 25685.1 |
| ShortRectangle | 11200 | -26641.5 | -40930.8 | 14289.3 |
| Lshaped | 13600 | 5558.8 | 820.3 | 4738.5 |
| L+Ishaped | 14400 | 89197.3 | 81999.9 | 7197.4 |
| Ushaped | 13600 | 45681.8 | 38863.3 | 6818.6 |
| Hshaped | 13600 | 32364.4 | 27289.1 | 5075.3 |
| Decagon | 8968 | -25740.6 | -25773.1 | 32.4 |
| Octagon | 9025 | -23949.3 | -24140.3 | 191.1 |
| Lvertical | 13520 | 19985.4 | -8128.5 | 28113.9 |
| PlusShaped | 11680 | 37878.0 | 37473.6 | 404.4 |
| Lladdered | 24640 | -5441.3 | -16233.6 | 10792.3 |

### 4.3.2 Wall Material, Wall Insulation Material and Thickness

To observe the effect of the wall material, insulation material, and thickness of the insulation material on the total energy consumption, a sensitivity analysis as seen in Figure 4.12 was performed. In the base case, a 50 mm rock wool insulated AAC wall is utilized, and several scenarios are generated by applying other insulation materials to the same wall material and the same insulation material to different wall materials, with altering the thickness of the insulation material between 10 mm and 120 mm. As in previous part, the values in Figure 4.12 represent the change in annual total energy consumption, and the values are shown in kWh.

As shown in Figure 4.12, while the energy consumption difference between the cases is quite high at low insulation material thickness, there are no significant differences after a certain thickness. It can also be observed that changing the wall material has a higher impact than changing the insulation material. Considering the R-values in Table 3.3, the lower energy consumption of drywall can be explained to its relatively high R-value compared to the others.

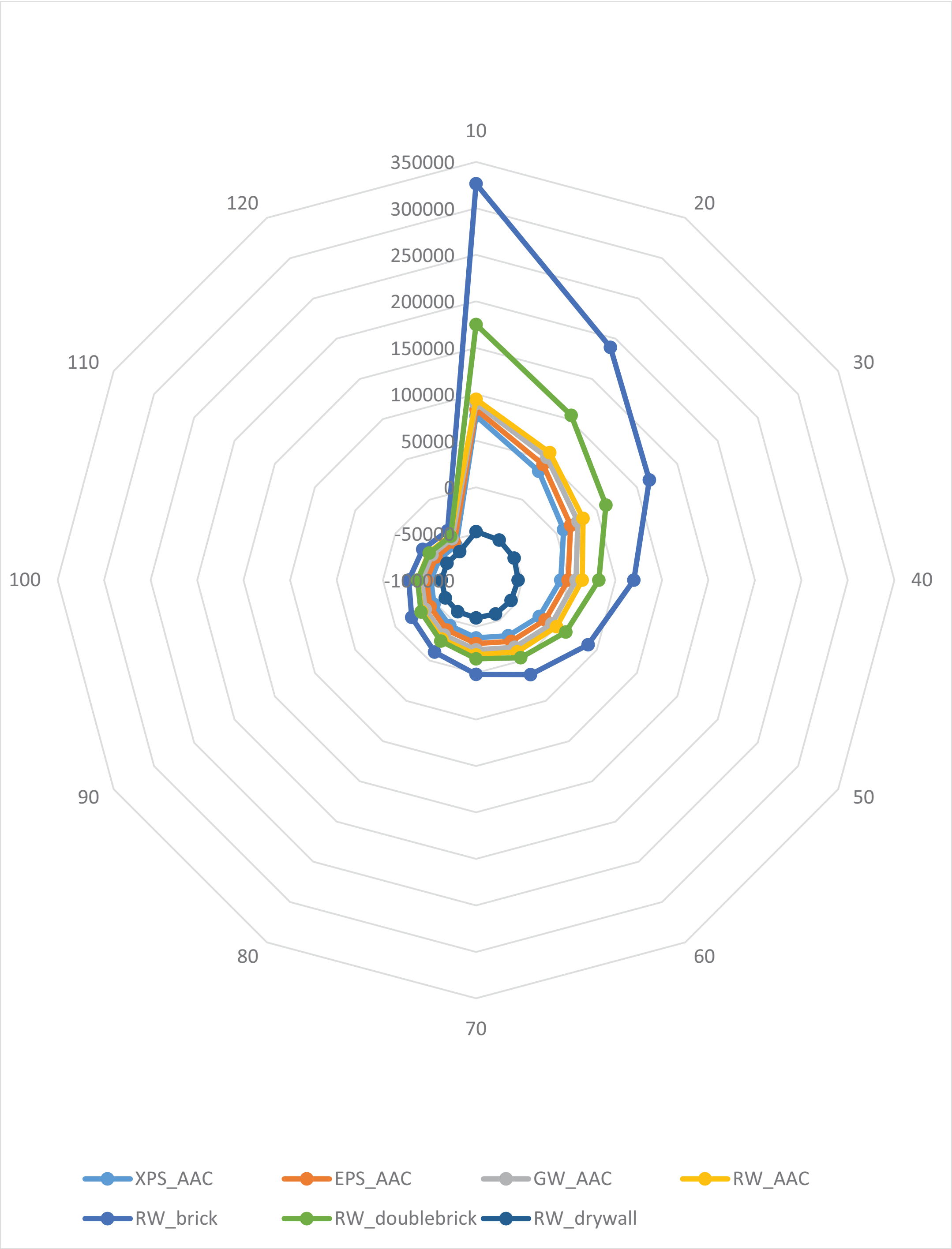


Figure 4.12. Differences of Energy Consumption due to Different Wall Material, Wall Insulation Material and Thickness

## 4.4 Determination of Most Effective Parameter

To determine the most effective parameters on the building energy performance, a sensitivity analysis was conducted. As shown in Table 4.1, a total of 185 analyses were created. Since displaying so many results in a single figure would be difficult and incomprehensible, and the main purpose of the study is to determine the most effective parameters, it was preferred to eliminate relatively unimportant parameters before visualization. Considering the results in Table 4.1, the differences in heating, cooling, and total energy consumption of all cases according to the base case were calculated and listed, and it was seen that the differences in total consumption change ranges between -157 021 kWh and 310 534 kWh. In order to eliminate relatively small values in such a range, 30% of the data that caused the highest change out of 185 cases were identified; the others were removed from the list and consequently results to observe are reduced to 55 cases. A sensitivity analysis was created among the remaining cases and the results of this analysis are shown in Figure 4.13. The expressions on the vertical axis in Figure 4.13 are the IDs, as in Table 4.1, and each represents a case.

According to Figure 4.13, considering the absolute values of the total energy changes of the parameters, it is seen that the most effective parameters are HVAC schedule, location (İzmir and Erzurum), the thickness of the roof insulation material (10 mm-glass wool insulated roof) and HVAC setpoints (cooling setpoints).

In most cases, the location of the project is determined at the beginning, and in such cases, this parameter is not a variable. Furthermore, considering that the HVAC schedule and setpoints may also vary depending on the person and building use, it would not be unreasonable to disregard these parameters in order to guide the building designers. If the rest of the parameters are sorted, the parameters that have the greatest impact on energy consumption are roof insulation material thickness (10mm, 20mm) and wall insulation material thickness (10mm), shape (L+Ishaped), window material (sdg4), and WWR, respectively.

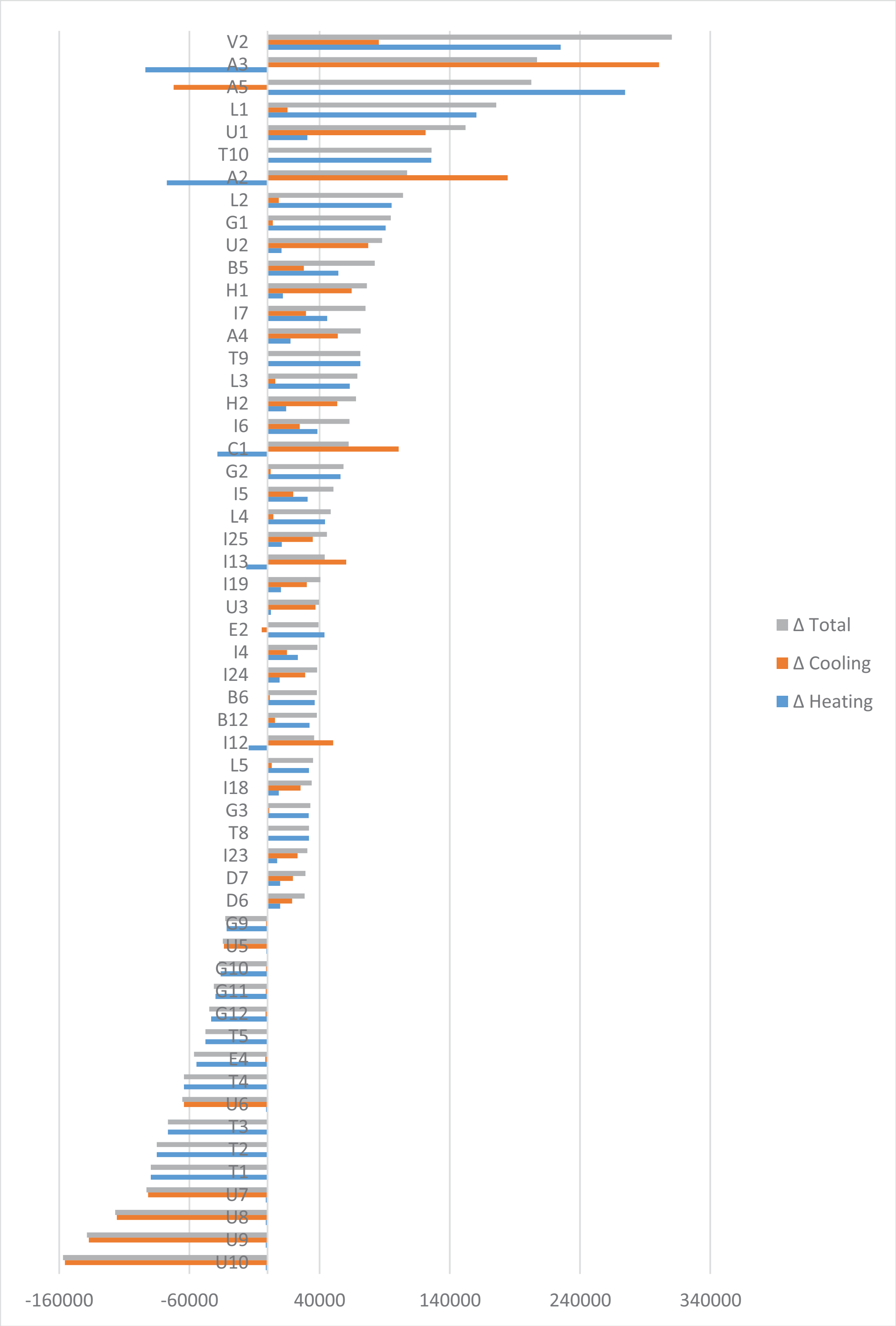


Figure 4.13. Sensitivity Analysis for Determining the Most Effective Parameters

Considering Table 2.7, which is mentioned in the literature review chapter and lists multicriteria studies, Singh & Geyer, (2020) was the study that dealt with the most parameters for 9 of the 13 titles mentioned in the table. Singh & Geyer, (2020) categorized the parameters and when the categories were ordered in order of importance, they obtained geometrical parameters, technical specifications and operational design parameters, window structure, and system efficiency parameters, respectively. As a result of the sensitivity analysis performed in this study, it was seen that the operational parameters, HVAC schedule and setpoints, have the most effect on building energy consumption similar to the Singh & Geyer's (2020) study. In addition, location and HVAC set point values, which are other most influential parameters in this study, are not included in that study.

None of the studies in Table 2.7 considered location and HVAC together, which are the most effective parameters determined as a result of the sensitivity analysis in this study.

# CHAPTER 5

# CONCLUSION

Conventional building energy modeling has some drawbacks, such as time-consuming model preparation, model inconsistencies, and high implementation costs. BIM-based analysis has the potential to overcome these drawbacks but still requires human involvement and a considerable amount of time to generate models for each design alternatives and perform energy analysis for each of these options. If parameters effecting the energy consumption of a building can be analyzed, instead of creating energy simulations for each case, the most effective alternatives can be tested by the designers. Moreover, an evaluation of these parameters may support the optimization of building energy performance. Periodic and initial cost values are required to calculate the life cycle cost assessment, and the annual energy consumption cost can be calculated through the consumption amount obtained as a result of these analyzes, and thus the most optimum case can be determined.

Building energy performance is a complex problem that depends on many parameters, and each parameter is in relationship with other parameters. The energy analysis was conducted multiple times in this study, with only one parameter changed at a time. This approach is preferred as the goal of this study is to see how the parameters affect energy usage rather than to get all conceivable combinations of parameters in order to achieve the best results. The results obtained through these analyzes were used to determine the most effective parameter by local sensitivity analysis.

## 5.1 Major Findings

The main outcomes of this study are determining the parameters used in the building performance assessments by performing a detailed literature search and performing an energy analysis by keeping all other parameters constant for each factor with a hypothetical case study regarding these determined parameters.

The energy consumption values obtained in this study can be used to support multi-objective optimization by calculating the life cycle cost for each case. The annual energy consumption amount produced by each alternative situation is associated with energy prices, the annual energy consumption amount is calculated, and the life cycle cost is obtained by summing up with the initial costs caused by these situations. The case that provides the least cost among the options can be considered as the optimum option. In addition, by increasing the number of objectives (initial cost, life cycle cost, annual energy consumption), the results of the multi-objective optimization problem can be determined by calculating the values of each alternative. As an example, consider the selection of insulation material. The initial cost of insulation material A is higher than material B, but its energy consumption is lower. If investing less money is the priority, A is selected, if energy saving is desired, B is selected. Likewise, after all of the options have been discovered, the best option can be selected in a similar manner. Alternatively, the value of the function can be calculated for each alternative by combining both the initial cost and the energy consumption in a single function, and the best one can be chosen.

Another significant finding of this study is the determination of the most influencing parameters through sensitivity analysis. Building designers can drive their projects in this way by prioritizing the parameters that are revealed to be the most effective as a consequence of this analysis, rather than conducting a new analysis.

## 5.2 Limitations and Future Works

The most important limitation of this study is the individual evaluation of each parameter on building energy consumption. Building energy performance depends on many variables, and the relationship of these parameters with each other has been ignored in this study. It has been observed that the correlation and dependence between parameters are effective on consumption, particularly when multi-parameter analyses were performed. However, analyses with a single parameter change in this study ignored this fact, hence this situation can be investigated further in future studies. Another limitation is about alternatives for parameters. For instance, this study deals with the cities in Turkey, and the materials that are commonly used in Turkey are included in the scenarios. As future work, cities from different countries which show different climatic conditions can be considered, and materials not considered in this study may also be included. Moreover, the required parameter adjustments for each simulation were made manually in this study. By automizing the simulation process (via algorithms or plug-ins), a procedure can be planned that requires less human involvement and is thus faster and less error-prone. Furthermore, the results obtained in this study are based on the one-dimensional effect of the parameters affecting the energy performance of the building, as in reality, all options could not be evaluated together. This situation severely limits optimization. Another objective such as initial cost, life cycle cost can be added to this study, and optimization of the energy consumption of the building can be carried out.

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