

A BIM-BASED ASSESSMENT OF THE IMPACT OF ENVELOPE DESIGN AND
BUILDING SURROUNDING ON THE TRADE-OFF BETWEEN ENERGY
EFFICIENCY, THERMAL COMFORT & VISUAL COMFORT

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MEHMET TURABI UYSAL

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submitted by **MEHMET TURABI UYSAL** in partial fulfillment of the
requirements for the degree of **Master of Science in Civil Engineering, Middle
East Technical University** by,

Prof. Dr. Halil Kalıpçılar
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Ahmet Türer
Head of the Department, **Civil Engineering**

Assist. Prof. Dr. Aslı Akçamete Güngör
Supervisor, **Civil Engineering, METU**

Examining Committee Members:

Prof. Dr. Rifat Sönmez
Civil Eng, METU

Assist. Prof. Dr. Aslı Akçamete Güngör
Civil Eng, METU

Prof. Dr. İrem Dikmen Toker
Civil Eng, METU

Assist. Prof. Dr. Güzide Atasoy Özcan
Civil Eng, METU

Assist. Prof. Dr. Saman Aminbakhsh
Civil Eng., Atılım University

Date: 09.09.2021



I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name Last name : Mehmet Turabi Uysal

Signature :

ABSTRACT

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Uysal, Mehmet Turabi

M.S., Department of Civil Engineering

Supervisor: Assist. Prof. Dr. Aslı Akçamete Güngör

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The problem of depletion and rapid consumption of natural resources has forced engineers to design houses that consume less energy with more sustainable materials. However, simply minimizing energy consumption is not enough; at the same time, it is necessary to keep the indoor quality at the maximum level for a healthier environment and higher level of production. BIM based design and analysis has the potential to help achieve both targeted energy needs and visual & thermal comfort levels. Previous studies looked into increasing visual comfort while considering the energy performance of the buildings or performed simulations to keep daylight performance and energy efficiency at an optimum level. Moreover, there was also some research on optimization in the field of costs, such as life cycle cost and life cycle energy relationship or the monetary analysis of visual and thermal comfort. However, an optimization study aiming to keep the energy need low while increasing the thermal comfort and visual comfort, in other words, a study that evaluates all three criteria at the same time, has not been encountered. In this study, an analysis to support a greener and more environmentally friendly design, which reduces the building energy consumption while increasing thermal and visual comfort at the same time, has been

performed by using BIM technology together with a multi-objective function to assess tradeoff between these criteria. The results of the analysis show how certain design parameters effect energy efficiency and thermal and visual comfort levels and provides a potential to support design decisions not only considering energy efficiency but also the comfort of the occupants.

Keywords: Building Information Modelling, Energy Efficiency, Thermal Comfort, Visual Comfort, Tradeoff Analysis



ÖZ

BİNA KABUĞU TASARIMININ VE ÇEVRESİNİN ENERJİ VERİMLİLİĞİ, TERMAL KONFOR VE GÖRSEL KONFOR ARASINDAKİ ÖDÜNLEŞİME ETKİSİNİN BIM TABANLI BİR DEĞERLENDİRMESİ

Uysal, Mehmet Turabi

Yüksek Lisans, İnşaat Mühendisliği Bölümü

Tez Yöneticisi: Asis. Prof. Dr. Aslı Akçamete Güngör

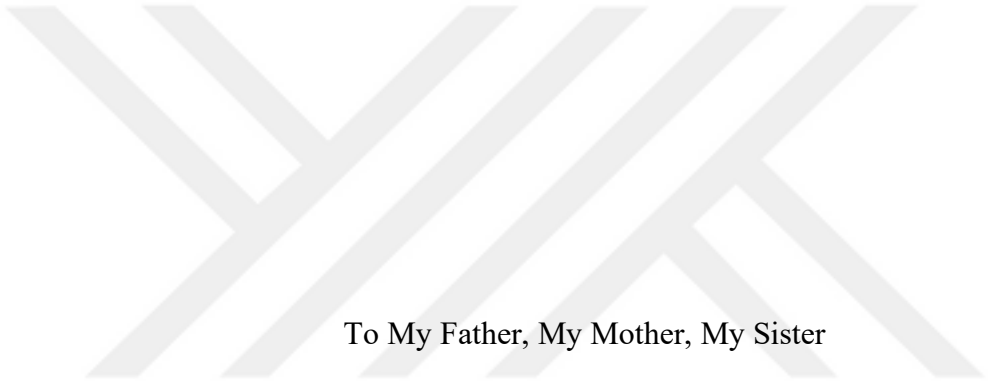
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Hızlı ve kontrolsüz şekilde artan Dünya nüfusunun yaratmış olduğu kaynak ve tüketim problemi; yakın gelecekte mühendislerin daha sürdürülebilir malzemelerle daha az enerji tüketen konutları projelendirmelerini zorunlu kılmıştır. Ancak sadece enerji tüketimini minimum seviyeye indirmek yeterli değildir; aynı zamanda daha sağlıklı bir ortam ve daha yüksek seviyeli bir üretim için bina iç mekân kalitesinin maksimum seviyede tutulması gereklidir. BIM tabanlı tasarım ve analiz hem hedeflenen enerji ihtiyaçlarının hem de görsel ve termal konfor seviyelerinin elde edilmesine yardımcı olma potansiyeline sahiptir. Geçmiş yıllardaki çalışmalarda yaşam döngüsü maliyeti ve yaşam döngüsü enerji ilişkisi ile, görsel ve termal konforun parasal analizi gibi daha çok maliyet alanında yapılan optimizasyonlarla beraber, binaların enerji performansını göz önünde bulundurarak görsel konforu artırmaya çalışan ya da gün ışığı performansını ve enerji verimliliğini optimum seviyede tutmak için simülasyonlar içeren araştırmaları görmek mümkündür. Ancak termal konfor ve görsel konfor artırılırken enerji ihtiyacını düşük tutmayı amaçlayan, bir başka deyişle maliyetten bağımsız birden çok kriterin aynı anda değerlendirildiği bir optimizasyon çalışmasına rastlanılmamıştır. Bu çalışmada, bina enerji tüketimini azaltırken aynı zamanda termal

ve görsel konforu artıran daha yeşil ve daha çevre dostu bir tasarımı desteklemek için, BIM teknolojisi ve çoklu görev fonksiyonu tanımlanarak bu kriterler arasında bir ödünleşim analizi yapılmıştır. Analiz sonuçları, belirli tasarım parametrelerinin enerji verimliliği ile termal ve görsel konfor seviyelerinin nasıl etkilendiğinin göstermekte ve sadece enerji verimliliğini değil, aynı zamanda bina sakinlerinin konforunu da göz önünde bulundurarak tasarım kararlarını destekleme potansiyeli sunmaktadır.

Anahtar Kelimeler: Yapı Bilgi Modellemesi, Enerji Verimliliği, Termal Konfor, Görsel Konfor, Ödünleşim Analizi





To My Father, My Mother, My Sister

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LIST OF ABBREVIATIONS

ABBREVIATIONS

API	Application Programming Interface
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BIM	Building Information Modelling
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CDS	Compactness Degree Scale
CIE	International Commission on Illumination
DA	Daylight Autonomy
DF	Daylight Factor
DGP	Discomfort Glare Probability
EEM	Energy Efficiency Measurement
EPBD	Energy Performance of Building Directive
EPC	Engineering, Procurement Construction
EPS	Expanded Polystyrene
GA	Genetic Algorithm
GHG	Green House Gases
HVAC	Heating, Ventilation and Air Conditioning
IESNA	Illuminating Engineering Society of North America
INEGI	National Institute for Statistics and Geography

ISB	International Society of Biometeorology
LCC	Life Cycle of Cost
LCE	Life Cycle of Energy
LEED	Leadership in Energy and Environmental Design
MCDM	Multi Criteria Decision Method
MRT	Mean Radian Temperature
PGSV	Predicted Glare Sensation Vote
PI	Temperature Control
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
sDA	Spatial Daylight Autonomy
SHGC	Solar Heat Gain Coefficient
UGI	Unified Glare Index
UGR	Unified Glare Rating
UTCI	Universal Thermal Climate Index
VCP	Visual Comfort Probability
VLT	Visual Light Transmittance
VPL	Visual Programming Languages
VT	Visual Transmittance
XPS	Extruded Polystyrene

LIST OF SYMBOLS

SYMBOLS

E_i	Illuminance from i th glare source at the eye (lux)
E_v	Vertical Eye Illuminance
G	Glare Index
I_{th}	Glare source in degrees
L_b	Surround Luminance or Adaptation Luminance (cd/m ²)
L_s, L_i, L_n	Luminance of the Source (cd/m ²)
L_v	The Veiling Illuminance (cd/m ²)
L_w	Average Luminance of the Sources (cd/m ²)
M	Metabolism of the human body (W/m ²)
M	Number of Sources in the Visual Field of the observer
N	Number of the Light Source
P, P_n, p_i	Guth position index
S	Thermal Load of the Human Body (W/m ²)
W_i, W_n, Ω_w	Solid Angle
θ_i	The Angle between the Target

CHAPTER 1

INTRODUCTION

European countries have a policy of less energy consumption when setting the necessary standards for buildings in new and future construction projects. When the Swedish data for 2006 were analyzed, office buildings with a total area of 32.3 million square meters ranked second for the energy consumption in the list of non-residential buildings with an energy consumption of 6.25 TWh (Jalilzadehazhari et al., 2019). It should not be forgotten that keeping the energy consumption at a minimum level is extremely important for the resource management. Especially in the literature, optimization studies related to energy consumption are mostly carried out in Scandinavian countries and countries close to the polar region, this can be explained by reasons such as the limited use of the sun during the winter months or insufficient angle of arriving sunlight. Besides, not only European countries but also some countries such as Argentina in the South American continent can generate less than 5% of the energy in their reserves in very unusual weather conditions, so various sectors are likely to face some problems (Bre and Fachinotti, 2017). Especially in Argentina, which meets 60% of their electricity needs in thermoelectric power plants, there is a risk due to problems such as the inability to use or supply the raw material resources required for energy production. In addition to this risk if the annual energy demand seen in projections for the next years increase for the whole world, it is inevitable that the need for energy efficiency in buildings will increase (Bre and Fachinotti, 2017). In addition to energy efficiency, indoor comfort indicators such as visual comfort and thermal comfort should also be emphasized. Minimizing the energy consumption should be a designer's goal for any project while providing the comfort zone. Therefore, studies on how to make thermal comfort and visual comfort for the building with minimum energy consumption are more important for countries. Also, it is known that with the increase in visual comfort and thermal comfort in the building,

people work more efficiently and healthier, and as a result, they gain more economic benefits (Jalilzadehazhari et al., 2019). Just as there is a balance in every field in nature, it is so important to achieve a sustainable and developing balance between thermal and visual comfort characters. An employee who does not have visual and thermal comfort will also experience a decrease in work efficiency due to increased dissatisfaction (Sandhyalaxmi and Raafe, 2014).

Visual comfort is difficult to achieve, but the most efficient and cheapest way is to use daylight correctly. According to Navada, lighting control is very advantageous in terms of money considering the long-term effects compared to the short term (Navada et al., 2013). Providing visual and thermal comfort has a large share in ensuring that employees are satisfied with their working conditions. The most effective method of providing thermal comfort in offices is to reduce the cooling load by minimizing the energy consumption of devices (Navada et. al, 2013). Daylight is a traditional method that has been used in the past to avoid using artificial light sources and is still used today (Sandhyalaxmi and Raafe, 2014). In addition, it has become necessary to make some changes in the materials used for the building due to various environmental and external reasons such as global warming, excessive carbon emission, excessive energy consumption. More than 50% of CO₂ emissions are due to urbanization and human-related activities (Fahmy and Elwy, 2016). Unfortunately, it is feared that this amount will increase further in the future and will face an uncomfortable future. Therefore, ineffective design strategies should be replaced with more mitigating solutions with the help of technology to avoid possible bad consequences. In summary, it has become necessary to make some changes in the materials used for the buildings due to various environmental reasons such as global warming, excess carbon emission, and excessive energy consumption. Sustainable materials are needed to increase the indoor performance of the building, including the life cycle cost and energy needs. Thus, it increases the performance value of the building and allows the development of different models to reduce negative effects such as cost and environmental impact. The adequacy of the optimizations with the new design and new materials to reduce the energy demand and to increase the comfort

indices such as thermal comfort and visual comfort can be discussed. It is much more important to complete the design with more transparent values and the specification criteria, contrary to the understanding that some designers say that no problem if it is better than before or if it is good enough (Mukkavaara, Sandberg and Shadram, 2019)

1.1. Several Terms to Understand Visual and Thermal Comfort

1.1.1. Visual Comfort

One of the ways to ensure visual comfort can be attributed to the absence of glare. Glare occurs after a sudden light gain or loss of light that occurs of an eye accustomed to its present environment (Laforgue et al. 1997). According to International Commission on Illumination (CIE), glare is defined as the light beam that causes the reflected objects to be indistinguishable and disturbs the user in an environment with excessive contrast distribution (Sandhyalaxmi and Raafe, 2014). It is divided into two categories according to the magnitude of the difference between the new and the old situation. These categories are named differently in the articles by Laforgue et al., (1997) and Sandhyalaxmi et al. (2014). While Laforgue et al. (1997) named the first as uncomfortable (or discomfort) and the second as the disturbing glare, Sandhyalaxmi et al. (2014) categorized it into disability glare and discomfort glare. The uncomfortable glare is a sudden change in the pupil due to different illuminance value in the environment. The disturbing glare decreases visual performance after entering the eye after excessive emission of light to the environment. Disturbing glare caused by sunlight is the main factor that affects visual comfort more than an uncomfortable one. Also, discomfort glare manifests itself before. Therefore, visual comfort can be guaranteed if discomfort glare is taken under control by taking it to the required level (Laforgue et al., 1997). Small-sized light sources or artificial light sources are recommended to handle uncomfortable glare. For discomfort glare, a formula called the Cornell Glare index has been developed (Eq. 1). A table with criteria on how to interpret the result obtained from the formula are shared below (Table 1.1). The values 24 and below in the table were taken as targets for glare prevention.

$$G = 10 \log_{10} \left[\frac{1}{L_b + 0,07 \cdot \Omega_w^{0,5} \cdot L_w} \cdot \sum_{i=1}^m L_i^{1,6} \cdot \frac{w_i^{0,8}}{p_i^{1,6}} \right] \quad (1)$$

- m: number of sources in the visual field of the observer
- L_i : the luminance of each source (cd/m²)
- W_i : the solid angle subtended by each source from the eye of the observer
- p_i : GUTH position index of the source which takes into account the variation of the eye reaction in the function of the position of the light source image on the retina
- L_b : surround luminance or adaptation luminance (cd/m²)
- Ω_w : solid angular subtended by the entire bay window
- L_w : average luminance of the sources (cd/m²)

Table 1.1 Connection between glare perception and the associated index (adopted Laforgue, 1997)

Glare Perception	Glare Index G
Just imperceptible	16
Just acceptable	20
Just uncomfortable	24
Just intolerable	28

CIE has defined another criterion called UGR (Eq. 2), and this value is the value found after dividing the visible light glare value by the background luminous value.

$$U.G.R = 8 \log \left(\frac{0,25}{L_b} \cdot \sum n \cdot \left(L_n^2 \cdot \frac{w_n}{p_n^2} \right) \right) \quad (2)$$

L_b : Background Illumination

L_n : Luminance of each source

N : number of the light source

W_n : solid angle

P_n : Guth position

According to the Illuminating Engineering Society of North America (IESNA) specification, the glare value in the room must be equal to or less than 28. (Eq. 3) While visual comfort is dependent on people's expectations, visual performance depends only on the natural or artificial light systems. Therefore, every lighting system may not meet some expectations even though there is a sufficient light level. This shows that the light setup directly and continuously affects the working performance. It should also be remembered that there is a physical and psychological effect. That is why visual comfort probability becomes an important indicator to install the visual system in the room to use it effectively (Sandhyalaxmi and Raafe, 2014).

$$L_v = 9,2 \cdot \sum_{i=1}^n \frac{E_i}{\varphi_i \cdot (\varphi_i + 1,5)} \quad (3)$$

L_v : The veiling illuminance in cd/m²

E_i : The illuminance from the i_{th} glare source at the eye in lux

φ_i : The angle between the target

i_{th} : Glare source in degrees

To control the brightness and lighting value, a curtain system can be used that changes the angle of incidence of sunlight in the vertical direction. Another way to ensure visual comfort is lighting control. Lighting control plays an important role to use more economical and efficient lighting, and to prevent excessive energy consumption (Navada et al., 2013). There are several ways of handling lighting control. Being selective in continuous lighting (shed lighting) for regulating the

demand, reducing the time of illumination when the building is idle, or using sensors that can be automatically switched on or off, are the possible solutions. The lighting control system is used in many buildings around the world and if properly designed and implemented, it contributes to a considerable amount of energy saving. Lighting control is also used as high quality and efficient energy lighting system that provides a balance between daylight and electric light sources to create a more comfortable and eye-pleasing environment (Navada et al., 2013). Electrical lighting controls can be applied or tried in buildings used for various purposes such as restaurants, large offices, conference rooms, and classrooms. Although it is widely used in buildings for such commercial purposes, its use in residences is also increasing day by day (Navada et al., 2013). Electric lighting control may not only benefit energy cost reduction. There is also a possibility that the lamps may extend their service life when used correctly. In short, it can interfere directly or indirectly, positively, with material quality and efficient use.

1.1.2. Thermal Comfort

Thermal comfort refers to satisfaction with the thermal environment. Thermal comfort has physical and psychological indicators that can vary from person to person, and not everyone may be satisfied in the current area. In short, everyone's understanding of thermal comfort is not the same. However, there are six different indicators of thermal comfort. It can be analyzed with concepts such as air temperature, radiant temperature, humidity, air velocity, clothing insulation, and human activity level. Definitions of these concepts will be given in the following subsections. These values shape numerical indicators used in thermal comfort measurement such as predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) (Sandhyalaxmi and Raafe, 2014). The PMV scale is a calculation model that determines general comfort conditions and limits. In the PMV indicator, which varies between -3 and 3, cold air is felt towards negative values and warm air is felt at positive values. The value '0' represents the neutral thermal sensation value (Orosa, 2010). However, it should not be forgotten that the temperature felt and coldness are caused

by the heat gained or heat lost. People who are exposed to other conditions and activities may not even feel comfortable when they enter areas with standard values. However, it should not be forgotten that there is a one-hour perception difference or adaptation period between entering an area from different conditions. For example, a person, no matter how cold is the weather, may take off his/her clothes immediately after running outside for a while thanks to the rise of body temperature, and then feels the cold again after a certain time. The six indicators of thermal comfort may change over time, but the only thing that will not change is the permanence of a concept called thermal comfort (Navada et al., 2013). Thermal comfort is simply a condition when a person feels neither too cold nor too hot with normal clothes. Thermal comfort is important for a person to feel good and to work efficiently. Therefore, values such as air temperature, humidity, and air movement are critical to provide the comfort zone. In the absence of air movement, in an environment where relative humidity rises to 50%, ambient temperature is the most important factor for thermal comfort (Navada et al., 2013). However, as mentioned in the introduction sentence, since the temperature indicator does not have a standard value and vary from person to person, a general comment about thermal comfort can be made as follows. There is always the possibility that employees in a very hot office may feel tired, while employees in a cold office may lose attention and focus. Therefore, if possible, a constant temperature should be maintained continuously. Even a small difference can affect operating performance.

Thermal comfort can be achieved by balancing the temperature inside the body and outside the body. The lost energy value and the energy gained from the external environment must balance each other. Among the various models, Fanger suggested a formula called Predicted Mean Value (PMV) (Eq. 4) with a result varying between -3 and 3, to measure thermal comfort (Laforgue et al., 1997). The equation and components included in the equation are explained below. The thermal perception values are also shared in Table 1.2.

$$PMV = (0,303 e^{-0,036M} + 0,028) S \quad (4)$$

M: metabolism of the human body related to the activity (W/m²)

S: the thermal load of the human body resulting from its thermal balance with the environment (W/m²)

Table 1.2 Thermal perception and the associated index (Laforgue et al., 1997)

Thermal Perception	PMV threshold
Cold	-3
Cool	-2
Slightly Cool	-1
Neutral	0
Slightly Warm	1
Warm	2
Hot	3

The Predicted Percentage of Dissatisfied (PPD) (Eq. 5) value is integrated with the PMV value and it is shaped according to the PMV value (Figure 1.1). For PMV ranging from -0.85 to 0.85, the percentage of dissatisfied (PPD) is 20 percent; while this value decreases to 10 percent when PMV is between -0.5 and 0.5, it reduces down to 6 percent when PMV has a value between plus-minus 0.2 (see Figure 1.1 and Table 1.3). Therefore, based on the reasonable PPD and PMV range, it can be said that there are three different comfort areas. The table summarizing these three different areas, the PPD formula that can be calculated with PMV, and the graphic reflecting the relationship between them are shared below.

$$PPD = (100 - 95 \cdot e^{-(0,03353 \cdot PMV^4 + 0,2179 PMV^2)}) \quad (5)$$

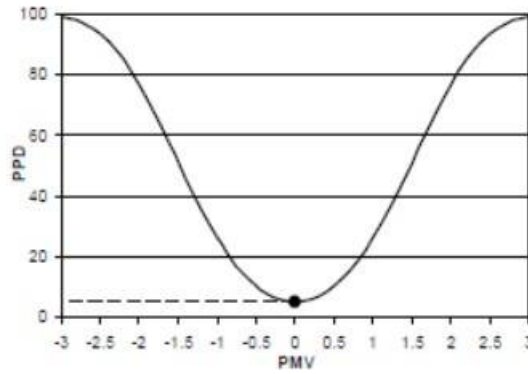


Figure 1.1 PPD values depending on PMV

Table 1.3 Predicted percentage of dissatisfied (PPD) based on the predicted mean vote (PMV) (Orasa, 2010)

Comfort	PPD	Range of PMV
A	<6	$-0.2 < \text{PMV} < 0.2$
B	<10	$-0.5 < \text{PMV} < 0.5$
C	<15	$-0.7 < \text{PMV} < 0.7$

When the graph between the PPD and PMV relationship is examined, even at the '0' value, which is considered to be the most ideal value of the PMV value, the PPD value represents 5 percent. This may prove that not everyone may adopt the same standard of thermal comfort and 100% satisfaction cannot be achieved as mentioned before. The thermal analysis deals with all thermal parameters inside and outside the room. This analysis includes temperature change, temperature difference, or other important radiometric quantities related to heat. Thermal analysis could also be very important for designers as it could form the main skeleton of the study. For a good thermal comfort design, systems such as heating, cooling, and ventilation should be used more efficiently, and a flexible process that can ensure the comfort of indoor users should be followed (Sandhyalaxmi and Raafe, 2014).

1.1.2.1. Metabolic Rate (met)

It is the amount of energy emitted by an individual's muscle activity. Traditionally, metabolism is calculated with met. (1 met = 58.15 W / m²) (Orosa, 2010). Met values determined as an example in the ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) specification are shared in the Table 1.4 below (ANSI / ASHRAE STANDARD 55-2004)

Table 1.4 Metabolic Rates for Typical Tasks (ANSI/ASHRAE STANDARD 55-2004)

Activity	Met Units	Metabolic Rate	
		W/m ²	(Btu/h·ft ²)
Resting			
Sleeping	0.7	40	(13)
Reclining	0.8	45	(15)
Seated, quiet	1.0	60	(18)
Standing, relaxed	1.2	70	(22)
Walking (on level surface)			
0.9 m/s, 3.2 km/h, 2.0 mph	2.0	115	(37)
1.2 m/s, 4.3 km/h, 2.7 mph	2.6	150	(48)
1.8 m/s, 6.8 km/h, 4.2 mph	3.8	220	(70)
Office Activities			
Seated, reading, or writing	1.0	60	(18)
Typing	1.1	65	(20)
Filing, seated	1.2	70	(22)
Filing, standing	1.4	80	(26)
Walking about	1.7	100	(31)
Lifting/packing	2.1	120	(39)
Driving/Flying			
Automobile	1.0-2.0	60-115	(18-37)
Aircraft, routine	1.2	70	(22)
Aircraft, instrument landing	1.8	105	(33)
Aircraft, combat	2.4	140	(44)
Heavy vehicle	3.2	185	(59)
Miscellaneous Occupational Activities			
Cooking	1.6-2.0	95-115	(29-37)
House cleaning	2.0-3.4	115-200	(37-63)
Seated, heavy limb movement	2.2	130	(41)
Machine work			

1.1.2.2. Cloth Insulation (clo)

It is the unit of measuring the insulation provided by the clothing to the body. The unit is denoted as $\text{m}^2\text{C}^\circ / \text{W}$ and $1 \text{ clo} = 155 \text{ m}^2\text{C}^\circ / \text{W}$. The clo value of a naked person can be taken as 0, and the clo value of an individual with normal clothing can be taken as 1 (Orosa, 2010). More clo values can be viewed in Table 1.5 below.

Table 1.5 Clothing Insulation Values for Typical Ensembles (ANSI/ASHRAE STANDARD 55- 2004)

Clothing Description	Garments Included ^b	I_{cl} (clo)
Trousers	1) Trousers, short-sleeve shirt	0.57
	2) Trousers, long-sleeve shirt	0.61
	3) #2 plus suit jacket	0.96
	4) #2 plus suit jacket, vest, T-shirt	1.14
	5) #2 plus long-sleeve sweater, T-shirt	1.01
	6) #5 plus suit jacket, long underwear bottoms	1.30
Skirts/Dresses	7) Knee-length skirt, short-sleeve shirt (sandals)	0.54
	8) Knee-length skirt, long-sleeve shirt, full slip	0.67
	9) Knee-length skirt, long-sleeve shirt, half slip, long-sleeve sweater	1.10
	10) Knee-length skirt, long-sleeve shirt, half slip, suit jacket	1.04
	11) Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	12) Walking shorts, short-sleeve shirt	0.36
Overalls/Coveralls	13) Long-sleeve coveralls, T-shirt	0.72
	14) Overalls, long-sleeve shirt, T-shirt	0.89
	15) Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37
Athletic	16) Sweat pants, long-sleeve sweatshirt	0.74
Sleepwear	17) Long-sleeve pajama tops, long pajama trousers, short 3/4 length robe (slippers, no socks)	0.96

1.1.2.3. Mean Radiant Temperature

Defines the radiant temperature of a person as a uniform temperature in an imaginary enclosure, in which a person would experience the same losses by radiation as in the real compound (Orosa, 2010).

1.1.2.4. Operative Temperature

It is the temperature on the wall and in the air that transmits the same heat to the atmosphere by convection and radiation (Orosa, 2010).

1.1.2.5. Relative Humidity

It is the relationship between the vapor pressure in the saturated condition and the partial vapor pressure of the water pressure in moist air.

1.1.2.6. Air Velocity

There may not be a definitive link between thermal comfort and air velocity. ASHRAE has confirmed that the airspeed increases at high temperatures and remains stable under comfort zone conditions. Air velocity, which may cause heat loss through the skin, has allowed temperature curves for certain velocities. It is known that air velocity affects parameters such as comfort, perception of indoor air quality, the health of the occupants, and energy consumption.

1.2. Gap

While many scientists prioritize thermal comfort more, visual comfort was not paid enough attention. It has been tried to be evaluated according to the number of windows or artificial light source (Laforgue et al. 1997). While a number of studies have been done on these two subjects, studies that include energy consumption together with these two indicators are relatively limited. Significant energy is consumed for HVAC and lighting in buildings. Recently, buildings covered with different materials raise the following question; How can thermal and visual comfort be achieved while reducing energy consumption? The thought of reducing energy consumption will guide the need for a new regulation, a new environmental certification, and new technology (Sustentech, 2016). Architectural building design, building systems, and indoor users, which have become three important issues for better building performance, should not be ignored (Lin and Yang, 2018). The design team can also be involved to make the building design renewable and sustainable. If the building can be well optimized in terms of design, the system capacity can be efficient. Although architectural design is an important criterion for building performance, it is not that easy to handle due to the complexity and confusion. Because architectural design includes not only external design but also issues such as

ventilation strategy, daylighting strategy, and services strategy that can affect each other independently or mutually (Lin and Yang, 2018). In addition, energy consumption and indoor thermal comfort are not compatible with each other. For example, providing the thermal comfort of the people inside of the building as much as possible means increasing energy consumption as well for heating or cooling the building. Therefore, these two factors should be considered together in the design phase and should be solved as a multi objective optimization problem.

Building design can have different effects on building performance in different processes of sustainable building design. Therefore, many problems may occur in different time intervals. Especially, initial problems should not be ignored, because if not neglected at the beginning they can be solved before they get bigger. Generally, the design process includes the conceptual design stage, the preliminary design stage, and the detailed design stage (Lin and Yang, 2018). The parameters that affect the building performance most, such as building shape, direction, window size, window wall ratio, interior design, are studied in the conceptual design stage. This phase can be overlooked in traditional methods during the design phase. Because making quantitative analysis of a completely unfinished building is difficult. Therefore, a roadmap about how to perform multi-objective optimization in projects should be created and implemented in order to reduce building energy consumption.

1.3. The Aim and Method

With the provision of thermal and visual comfort, there is an increase in the life quality, living conditions, and working performance of the people in the building. Attention should be paid to comfort indices, which contribute positively to daily life, especially in new projects or buildings. Therefore, the materials used in the building and the systems installed to provide comfort indicators should be carefully selected during the design phase. Also, inefficient methods should be avoided for obtaining comfort indices. Because inefficient solutions will always return to the building stakeholders as excess energy use. Keeping energy consumption at a minimum is very important not only because of economic concerns, but also not to use country resources

in vain, not to harm nature, and not to trigger global warming. Therefore, it would be more correct to evaluate energy consumption as a whole with comfort indices, within the scope of multi-objective optimization during the design phase. Although the designs to be made to perform multiple tasks at the same time are likely more expensive economically, it is predicted that the savings and profit obtained from energy consumption, in the long run, could cover all costs and losses. In this thesis, a trade-off analysis between energy consumption, visual comfort and thermal comfort has been done based on BIM technology. Visual comfort will be provided by providing sufficient daylight in the room and preventing glare. Thermal comfort, on the other hand, will be provided by taking the amount of energy consumption as a reference with the help of the right material selection. Results will be obtained by using simulation programs for both visual and thermal comfort, comparisons will be made and the most efficient combinations will be found by using multi objective functions. Different window types, building orientation, the location of surrounding buildings, different window wall ratios and different insulation material thicknesses will be used in the study. Each result will be compared with the threshold values or indicators obtained from the literature and will be analyzed according to comfort and energy consumption priority. As a result of the study, it is aimed to show how much the energy consumption and comfort indices change, based on the effect of the selected materials for design, in order to help reducing the energy consumption to a minimum by contributing to a different perspective of the building design.

CHAPTER 2

LITERATURE REVIEW

2.1. Previous Studies without the use of BIM

2.1.1. Measuring Thermal Comfort

According to the Energy Performance of Buildings Directives 2010 regulations, a limit of 60-70 kWh was regulated and encouraged for the annual heating consumption per house during the building construction phase in Europe. In addition, green building standards have been introduced that contribute to the comprehensive life-cost of the project in terms of many criteria (Baranova et al., 2017). The most important and primary goal in these applications is to reduce the negative impact on the environment, to create a comfortable environment for human life, to create control in energy consumption, and to increase used materials efficiency. Sometimes one of the main problems can be overheating in summer, even in buildings that are well built-in terms of energy performance. So, a cooling system may be required. One of the aims of the studies carried out in Europe is to reduce the energy spent on cooling processes as much as possible and at the same time to increase the overheating problem and indoor environmental conditions as much as possible. In Estonia, within the scope of the EPC certificate (Engineering, Procurement Construction), dynamic indoor temperature simulations were made while the building was still in the design phase and it was ensured whether thermal comfort was provided during the summer period (Baranova et al., 2017). In addition, the importance of correct energy design under unstable weather conditions has been underlined in Russia, and regulations have been introduced for heating and ventilation. It may be important to find a balance between the building's thermal insulation level, ventilation system, and thermal comfort relationships. For example, despite the increase in the thermal insulation layer on the outer surface of the building and the reduction of energy consumption with the mechanical ventilation system with heat recycling, there is still a risk of overheating.

Besides, studies are showing that extra thermal masses and latent warming harm thermal comfort (Baranova et al., 2017). Baranova's study aims to show how different ventilation strategies affect annual energy consumption in Saint-Petersburg, Russia. Throughout the research, IDA-ICE 4.7 software was used to obtain various numerical values such as thermal comfort index, indoor air quality, energy consumption. The building to be analyzed was designed in an Autodesk Revit and transferred to the simulation software in IFC format. The designed building (Figure 2.1) has been analyzed using parameters such as cooling, heating, total annual energy consumption, and thermal comfort.



Figure 2.1 The building model in IDA-ICE & Floor plans of the residential building (Baranova et al., 2017)

The ventilation systems used in the study and affecting thermal comfort are shown in the Table 2.1 below.

Table 2.1 Types of the ventilation system (Baranova et al., 2017)

TYPE OF VENTILATION SYSTEM	№	NAME OF VENTILATION SYSTEM IN IDA-ICE	DESCRIPTION	INFILTRATION SET IN IDA-ICE
ICE				
NATURAL	A	«Never open»	Windows are always closed. Mechanic cooling system is not used.	Type: fixed infiltration. Flow: 0.7ACH
	B	«Always open»	Windows are opened in the summer from 8.00 till 18.00, during the heating period (from September to May) are closed. Mechanic cooling system is not used.	
	C	PI (proportional-integral) temperature control	Windows are opened in the way to keep the room temperature close to the set point value 25 °C except midday when it is too hot outside for the window ventilation to be efficient enough. Mechanic cooling system is not used.	
MECHANIC	D	Air Handling Unit (AHU) with Variable Air Volume (VAV) with/without heat-exchanger + thermal control + «Never open»	Windows are never opened. Mechanic ventilation system (with/without heat recovery) which regulates depending on the operative critical temperatures is used.	Type: wind driven flow. Air tightness: 0.5ACH at pressure difference 50Pa
	E	AHU with VAV with/without heat-exchanger + thermal control + PI temp control	Windows are opened in the way to keep the room temperature close to the set point value 25 °C. Mechanic ventilation system (with/without heat recovery) starts working if PI temp control is not able to prevent overheating.	

A two-story house was designed for the study, and analyzes were made in the living room of the first floor and the bedroom on the second floor. Energy values and parameters used in the simulation are shown in the Table 2.2. According to the occupancy schedule, any internal gain is considered to be absent in this period, since from 8 am to 5 pm (working time zone) building is considered occupied Heat losses were calculated all day on the weekends.

Table 2.2 Values of building parameters used in the simulations (Baranova et al., 2017)

<i>Parameter</i>	<i>Value</i>
<i>Number of floors</i>	2
<i>Floor height</i>	3 m
<i>Floor area</i>	466.5 m ²
<i>Model volume</i>	1349.8 m ³
<i>Model envelope area</i>	843.8 m ²
<i>Window-to-wall ratio</i>	41%
<i>Heating set point</i>	20 °C
<i>Cooling set point</i>	25 °C
<i>Min CO₂ control level</i>	700 ppm (vol)
<i>Max CO₂ control level</i>	1100 ppm (vol)
<i>Heat recovery efficiency</i>	75%
<i>Average hot water use</i>	25 L/per occupant and day
<i>U-values of building envelope components (W/(m²·K))</i>	
<i>External wall</i>	0.259
<i>Roof</i>	0.158
<i>Foundation</i>	0.112
<i>Window</i>	1.06
<i>Door</i>	1.09

For the first case, the windows were never opened throughout the year. Ventilation was made only from the spaces in the outer shell of the building and the air exchange in the inlets and outlets. As can be seen from the result shown below, severe overheating has occurred. The number of hours per year that exceeds 25 degrees was measured as 3140 hours for the bedroom and 4510 hours for the living room respectively. The cause of overheating has been explained as sunlight and internal heat gain. At the same time, as extra energy will be spent for thermal comfort, the position where the windows are fully open, which is the more economical situation, was analyzed first. Almost the same energy consumption was realized as in the first case. As can be understood from the figure, while the average temperature in the bedroom was below 25 degrees (Northern Front), this temperature in the living room rose above

30.2 degrees (South Side). However, it is not possible to keep the windows open continuously due to noise pollution. In terms of energy balance, the third scenario is not much different from the first and second cases, while it is more in terms of the number of times the room temperature is more than 25 degrees. For the fourth case, two different types of ventilation systems were tried, and it was observed that there was a serious decrease in the energy required for heating in the system with heat exchange. It has been measured that the energy spent on cooling is almost the same in these two types, with an 8.5 times difference in heating energy between them. However, the number of hours when the temperature was above 25 degrees was found to be higher than in case 1 (Case A) (Figure 2.2). The measurements made in the fourth case were obtained by keeping the windows closed. In the fifth case, attention was paid to the room temperature while keeping the windows open, an attempt was made to fix it at 25 degrees, in other words, to increase thermal comfort. If the temperature cannot be adjusted to around 25 degrees, then mechanical ventilation will be activated and the temperature will be kept constant. According to the findings obtained after the analysis, it was seen that after the transition from the closed position of the windows to the PI (temperature control), there was a 4% decrease in energy and the number of hours above 25 degrees was almost 11 times less than the A (case 1). Also, it has been observed that using without heat exchanger in the mechanical ventilation system is unreasonable and a heat exchanger is indispensable. The summary data obtained from the study are presented in the Figure 2.2 and Figure 2.3 as graphs. A heat exchanger is a system used to transfer heat between two or more fluids. Heat exchangers are used in both cooling and heating processes. The fluids may be separated by a solid wall to prevent mixing or they may be in direct contact. Also, the thermal comfort provided partially is insufficient when the window is open, so it was recommended to keep the PI system at home. In this way, it helps to provide thermal comfort in the room.

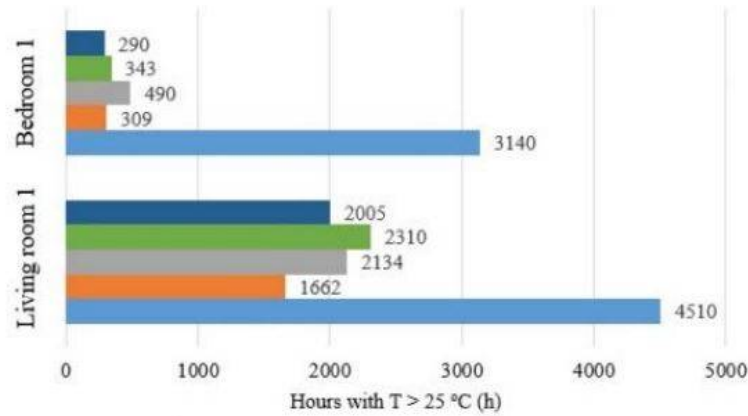


Figure 2.2 The number of hours with $T > 25^{\circ}$ (Baranova et al., 2017)

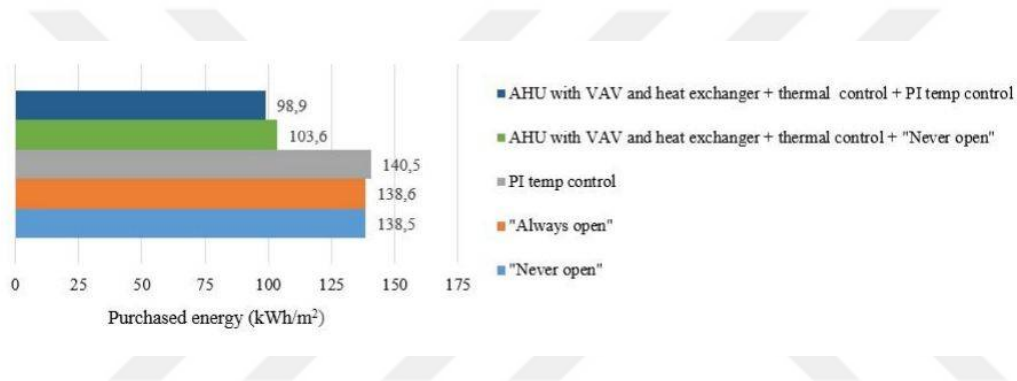


Figure 2.3 Annual purchased energy (Baranova et al, 2017)

2.1.2. Visual Comfort Measurements

Considering the development process of the lighting controllers, the control system has been developed according to user demand. A design has been developed that prioritizes visual comfort when the user is in the room, does not fall below a certain threshold value, and focuses more on thermal comfort when the user is not in the room. Later, a system was developed for an automatic shadowing device controller and designed with GA (Genetic Algorithm) and systems that tell users how the blind position should be were designed (Navada et al., 2013). Some studies are obtained and analyzed to measure how much energy the lighting control system works with an automatic sensor compatible with daylight conserves. After the studies that read and

analyze the desired threshold value to measure whether the LED observes the user needs regardless of the presence of external light sources, studies have been carried out to improve the energy efficiency of the dim light balance by the fuzzy logic technique (Navada et al., 2013). One of them is daylight harvesting. Daylight Harvesting is to reduce the consumption of artificial lighting used inside the building when there is daylight available (during the daytime). All harvesting daylight systems have sensors that measure the brightness, illuminance, and illuminance level. Automatic sensors work with integrating the electrical lighting system with daylight when daylight is at an insufficient level. With the signal coming from the photosensor, the switch opens automatically and the source provides light. In short, daylight harvesting is also intelligent energy-saving dimming (Navada et al., 2013). An adaptive scheme has been developed using daylight harvesting for thermal and visual comfort. The light that needs to enter the room is provided by curtain control. It is aimed not only to let the optimum luminance inside but also not to spend extra energy to cool the room due to the increase in temperature caused by excessive light. A window on the west side of the room was used for the study. At first, it was confirmed that the illuminance value of the entering light gradually increased after the curtains were left open completely and, a study aimed at providing both visual and thermal comfort by arranging the curtain height was continued later. As a result, a graphic showing the relationship between illuminance and temperature and the formula was found with the help of regression analysis. That result appears in Figure 2.4 below.

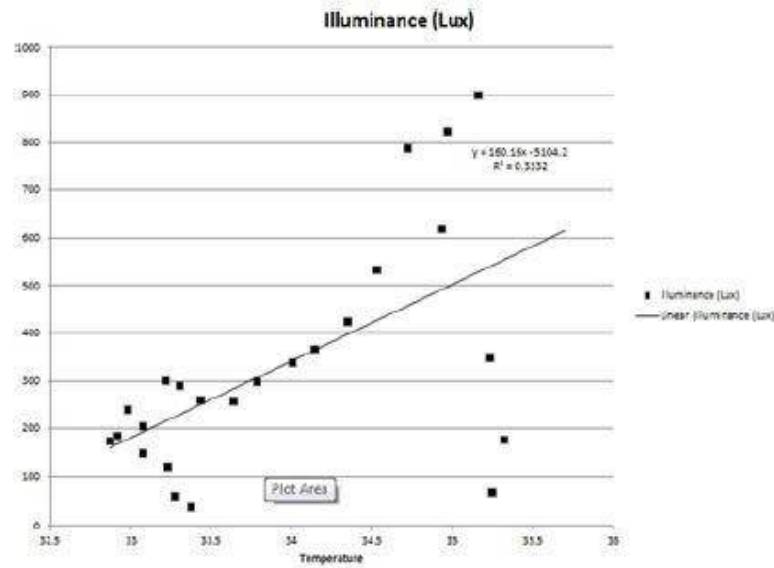


Figure 2.4 Illuminance vs temperature (Navada et al., 2013)

Since thermal and visual comfort vary both physically and perceptually according to people, solar rays that affect visual and thermal comfort directly and affect energy consumption with GHG indirectly should be optimized especially in areas with arid climates (Fahmy and Elwy, 2016). Fahmy studied a study in Egypt with this type of climate. In the study, it was investigated how to arrange the city geometrically with the parametric technique method by evaluating the mutual effects and mutual relations of thermal and visual comfort with the help of a Compactness Degree Scale which was scaled between 0.1 and 10. It is calculated by multiplying the overall floor area ratio and the average number of floors and starting with the 0.1 value. The main purpose of the article is to compare visual comfort and thermal comfort according to the CDS scale in areas with very dry climates, to show how the available daylight can be used most efficiently by increasing the quality of life of the people using the building. In other words, it is a contribution to city planning techniques. The study was carried out on U-shaped buildings measuring 15x21 meters and a 12-meter-wide street separated from each other. 120 different iterations were made for the CDS value ranging from 0.5 to 10 with 0.5 intervals. Six different floor area ratios were chosen between 33.3% and 50%. For the calculation of the thermal comfort indicator, Ladybug for Grasshopper software was preferred, and the Mean Radian Temperature

values, which are called MRT, arranged according to the arrival of the sun's rays, were read. Also, the Universal Thermal Climate Index (UTCI) criterion, published by the International Society of Biometeorology (ISB), is related to parameters such as Dry Bulb Temperature, Relative Humidity, or Wind Speed, was taken as the basis. Although this method does not take into account that the sun rays absorbed by the ground or rays with a longer wavelength reflected from the building and it perceives the building geometry as the object shading the sun's rays, it is still preferred for different UTCI values between shaded or unshaded objects (Fahmy and Elwy, 2016). Diva for Rhino software is preferred for the calculation of visual comfort criteria. Although the acceptable light threshold value varies between 100 and 2000 lux under different conditions, hourly illuminance values were calculated at the ground level. The results were evaluated according to the data read between 6:00 am and 6:00 pm on July 7. Looking at the results in terms of outdoor thermal comfort, it is seen that the temperature varies between 38 degrees and 45 degrees. As an example, one of the sample results of outdoor thermal comfort is shared in Figure 2.5 below.

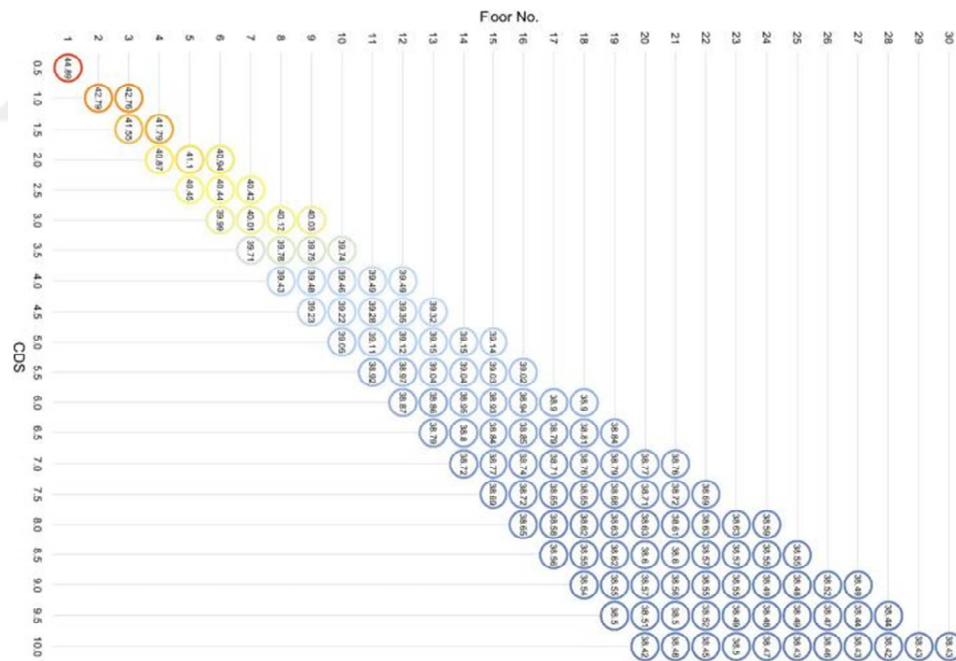


Figure 2.5 UTCI values at 45° orientation (Fahmy and Elwy, 2016)

Different illuminance values have been observed in CDS values that vary according to the illuminance results, but it can be said that in Figure 2.6, all of them are more than 1000 lux. As a result, it was mentioned that the two results were reached in the study. The first one is that there is no significant difference in terms of thermal comfort after 6 CDS values. Therefore, according to the environmental and urban planning of the Egyptian country in which the aforementioned study is located, it has been found that the building height should be a maximum of 12 floors. Another result is that it is suggested that a design should be made to accommodate 150 people in 1 Fed area (approximately 4200 m²).

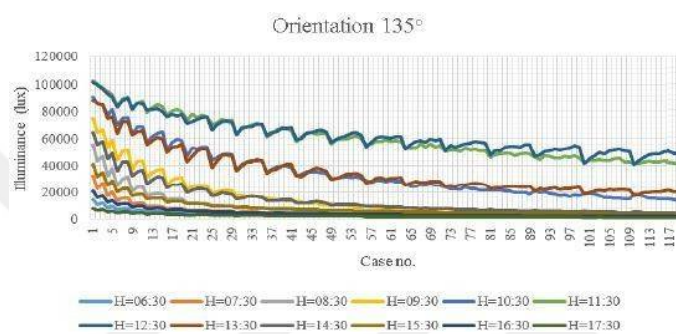


Figure 2.6 Hourly illuminance values for each case at 135° orientations (Fahmy and Elwy, 2016)

2.1.3. Visual and Thermal Comfort Studies

The study in Laforgue (1997), opinions about thermal and visual comfort parameters were collected first and then modeled. In subsequent simulations, thermal comfort was measured with PMV value, and visual comfort was evaluated according to the Cornell glare index. Visual and thermal comforts were calculated using two different software (Genelux and TRNSYS) measuring according to the model defined by Laforgue in Figure 2.7. Cornell glare index is a value for predicting the presence of glare as a result of daylight entering an area.

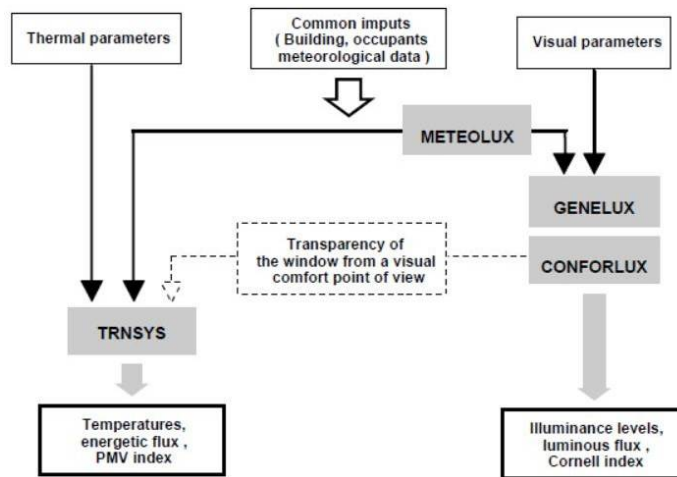


Figure 2.7 Software Operation Figure (Laforgue, 1997)

Measurements were made at various points for the visual comfort indicator. Horizontal illumination at a height of 0.85 meters from the ground, vertical illuminance at a height of 1.20 meters from the floor, vertical illuminance at a height of 1.20 from the ground on the wall on the north facade, and vertical illuminance based on a point on the inner surface of the window were measured (Figure 2.8). A small setup was used for measurement and it is shared in the figure below.

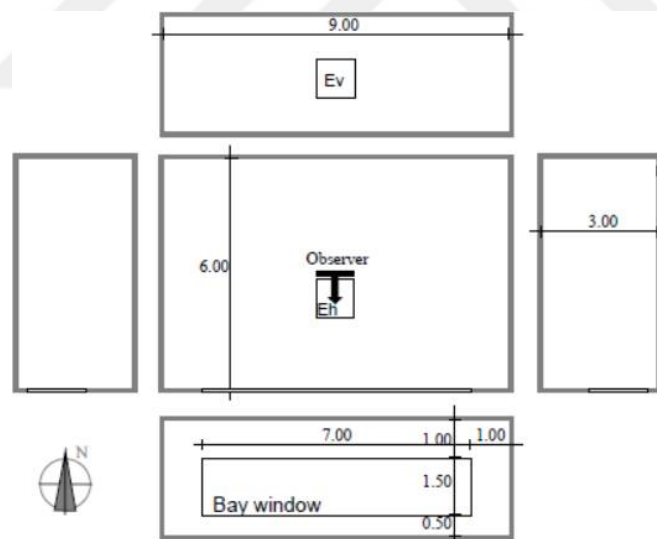


Figure 2.8: Test cell plan, (Laforgue, 1997)

The results are shared in Figure 2.9 below, and it has been observed that it shows a similar trend although each separate measurement has different values, in

other words, like polynomial functions with different head coefficients and the same curves.

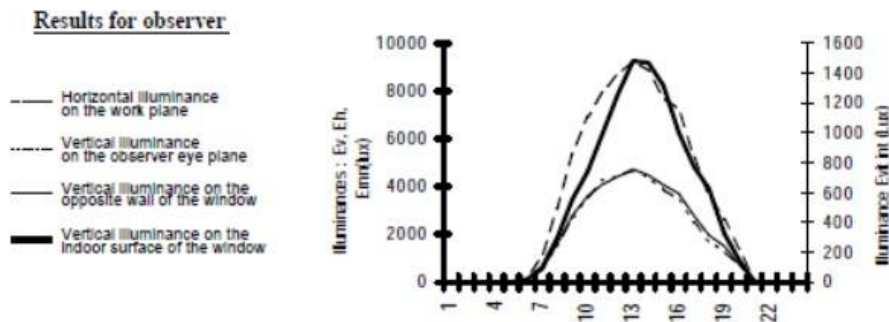


Figure 2.9 Evolution of luminous illuminances versus time (Laforgue, 1997)

The thermal comfort of the interior conditions of an office building has been defined, and a system called window occultation system has been proposed to solve the problem of glare and overheating in offices with larger windows. After the study, the design named glare meter was developed. It is mentioned about the measuring device that prevents the use of artificial light while there is sufficient daylight inside and activates in the case of absence. The quantity and balance of the combination of photometric and radiometric will enable us to obtain a more appropriate, more efficient comfort zone (Sandhyalaxmi and Raafe, 2014). To achieve sustainable comfort, phenomena such as temperature, relative humidity, illuminance, and glare have been dealt with. In Sandhyalaxmi's study, a building modeled as 3.75x3.75x2.5 meters; PMV, PPD, Visual comfort probability (VCP), and unified glare index (UGI) values were examined. Some assumptions have been made for the calculation of PMV and PPD. For the activity value, 1 met (or 1.2 met value) used when standing still, 0.15 m / s- 0.20 m / s was used for airspeed and it was accepted that there was no ventilation in the room. Clothing insulation was taken as 1.1 clo, which is the value when wearing the average clothing, the number of people in the room was chosen as two people. In the study, other required values such as temperature or relative humidity were obtained through a sensor, and PMV and PPD values were measured at set temperatures and certain curtain angles. Values below 23 degrees were negative and values above 25 degrees were positive. For example, the screen position at 45 degrees and the PMV at 24 degrees has been observed as zero, and the PPD value is 5%. Again, the PMV value

was found to be 0.0067 (almost thermal neutrality) and the PPD value was again 5% for the angles where the curtain position ranged from 30 degrees to 60 degrees. An example graphic of the study is shared in Figure 2.10 below.

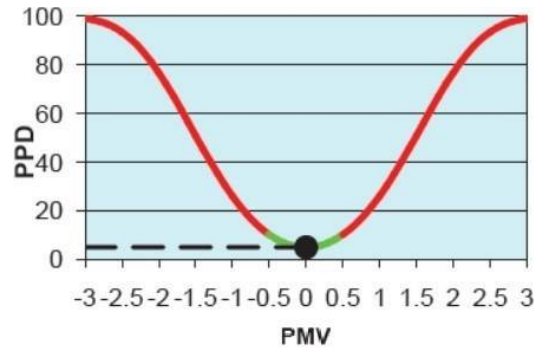


Figure 2.10 PPD vs PMV at 24°C, blinds position = 45° and relative humidity =54%

The daylight Factor gives an idea of how much the window or curtain needs to be opened to provide the minimum light in the room. To express mathematically, it can be said that it is the percentage ratio of interior luminance to exterior luminance. This rate can go up to 3.8% on a sunny day without clouds (Sandhyalaxmi and Raafe, 2014). In Manipal (a province in India) where Sandhyalaxmi studied, optical sensors were used at a height of 0.82 meters from the ground to measure the interior illumination value, and it was observed that the maximum illumination in the center of the room was 625.3 lux while the curtain angle was 45 degrees. Besides, the brightness of the room is directly proportional to the temperature. One of the parameters providing this ratio is the radiometric value and the other is the photometric value, but there is also a relationship between these two components. This shows that the light plays double. The increase in the amount of light with the increase of temperature indicates that some photon formats bounce off the interior surfaces and turn into heat format. Of course, it is understandable that this fact is seen more in summer than in winter. In the study, software named DIALux was used for lighting system installation and measurement. The working plane is divided into grids. Uniformity ratio, which is a measure, has been included in the study so that the human brain can perceive how much the light is dispersed into the room. Although the ideal value is 0.1 according to IESNA standards, it is also an acceptable value when this

ratio is less than 0.4 (Sandhyalaxmi and Raafe, 2014). It was determined as 0.146 in the study. The previously predicted illuminance value of 625.3 lux was found to be 628.33 lux, which is very close to the estimated number in the center of the room, and the UGR value, which is the glare criterion, was found to be 16. With this glare index, activities that are very important to see, such as sewing and embroidery, can be done very comfortably. The average illuminance value was found to be 201 lux, but with this value, it is barely possible to see every corner of the room without difficulty. Of course, this result was achieved when the curtains were closed, and when the curtains were lifted, a sufficient amount of light began to enter. The method of re-adjusting the curtain position is not only efficient but also cost-effective. Illuminance value jumped to 541 lux in the curtain opening between 30 degrees and 60 degrees. The illuminance value that increases with the change of the curtain angle does not cause visual discomfort. According to IESNA standards, many activities can be done at this value. However, it was also noted in the study that the sunshade curtain used to prevent heat accumulation in the room should be made of non-reflective material. As a result of the study, it was stated that thermal comfort was achieved when the thermometers showed 24 degrees, and the curtain position was located between 30 and 60 degrees. Hence, it should be ensured that the temperature in the room and its surroundings are close to this value. The best method for having sufficient illuminance is to use blinds. Glare is prevented by using polarized material. In systems designed to be the main source of illumination is artificial light should be kept at glare 18 and below. To reduce the carbon footprint, the tinted paper should be used on the windows to prevent infrared rays from the sun. In this way, both the thermal heat gained from the sun will be reduced by 74%, and energy savings will be achieved by not using the air conditioning system that should be used as a result of heating (Sandhyalaxmi and Raafe, 2014). A comment was made to the conclusion part of the study. No modeling has been made that keeps both thermal and visual comfort at the same time. For people not to be negatively affected by only one side, there must be a balance between them.

2.1.4. Energy Efficiency and Thermal Comfort

It has become necessary to make variations by using parameters such as building direction, interior and exterior wall type, roof type, building geometry, shading, window type, window permeability, ventilation. Since some parameters do not have a linear proportion to thermal comfort, it would be more correct to optimize (Bre and Fachinotti, 2017). In addition, the more the number of iterations, the more and more complex the variety of variations will be, so it makes more sense to do the optimization with a smart program. So one of the aims of the authors' study is to develop a suitable computing device for multitasking building performance optimization and show whether it works or not. It is to contribute to the multitasking definition of not only the performance of homes during the warming period but also in cold conditions. The determined tasks are to improve comfort based on natural ventilation, to reduce energy consumption used in the cooling system, to prevent environmental adverse effects, to increase thermal comfort, to reduce carbon emissions, and to minimize life-cycle costs. The situation in which a single solution dominates the outcome may be the case when other outcomes are not feasible, or when other multitasking objectivities make the outcome worse (Bre and Fachinotti, 2017). However, there is no single result in optimizations using the Pareto solution. In Pareto optimization, if there is a non-dominated solution, it is called Pareto-optimal, and the solution in which the solution is provided with at least two non-dominated solution sets is called Pareto Front. The Pareto optimization scheme is shared in Figure 2.11 below.

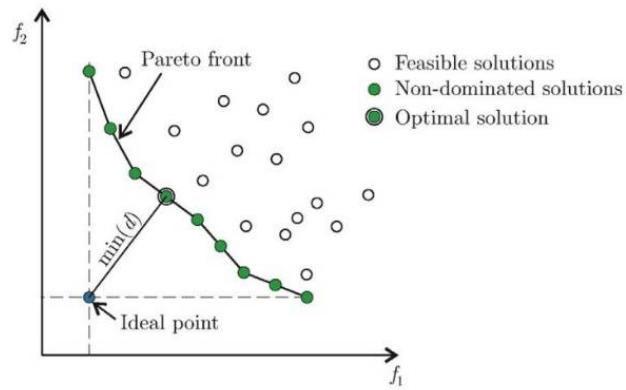


Figure 2.11 Schema of the Pareto front, the ideal point, and the final optimal solution for the minimization of two contradictory objectives f_1 and f_2 ,

In the article, two cases were created in a sample dwelling selected in Argentina. While 12 variables were used in the optimization named Case A; Case B optimization has been diversified with 22 variables. The Table 2.3 and Table 2.4 below can be examined to understand what the variables are.

Table 2.3 Design Parameters, (Bre and Fachinotti, 2017)

Variable	Parameters
X_1	Building Azimuth
X_2	Window Shading Size
X_3	Solar absorptance
X_4	Window Infiltration Rate
X_5	Door Infiltration Rate
X_6	Window Area
X_7	Window Width

Table 2.4 Categorical design variables

Variable	Description	Level
x_8	External walls	1: Wood with air gap 2: Hollow brickwork layer with mortar finish 3: Double hollow brickwork layers with insulation and mortar finish 4: Wood with insulation and plaster finish 5: Concrete block with cement-plaster finish 6: Double concrete block with insulation and cement-plaster finish 7: Concrete
x_9	Roof type	1: Concrete with plaster ceiling 2: Concrete and hollow ceramic block with plaster ceiling 3: Ceramic tile, air gap and wood liner 4: Ceramic tile, air gap and concrete liner 5: Ceramic tile, air gap, insulation and concrete liner 6: Ceramic tile, air gap, insulation and wood liner
x_{10}	Window type	1: Single clear 3 mm thick glass 2: Single clear 6 mm thick glass 3: Double clear 3 mm thick glass with air gap 4: Double clear 3 mm thick glass with air gap
x_{11}	Internal walls	1: Wood with air gap 2: Hollow brickwork layer with mortar finish 3: Wood with insulation and plaster finish 4: Concrete block with cement-plaster finish 5: Concrete
x_{12}	Floor type of the first floor	1: Concrete with ceramic floor 2: Concrete with wood floor 3: Insulation, concrete and ceramic floor

While some of the variables in the table may vary between these values, including the minimum and maximum values, some are selected as categories (single value). For Case A and Case B, the following results are obtained from the optimizations made by considering the heating and cooling performance, thermal comfort, and minimum energy in Figure 2.12.

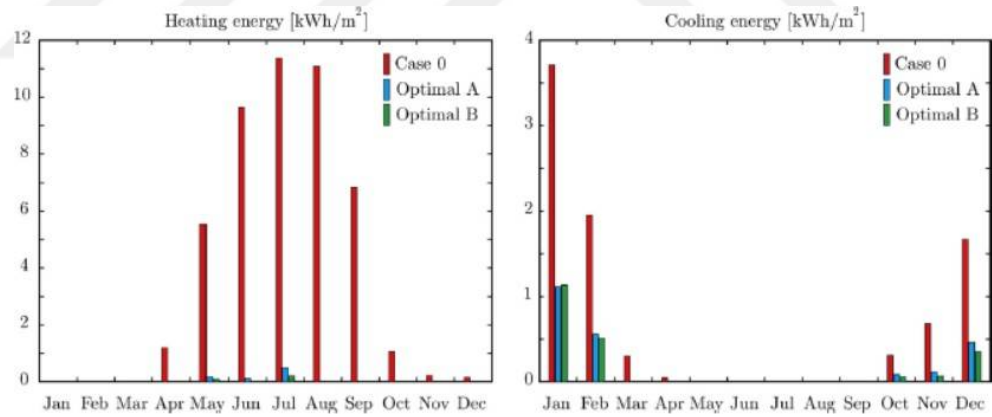


Figure 2.12 Monthly heating and cooling energy consumption in bedrooms for the analyzed cases

When analyzed for Case A or Case B, it was seen that the system (base case) for the air conditioning system in bedrooms was inefficient. As a result of optimization, it has been determined that between May and July (since Argentina is located in the Southern Hemisphere), the energy spent for heating in homes is less than 2% of the energy spent for base case heating throughout the year. As a result of the optimization, the energy spent on cooling (needed from November to March) has decreased by up to a quarter compared to the base case. In the figure below, the pre and post-optimization values of the naturally ventilated living room are shown together with the operative temperature in Figure 2.13.

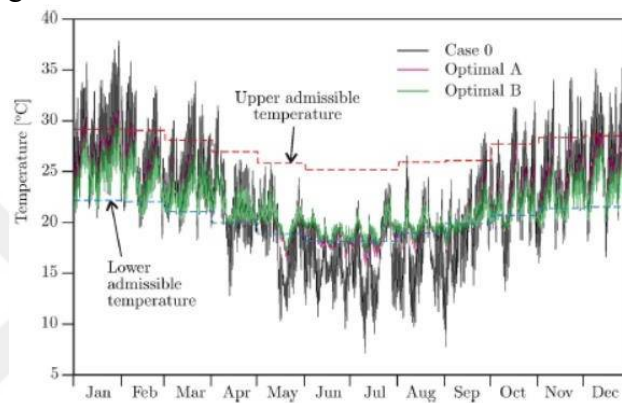


Figure 2.13 Hourly operative temperature at the living room for the original and the optimal designs (Bre and Fachinotti, 2017)

The differences observed for Case A and Case B were more apparent in the middle of summer and winter (January 9th, mid-summer; July 10th, mid-winter). For the base case, comfort could not be provided during these time intervals. While 90% of the occupied hours were out of the comfort range for Case A on very hot days, this ratio could be reduced to 30% for case B. While the uncomfortable rate was 70% of the occupied hours for Case A in very cold weather, this rate was determined as 10% for Case B. Therefore, the structure designed for Case B offers better optimization all year round as it performs better in hot and cold weather. The parameters obtained as a result of optimization for cases A and B are shared in the Table 2.5 and Table 2.6.

Table 2.5 Design variables for the optimal heating and cooling solution for Case A (Bre and Fachinotti, 2017)

Design variable	Optimum
Building azimuth	270° C (surface 4 facing North)
Window shading size	100%
Solar absorptance of external walls	0.5
Windows infiltration rate	10 ⁻⁵ kg/s/m
Doors infiltration rate	0.02 kg/s/m
Ventilation area fraction	50%
Window width	Level 3
External walls	Level 6
Roof type	Level 5
Window type	Level 4
Internal walls	Level 5
Floor type of the first floor	Level 1

Table 2.6 Design variables for the optimal heating and cooling solution for Case B (Bre and Fachinotti, 2017)

Design variable	Surface	Optimum
Building azimuth		270° (surface 4 facing North)
Window shading size	1	75%
	3	100%
	4	50%
Solar absorptance of external walls	1	0.3
	2	0.3
	3	0.7
	4	0.9
Windows infiltration rate		10 ⁻⁵ kg/s/m
Doors infiltration rate		0.02 kg/s/m
Ventilation area fraction		50%
Windows width	1	Level 1
	3	Level 1
	4	Level 4
External walls	1	Level 6
	2	Level 6
	3	Level 6
	4	Level 6
Roof type		Level 5
Window type		Level 4
Internal walls		Level 5
Floor type of the first floor		Level 3

In this study, optimization has been made to improve energy efficiency and thermal comfort in residences. Various parameters have been used to discover the optimum trade-off between heating and cooling performance. Compared to the base case, it was observed that the number of hours decreased by 99% and 95% spending on cooling and warming respectively. As a result, energy consumption has been reduced (Optimization data also confirm this situation in Table 2.7).

Table 2.7 Thermal and energy performance for Case 0 (reference) and the optimal solutions of Cases A and Case B (Bre and Fachinotti, 2017)

Objective	Case 0	Case A	Case B
f_{heat}	1	0.05	0.03
f_{cool}	1	0.15	0.13
Heating degree-hours [$^{\circ}\text{C h/year}$]	1454.41	120.47	80.25
Cooling degree-hours [$^{\circ}\text{C h/year}$]	2235.78	44.51	7.84
Heating energy demand [$\text{kWh/m}^2/\text{year}$]	44.39	0.88	0.35
Cooling energy demand [$\text{kWh/m}^2/\text{year}$]	11.57	2.34	2.13

Another result obtained by considering the optimization values in the article, external walls and roofs should have low thermal transmittance and high thermal capacity, and high thermal delay, the internal ones should have high thermal transmittance and capacitance and low delay, the windows should have low transmittance among others (Bre and Fachinotti, 2017). Optimization-based approaches are made to strengthen the buildings to be designed or existing buildings. In particular, optimization is performed to determine parameters such as building shape and building envelope futures in design. Also, how efficient building envelope, heating, and cooling systems can be used to reduce energy consumption and lifetime costs in residential buildings can be achieved through optimizations. There are studies such as a sequential search approach, genetic algorithm, and particle swarm optimization in previous studies (Griego et al., 2012). In Griego et al.'s study, the sequential search approach technique was used again to offer a better residence. First, the general analysis methodology was determined, including the characteristics of typical houses in Salamanca (Mexico), the province of the study, and the most ideal energy efficiency and thermal comfort model were presented for new and existing residential buildings. Various combinations for energy efficiency measurement (EEM) in the study were carried out on existing and newly designed buildings in Salamanca, Mexico. Although the building characters are considered to be the same, the analysis to be applied differently due to the implementation of EEMs and cost prices. Various energy efficiency and thermal comfort measurements have been applied to reference houses. Thermal comfort was measured by measuring the PMV (Predicted Mean Value) values at each hour of the year recommended by the Fanger comfort model.

Additional energy analyzes were also applied to thermal comfort analysis. It aims to produce an ideal solution to equalize the conditions of the building designed by improving the thermal comfort level with the building designed without considering the working thermal comfort. Referenced Homes were chosen after considering the characteristics of houses in Salamanca province and after five houses were visited in the region. During the visit phase, comprehensive data such as building materials, building residence area, two years of utility data, building usage calendar of residents, thermal comfort level were obtained. The information obtained is summarized in the table below. Other reference buildings in the town of Toluca, another province of Mexico, have been included for a more comprehensive study of the buildings for reference. The three houses in the town of Toledo are divided into small, medium, and large houses according to income level. It is common to use heating and cooling systems in homes in both provinces. Therefore, electricity consumption arises from various and very different equipment. The characteristic of Salamanca is that it is 1720 meters above sea level, the temperature rises to 30-35 degrees in May, and the temperature drops between 0 and 5 degrees in the winter months. However, the average temperature is between 15-20 degrees. Toluca, on the other hand, has a cooler climate since it is 2680 meters above sea level (Griego et al, 2012). In the study, the annual energy consumption of the houses in Salamanca is predicted as the average of five houses, while various equipment and lighting loads are assumed as the average of the first four houses (Table 2.8). The reason why the fifth house is not included here is explained as having too much equipment in the house, which represents the home of people with very high incomes. When the materials used in the building were examined, similarities were found for both provinces. The walls are made of reinforced concrete and red clay bricks. Roofs are again made up of reinforced concrete floors. These and similar observations were supported by data from the National Institute for Statistics and Geography (INEGI for its acronym in Spanish) (Griego et al., 2012). The reference houses were used in the study to develop a baseline model for conditioned houses. The difference between a conditional house and the unconditional house is whether there is a set point for HVAC or not.

Table 2.8 Housing characteristics for collected data and reference homes (Griego et al., 2012)

Home characteristic	Home 1	Home 2	Home 3	Home 4	Home 5	Salamanca reference home	Toluca social housing	Toluca medium housing
Occupants per home	4	2	5	3	3	4.1	4.2	4.2
Building area (m ²)	128	71	132	211	400	110	68	108
Number of bedrooms/bathrooms	3/1	2/1	3/2	3/2	3/3	3/2	3/1	3/2
Average annual LPG consumption (MJ) ^a	6010	14,423	21,634	21,634	24,411	17,622	10,500	22,300
Annual electricity consumption (kWh) ^b	1807	1269	2587	2085	3347	1962	611	2166
Refrigerator (kWh/year) ^c	429	473	487	360	578	465	222	764
Washing machine (kWh/year) ^d	110	115	200	120	118	133		
Miscellaneous equipment (kWh/year) ^e	515	276	1026	328	1205	536		
Lighting (kWh/year) ^f	753	405	874	1278	1446	827	333	1402

^a From receipts for Homes 1 and 5, Home 2 reported approximately 30 kg LPG/month and Homes 3 and 4 reported approximately 45 kg LPG/month.

^b Two year average of utility data specific to each home.

^c Annual kWh from each homes refrigerator NOM-015-ENER-2002 energy rating.

^d Homes 1–2 have washing machine NOM-005-ENER-2010 energy rating data, while the other homes were estimated based on reported loads/week from site visits.

^e Miscellaneous equipment is the difference between all known loads and the total annual energy use.

^f Counted all lamps and corresponding wattage during site visit, annual kWh is based on 6 h a day usage.

Among the previous studies mentioned in the article, it is stated that electrical energy is used the most for heating and cooling in Mexico. In order not to estimate the amount or cost of energy spent annually for heating and cooling processes (overestimated), the setpoint value was chosen carefully, 20 degrees for the heating process and 24 degrees for the cooling system were deemed appropriate (Griego et al. 2012). In the study, it was mentioned that more than 18000 combinations were tested both in conditional and unconditional houses to minimize the annual energy consumption and maximize energy savings, and thus existing houses and reference houses were created. Simulations were made thanks to the developed BEOptE software. Life cycle cost was used as a criterion for money in the analysis. Various criteria such as the unit price of gas and electricity to estimate the annual cost savings associated with the annual energy savings, the mortgage period of the home, mortgage interest rate, inflation rate, and the normal discount rate have been considered. (Various numerical values were presented in the study. Example: 0.10 \$ / kW electricity, 0.47 \$ LPG cost, 2012 figures) Energy modeling has been made by taking the building parameters and annual energy consumption values shown in the table as a reference. Since no heating and cooling systems are generally used in the houses in Salamanca, it has been confirmed in the energy modeling whether the unconditioned houses reflect the indoor thermal conditions correctly. So measurements were taken and recorded on the first and second floors during two weeks between April 26, 2011, and May 11, 2011. The result obtained was compared with the data obtained from the analysis in Figure 2.14 and Figure 2.15.

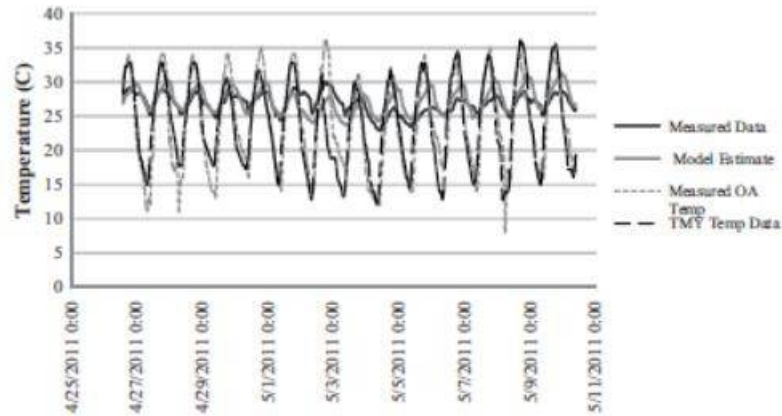


Figure 2.14 First-floor temperature validation (Griego et al., 2012)

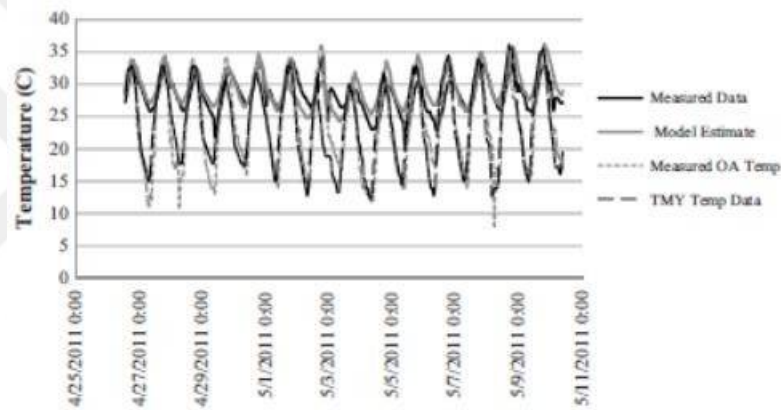


Figure 2.15 Second-floor temperature validation (Griego et al., 2012)

The fanger comfort model was used to observe the PMV value at any time of the year. PMV is found by the energy balance equation. The energy balance is the same as convective heat loss, radiation heat, sweat evaporation, and the internal energy that the body gains such as clothing, the surface of skin energy. After knowing the values such as activity, environment temperature, clothing level, air velocity, etc., the temperature in the skin can be estimated. How these values were taken is explained with examples in the article. While the metabolic activity value is 72W per person

while sleeping, this number can vary between 171-207W while eating. This value is 112 W per person for any average activity. While trousers and long sleeve t-shirts are worn, clothing is 1, with trousers and short shirts this value decreases to 0.75. Since it is assumed that thicker clothes will be preferred in winter and shorter and comfortable clothes will be preferred in summer, cloth level values have been determined by considering this situation. While air velocity is accepted as 0.0034 m / s, the work efficiency value is taken as 0 by assuming that all the energy produced by the body has been converted into heat. Before any optimization work is done, the energy costs for the homes selected as baseline are \$797 and \$557, respectively, for conditioned and unconditioned situations. These values precede any thermal comfort and energy efficiency implementation. The cost of increasing the thermal comfort level for a typical home in Salamanca is \$240 per year. For the unconditional situation, energy savings of 17.3% were achieved after optimization, and the energy consumption cost was reduced to \$433. This situation is reflected in a 35% saving in the conditional casing at \$ 542. When the data is examined, it was observed that the most energy savings are in hot water and electricity for the unconditional case, while for the conditional case, in addition to the savings specified in the unconditional casing, the cooling activity that decreases after the roof insulation is specified. In the unconditional building modeling for PMV values, it has been observed that it is above “1” in 1550 hours of a year and below “1” in 150 hours. Contrary to this situation, it has been observed that the conditional building model provides thermal comfort throughout the year. The above data were originally found for the houses selected as baselines. To compare values, the thermal comfort indicator was determined after optimization. Although the initial results showed a significant gain in energy consumption and efficiency, on the contrary, there was no sharp improvement for PMV values. However, the situation changes, and serious progress is achieved when the optimum set used in the conditioned casing is applied to the unconditional set. In the study, it is also underlined that Mexico will achieve a very serious efficiency in the field of energy with the use of sets obtained in conditioned and unconditioned casings

in the coming years. However, the set obtained in optimization was not mentioned in the article, only the study and results were shared.

2.1.5. Energy Consumption, Visual Comfort, and Thermal Comfort

There is a study on how to increase the quality of thermal and visual comfort while reducing the energy consumption of a building whose exterior is exposed to sunlight in Rio de Janeiro, Brazil (Sustentech, 2016). The results are obtained from simulations using different types of glass and sunscreen materials. As a result of the study, the importance of the result was obtained by benefiting from the strong relationship between exterior windows and automated internal shading to increase the comfort and energy efficiency of the building stakeholders. Internal Shading automation is a dynamic solar shading that takes into account the outdoor climate conditions and the sun position during the day to save energy and ensure the comfort of the users. It aims to increase sunlight at a maximum rate and to prevent glare and warming. The study has two main aims. To reduce energy consumption based on the integration between different levels of shading, lighting, HVAC automation and to prove whether interior shading and interior curtains affect thermal and visual comfort. Seven different glass types with different SHGC (solar heat gain coefficient) and VLT (Visual light transmittance) values and two different coating types (with and without alumina) were used. The study on energy efficiency has been carried out at three different levels. In the first, the values were measured without any automatic system, while in the second there was an automatic lighting system with the help of detectors, and in the last one, there was a set-point degree that was adjusted for HVAC in addition to the automatic lighting system. A baseline model was created for comparison; while shading was applied on one side, manual internal shading was applied on the other side. An exemplary result obtained from the study are shown in the Figure 2.16 below.

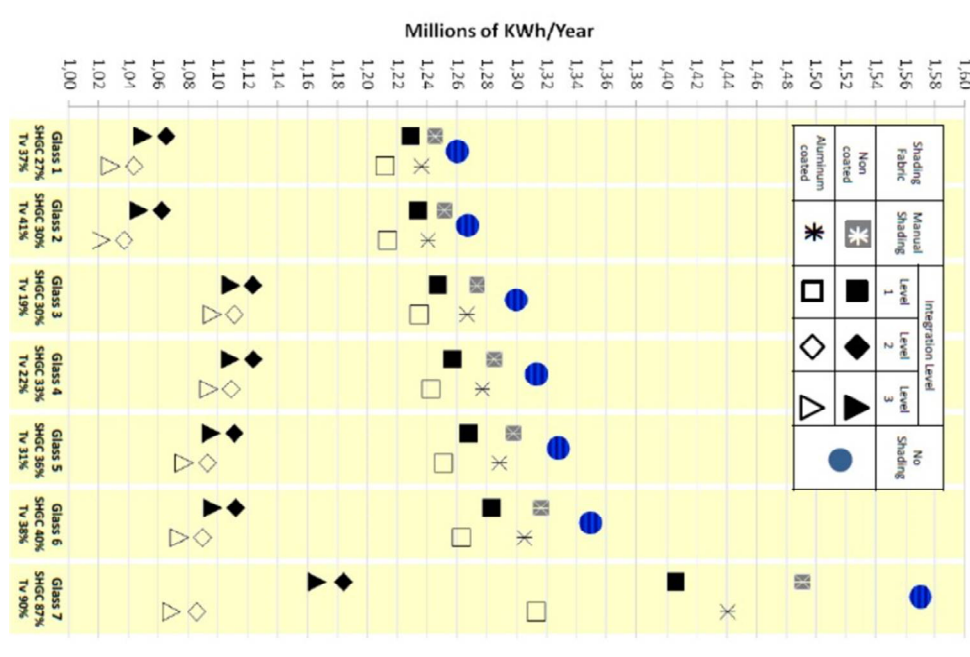


Figure 2.16 HVAC + lighting energy consumption (Sustentech, 2016)

With the IL1 method (automated internal shading), a decrease of 2% to 16.4% was observed in the amount of energy consumption used for HVAC. In particular, it has been found that aluminum-coated materials with higher SHGC values perform better. When IL2 was analyzed, savings between 12.3% and 30.8% were achieved, while these percentages were found between 13.5% and 31.9% in IL3 values. In the study, the following method was applied to measure how the thermal comfort of the people living in the building is affected by automated shading. Considering that temperatures above 25 degrees are not suitable for thermal comfort, the hour duration above 25 degrees (that is, the time qualified as uncomfortable) was measured and how the thermal comfort was affected was analyzed. If the results are obtained from the study, it can be seen that thermal comfort increases between 40.7% and 86.1% with IL1. The most comfortable material has been the glass type with a higher SHGC value. This result is also valid for the type of material covered with aluminum. Thermal discomfort is less common in aluminum-containing material than without. For the visual comfort calculation, the calculation was made by referring to the points 0.5 meters away from the exterior (window wall). After the threshold value determined as 4000 lux, the analyzes were carried out considering that the visual comfort would be

impaired or would be bad. With the use of Automating Internal Shading, the daylight illuminance value in areas near the window has significantly decreased. This decrease in luminance value reduced the visual discomfort and increased uniformity within the room. The daylight illumination value in the 0.5-meter range was reduced between 73.3% and 94.7%, and more reductions were observed in materials with higher VT values. Facades with automatic opening internal shading that do not penetrate direct sunlight have increased the clarity of these areas without compromising visual comfort.

2.2. Previous Studies using BIM

2.2.1. BIM

While increasing the thermal and visual comfort, which is thought to be necessary for the building, the reduction of energy consumption at the same rate will be possible when useful platforms such as BIM become widespread among engineers, architects and experts, to exchange data with each other and benefit from these data (Jalilzadehazhari et al., 2019). With the widespread use of BIM technology, it will not only be wrong to say that the energy problem will be solved, but it will also be incomplete. Because BIM also reduces design errors, construction costs, and construction manufacturing times. For these benefits to be realized, projects based on BIM technology should include optimization algorithms. For these reasons, there has been a rapid development in the field of BIM (Jalilzadehazhari et al., 2019). Various techniques have been tried in the construction industry to reach the most ideal solution. Previous applications related to energy have generally been on thermal performance. Despite the increase in technology and computational writing related to multi-objective optimization in building design, the assistance among the stakeholders who make the designs has not increased to that extent. These constraints and difficulties can be overcome by using BIM technology and its algorithms, as well as by the simultaneous processing, automation, and analysis of variable parameters of models with different penetration areas (Sandberg et al., 2019). Integration between different models using BIM technology, API (called application programming interface), and

IFC (which is a natural file format) provides applicability and workability at the same time. The integration of systems compatible with different domains with the support of IFC, which is the standardized format for information exchange with BIM, has made the idea of centralized information. The idea of centralized information is similar to the master model concept. The model concept comes from the manufacturing that uses CAD-CAM (computer-aided design- computer aided manufacturing) software whose main purpose is to create automatic connections between the main model and its sub-models (Sandberg et al., 2019). In the context of the manufacturing industry, the main model approach aims to define products such as CAD, CAM, CAE, or other analysis types. Any minor changes in the product description of the main model automatically propagate to all compatible models. There are workflow charts that can perform fully automatic design and analysis previously used in jet engine optimization (Sandberg et al., 2019). This master modeling, which can be shown as an example like Matlab, includes programmable automation modules called API. Also, with the help of special software defined as glue, it has made a fully automated workflow applicable for API and macros optimization. This special software helps to analyze, change parameters, and create models. In other words, it completes and supports automation in a shorter time than it should be. Later, special software such as Grasshopper or Dynamo grouped as visual programming languages (VPL) were developed and started to be applied (Sandberg et al., 2019). Just like different software technologies, different applications and developments have taken place within BIM. First, more advanced technical devices and software required for early design were developed, then software such as Revit, which is used to calculate the embodied energy by entering the data of the materials to be used, was developed thanks to the feature called green template. In this way, the information could be used in the transition to other software, and the interoperability problem was partially solved at the same time. Other research has conducted studies on building performance simulation and integration between BIM software. For example, a framework has been drawn that there is a relationship between energy efficiency and investment cost. This framework is based on Revit and Autodesk Green Building Studio. In Sandberg's study (2019), how to create an

optimization between BIM and VPL (Visual Programming Language) was discussed. Project information, building geometry, thermal properties of the building material were used to create analytical energy modeling. Revit's API and gbxml extension were used in this energy modeling. Also, data in modeling can be supported by Revit's IFC extension. The researchers have presented various frameworks on how to make connections between the BIM model and file formats mostly used to make energy-related calculations during the design phase of the building (Sandberg et al., 2019). Researchers have made LEED simulation by using Revit as a reference, converting the gbxml extension to FZK viewer, including HVAC accounts. Moreover, researchers again used the extensions of Revit like IFC, gbxml, IDF thanks to the software that is called Virtual Design Software in terms of different perspectives such as life cycle cost, HVAC, daylight, or the number of rooms.

2.2.2. Energy Consumption and Cost

Although previous studies have mentioned the potential benefits of the natural file format before BIM technology, there are still some question marks about how to model BIM, which balances the needs of the specifications of various disciplines with the new technology. In the frameworks with natural file formats, more logical methods are defined in Virtual Design Studio components and theoretically, more models are produced. However, there are deficiencies in how to model relationships such as LCE and LCC, which are very useful in building performance optimization, including conflicts and choices between design tasks (Sandberg et al., 2019). Identifying these problems has been the main subject and goal of Sandberg's study. In the study, how to optimize life cycle cost and life cycle energy is explained with equations and a framework for a solution is shown in (Figure 2.17). During the method review, it was repeated until the desired results were obtained from the developed prototype, in other words, the procedure has repeated itself until optimization was achieved.

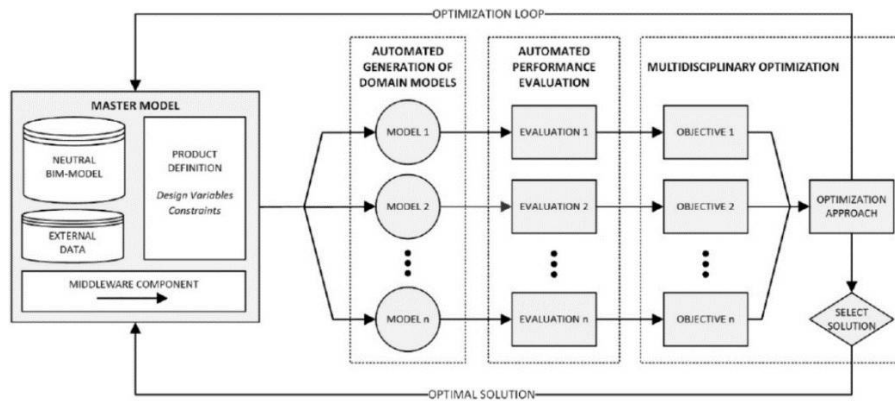


Figure 2.17 The proposed framework for enabling multi-disciplinary optimization (Sandberg et al., 2019)

The model created in this study consists of the neutral BIM model, external data, a product definition, and a special software component. One of the aims of the study is to develop different components and parameters to automatically generate models for different working areas for performance calculation and optimization. Modeling changes after each iteration, new models are optimized on the condition that they stick to the main framework. The aforementioned BIM neutral model provides the main values of both the proposed framework and the inputs and outputs. The neutral BIM model, which is used to help express thought ideas and product data based on natural format, reduces the number of trips and arrivals between the proposed framework and other applications. The Neutral BIM model includes comprehensive information flow including the geometric representation of the building. It contains a snapshot of the project's organization and current status. Rather than being the first model that stands out in the calculation and optimization stages, its main purpose is to offer an option in the first design and optimization solution (Sandberg et al., 2019). Since the most ideal solution is sought using different parameters while optimizing, the product definition should be specified in the frame. The description of all different products and different ways of arrangement should be included. For a better design solution, it will be successful to specify what the design parameters will be and which part of the building to be built (Sandberg et al., 2019). For example, which material will be used for thermal insulation, how much the thickness will be, or what the different window types should be. While some of these parameters may change at

certain intervals, some of them can be tested only by using different materials. Those with upper and lower limits are called continuous, those without any limit value are called discrete. For example, different types of insulation materials are examples of discrete while the material thickness is continuous to change in different sizes. Although the neutral BIM model offers many advantages during the optimization phase, it may need different data or extra information. Also, the BIM model may be missing at any stage of optimization, such as program transitions or defining climate data although it provides a snapshot of the designed building. The main priority of this external data is to provide domain information. To complete the optimization in modeling, the problem of interoperability between models must be solved at the same time. The middleware component specified in the framework and whose purpose is automatic process execution must be included. The main role of the middleware component is to provide communication and coordination (Sandberg et al., 2019). BIM neutral model, shaped between external data and domain models, means to be able to integrate new data generated after optimization and calculation. The domain and master model mentioned are indicated in the Figure 2.18 below.

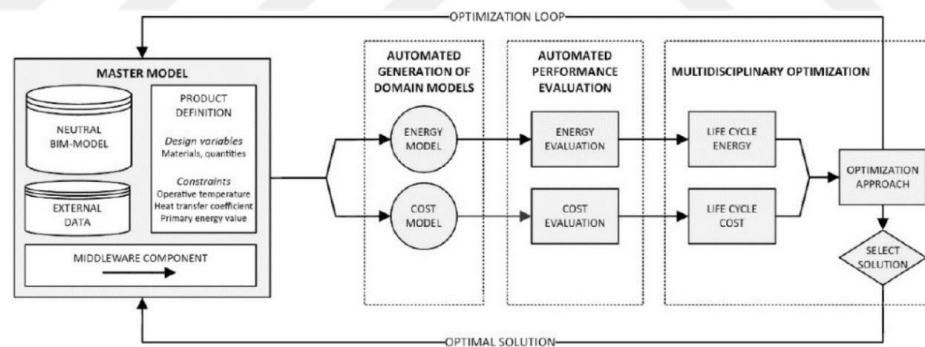


Figure 2.18 Outline of the developed prototype for the optimization of LCE and LCC (Sandberg et al., 2019)

As can be seen from the Figure 2.19 shared below, the study was conducted to ensure optimization between LCE and LCC.

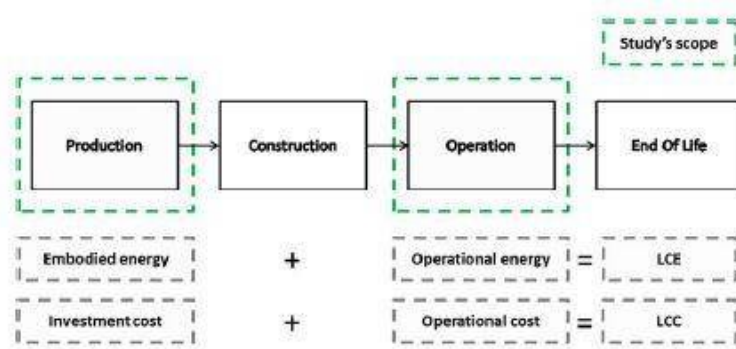


Figure 2.19 The scope of LCE and LCC in the prototype (Sandberg et al., 2019)

The residence in Sweden with a total of 256 m² glass surface of 6 floors, 2.8 m floor height, and 4374 m² residential area was selected. In the study, IFC was used as a neutral format for BIM, so that it can be run simultaneously in different software, in other words, the problem of interoperability has been overcome. The IFC extension is derived from Autodesk Revit and Graphisoft ArchiCad. Grasshopper software, which can work with Rhino3D software, has become the main implementer of the master model. Besides, it has been a special software for import and export data for multi-discipline optimization. In short, while building geometry and material information were taken from IFC and MySQL data extensions, respectively, mathematical calculations for optimization were performed from Grasshopper. The exterior view of the building built for the case study is shared in the Figure 2.20 below.

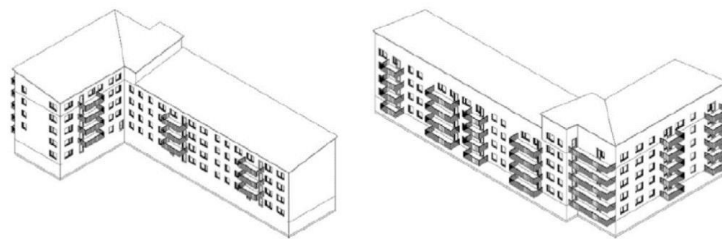


Figure 2.20 The multifamily residential building used in the case study (Sandberg et al., 2019)

Different windows, various insulation materials, and quantities have been used to achieve the best result in case analysis. The reason for working with insulation materials separately is that it has a very significant impact on LCE and LCC costs

(Sandberg et al., 2019). In total, seven different variables were used, four of which were continuous and three of them were discrete.

2.2.3. Energy Consumption, Cost & Comfort Study

In particular, there may be some limitations in optimization modeling to apply multiple different purposes in projects. To give an example of these different purposes, it can be said to increase visual and thermal comfort while limiting energy consumption and costs following the requirements and specifications of the EPBD (Energy Performance of Building Directive) (Jalilzadehazhari et al., 2019). For this reason, BIM and its derivatives applications can be expanded and preferred to overcome such restriction problems. In other words, more efficient results will be obtained by developing a decision-making method based on multiple criteria by sacrificing another goal while achieving one goal. MCDM (Multi- Criteria Decision Method) can also be used to satisfy the interests of both building stakeholders and building owners to the same extent. According to Jalilzadehazhari et al. (2019), an optimization algorithm that considers visual comfort, thermal comfort, life cycle, and life cycle energy consumption together has not been developed and has not been integrated into BIM-centric platforms. For this purpose, a study was conducted to take an office in Sweden and test the developed algorithm. In the study, results were tried to be obtained over two scenarios. While the importance of visual and thermal comfort is more important in the first scenario, cost reduction has been determined as the main target in the second scenario. Building stakeholders want to increase visual and thermal comfort, on the other hand, it has been observed that building owners think more about cost and energy consumption. The mentioned optimization work was carried out in three steps. First, the mentioned office was modeled in 'Revit 2016'. Revit can also be preferred as it increases both collaboration and communication among stakeholders. It should not be forgotten that it also minimizes possible design errors. Then the BIM model was converted to Green Building extension format gbxml and then Energy Plus Input Data File extension idf. While gbxml provides data transfer in the transition to engineering and architecture programs, idf is used in the transition

to Design-Build, which is an auxiliary simulation program in building comfort calculation, energy need, and life cycle cost estimations. In the last step, the data obtained was optimized by the mode Frontier software. In the software, new design variables were constantly tried and iterated until they reached the optimum state. When the maximum number of iterations was completed, results were obtained according to multiple criteria, this process is summarized in the Figure 2.21 below.

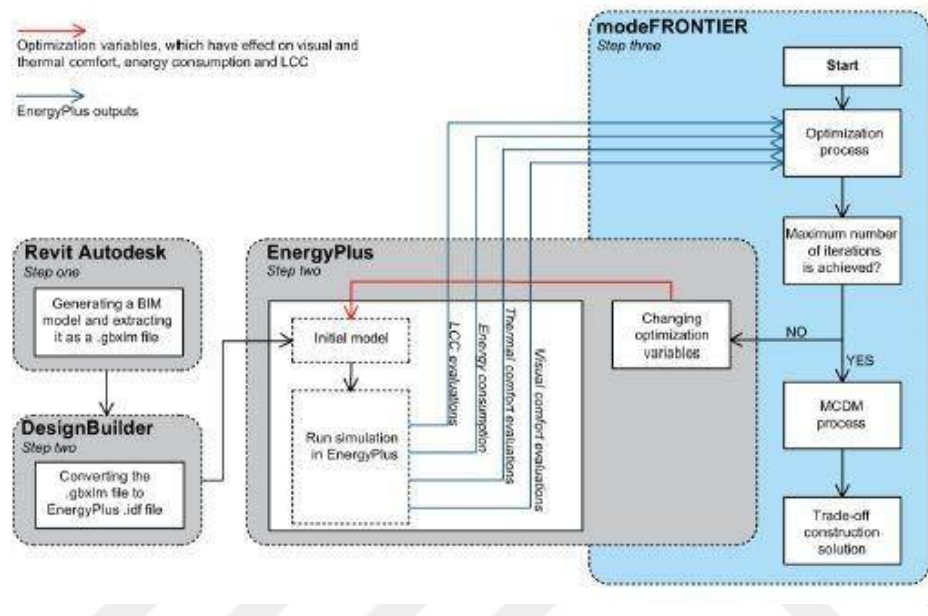


Figure 2.21 Schematic illustration of the applied methodology (Jalilzadehazhari et al., 2019)

While the office building in Sweden, which has a total area of 2821.5 square meters, is modeled in BIM, climate information has been given according to the third climate zone. According to the planning of the national board of housing in Sweden, there are four different climatic zones in the country, the coldest region with the northern parts of the country is the first climate zone, while the southern part, which is the warmest zone, is called the fourth zone (Jalilzadehazhari et al., 2019). After the necessary location and geometry information was completed in the BIM model, the thermal characters of the materials and the building utilization schedule of the building stakeholders were uploaded to the model, and then gbxml format was created. Three different energy-efficient windows, five different types of roofs, five different types of flooring, and five different types of exterior walls were used in the modeled office

building. Using these different parameters, Energy Plus software was chosen to calculate the required values. Two criteria were considered while calculating visual comfort. While the number of hours exceeding the 500-lux illumination value determined by the researchers and selected as the threshold value for visual comfort was the first criterion, the second criterion was the number of hours exceeding the glare value determined by the author and selected as 22. For the measurement of the glare value, certain points in the building were determined and calculations were made over those points. To measure thermal comfort and energy need, components called PPD (Predicted Percentage Dissatisfied) and total energy demand (Et) were preferred, respectively. Total energy; encompassing electricity used for lighting, energy used for heating and cooling, and ventilation; PPD value was tried to be kept below the reference value. For the total cost, the present net value was calculated; expenses such as investment, operation, and maintenance costs are included. The materials used and their properties are summarized in the Table 2.9 below.

Table 2.9 Various building envelopes considered when using the incorporation (Jalilzadehazhari et al., 2019)

Building Envelopes	U-Value (W/K·m ²)	Investment Costs (SEK ¹ /m ²)	Lifespan	Description
Windows [30]				
Type 1	0.9	4665	30	VT ² = 65%, SHGC ³ = 45%
Type 2	0.8	5830	30	VT ² = 63%, SHGC ³ = 43%
Type 3	0.7	6020	30	VT ² = 60%, SHGC ³ = 41%
External walls [31]				
Type 1	0.18	1403.6	30	
Type 2	0.14	1433	30	
Type 3	0.12	1505.7	30	
Type 4	0.1	1530	30	
Type 5	0.09	1599	30	
Ground floor [31]				
Type 1	0.15	589.5	30	
Type 2	0.12	711.4	30	
Type 3	0.1	758	30	
Type 4	0.09	880	30	
Type 5	0.08	956	30	
External roof [31]				
Type 1	0.13	389	30	
Type 2	0.12	411	30	
Type 3	0.1	426.2	30	
Type 4	0.09	445.4	30	
Type 5	0.08	463.4	30	

¹ SEK: Swedish crowns; ² VT: visual transmittance; ³ SHGC: solar heat gain coefficient.

After applying 375 different material options in total, trade-offs were applied according to the analytical hierarchy method. As mentioned above, results have been obtained according to two different scenarios. For the first case, visual comfort was more prioritized, while in the second case, the cost was considered. The material preferences obtained as a result of these decisions are indicated in the Table 2.10 below.

Table 2.10 Trade-off design alternatives (Jalilzadehazhari et al., 2019)

Scenarios	First Scenario	Second Scenario
	Visual Comfort Is the Most Important Objective When Applying AHP	Life Cycle Cost Is the Most Important Objectives When Applying AHP
	First trade-off design alternative	Second trade-off design alternative
Window	1	1
Ground floor	5	1
Roof	5	3
External wall	5	2
PPD	6.20%	6.50%
E_t	62.5 kWh/m ²	64.7 kWh/m ²
K_n	8.5 MSEK	8 MSEK
Total investment	5.75 MSEK	5.2 MSEK

CHAPTER 3

METHODOLOGY

3.1. Methodology

The world population increases naturally and the life expectancy rises due to advancements in healthcare and technology. Accordingly, energy resources are consumed rapidly. As a result, the demand for energy resources is increasing day by day. Therefore, a way of saving energy consumption should be sought while different energy resource materials are being searched. For this reason, universal solution proposals for energy sources should be continued, be researched and be developed. Especially it is very important to complete new projects with less energy consumption comparing with older buildings against the risk of depletion of existing energy resources. In addition, while minimizing energy consumption values, indoor user comforts such as thermal and visual comfort should be improved. As a result of this, an important design parameter can be handled by providing the people comfort. By using BIM technology, it is possible to design greener and more environmentally friendly structures.

The use of BIM has become mandatory in many parts of the world for the AEC sector. Because it provides serious time savings and ease of use in the design of complex projects with many variables and many components. Also, BIM is very useful and feasible as it can perform multiple tasks simultaneously in more complex design optimization of buildings. It takes a lot of time to make a design and to evaluate by changing different design parameters for each different criteria without any BIM help. Therefore, it is inevitable to use BIM and BIM integrated or compatible programs. The methodology of the study is mainly consistent of five different steps. The different steps followed in the study can be seen in Table 3.1.

Table 3.1 The steps followed in the thesis study

NO	STEPS	EXPLANATION	USEFUL SOFTWARE
1	Prepare BIM Model	Project Information, Building Geometry, Material Properties	Autodesk Revit
2	Define Parameters	Variables, Material Types	-
3	Define Objective Functions	Multi-Objective Functions	Octave
4	Making Iterations according to Scenarios	Trying different options and materials	DIVA, Ladybug, Honeybee
5	Finding Optimal Solution	New Set of Solution	Octave

For the analysis, a sample office was modeled by using Revit 2018 software, in the first step. The location of the modeled building was selected as Ankara and the energy consumption, thermal comfort simulations required for the study were made according to the climate information of Ankara. In the case study it is also examined whether there is a trade-off relationship between the energy consumption, visual comfort, and thermal comfort of the modeled building. The first floor of the building is designed to be used as a basement, and the second and third floors are designed to be used for offices. It has a sitting area of approximately 965 m², and has habitable area of 4374 m² in total.

The window to wall ratio for the 2nd and 3rd floors is approximately 100% and one floor has approximately 325 m² of glazing area. Floor heights are designed as 3 m for the basement and 4.40 m for office floors. The exterior view and architectural floor details of the building designed in Revit software are given (Figure 3.1-3.2).

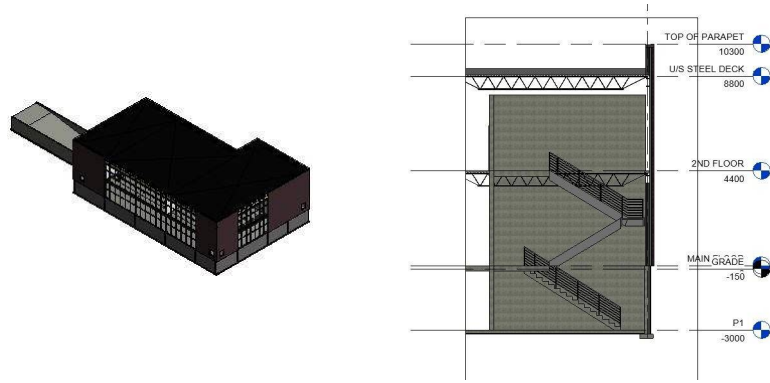


Figure 3.1 The modeled building in 3D and its section

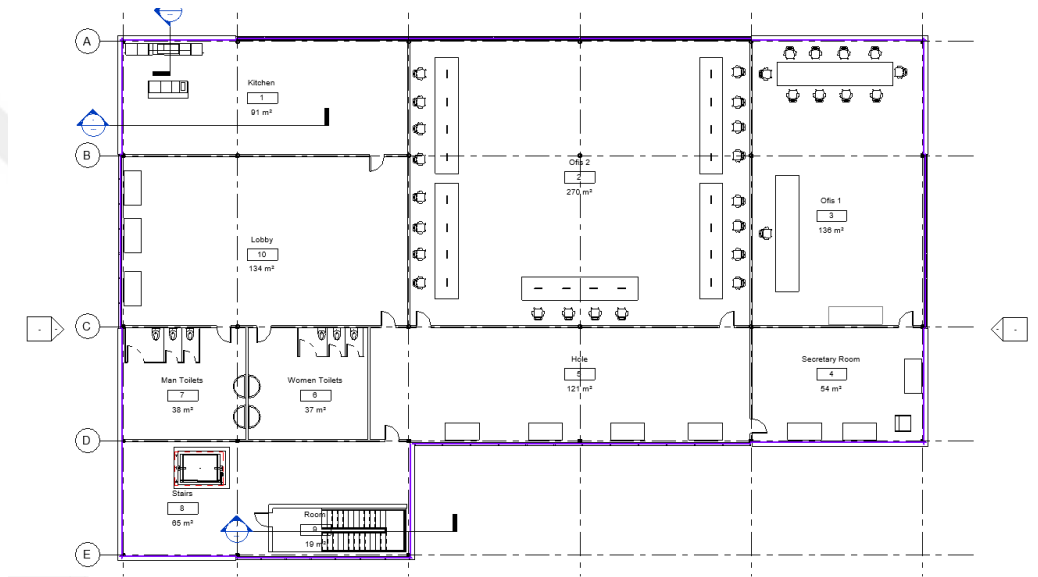


Figure 3.2 Floor plan of the modeled office

In the next step, design variables and materials has been defined. A total of five different design variables were used in the modeled building. They are insulation material thickness, building rotation, surrounding building, window types and window-wall-ratio. In Table 3.2, a list of insulation materials and their thermal conductivity and thickness values can be observed. The rest of the design parameters with their simulation alternatives has been summarized in Table 3.3. In the optimization studies mentioned in the literature review, the parameters among the variables that seriously affect the life cycle cost and life cycle energy result were used and that is the insulation material thickness. The main reason for this is that in studies

such as life cycle cost/life cycle energy (LCC/LCE), where cost and energy consumption are analyzed, insulation material thickness has a positive effect on energy consumption, on the other hand it has negative effect on cost. Therefore, it could be said that there is a trade-off relationship for the energy consumption and the cost. Hence, the insulation material thickness parameter was included among other parameters in the list for this study as well, and it was investigated whether it provides any trade-off relationship or not for the multi-objective functions which are going to be explained in the following step.

Table 3.2 A list of the insulation materials considered as the discrete variables in the study

Index Number	Materials	Thermal Conductivity (w/mK)	Constraints (cm)
1	Extruded Polystyrene (XPS)	0,035	2-10
2	Expanded Polystyrene (EPS)	0,035	2-10
3	Glass Wool	0,040	2-10

Table 3.3 A list of the discrete variables in the study

Index Number	Parameters	Options
1	Rotation of Building	0 30 60 90 120 150 180 210 240 270 300 330 360 (indegrees, °)
2	Surrounding Buildings	Yes/No
3	Window Types	1 2 3 4 5 6 7 8 9 10 11
4	Window Wall Ratio	25 50 75 100

The other parameter is surrounding buildings. A 25-meter building is modeled on the north facade of the office building, a 5-meter building on the south facade, and an 11-meter building on the west side. Since there is a car park entrance on the east front according to design, no building has been added. Also, the reason why buildings

are modeled at different heights is to try to understand the facade effect. It is not possible to determine the height of the buildings around the facade or to adapt the surrounding buildings according to this height in any project to be made. In other words, environmental conditions may not always be suitable for the project, but the study has created an exemplary result to observe how the surrounding buildings affect the energy consumption and thermal and visual comfort. Another parameter of the study is rotation of the building. Both surrounding buildings and the designed office buildings were analyzed by rotating them. The rotation has been done in the counter clock wise direction by 30 degrees each. Totally, twelve different orientations have been applied and analyzed. The last two parameters are related with the windows. Eleven different window types have been tried for the study. Window's names and their properties are shared in Table 3.4. There are windows on each facade of the designed office building. To observe how the window-wall ratio affects the analysis, the window wall ratio parameter was included in the study. In the initially designed model, windows with the same height as the floor height have a 100% window to wall ratio. The total length of the outer wall is approximately 70 meters and total windows have a width of approximately 74 meters on the facades. Both the walls and windows are 4.40 meters long, which is the height of the floor in between stories.

As stated above, to expand the analysis parameters and understand their effect on the analysis, window-to-wall ratio variations were made by changing the window heights. Only heights were changed without changing the window positions. The elevation changes are adjusted to be equidistant from the lower and upper limits. For example, if the window height of 4.40 meters was to be set as 3.00 meters, it was arranged not to be 1.40 meters below the ceiling border, but 0.70 cm below both the lower and upper limit. Four different window-to-wall ratios were used in the scope of the study. These are 100%, 75%, 50% and 25%.

Table 3.4 Window types and properties

#	Glass Type (Product)	Glass Thickness (Inches)	Visible Transmittance (% Daylight)	U-Factor (Winter) (W/M ² k)	Solar Heat Gain Coefficient (SHGC, %)
1	Single White Laminated w/Heat Rejecting Coating	0.25	73	1.06	0.46
2	Single Pane Glass (standard clear)	0.25	89	1.09	0.81
3	Double Bronze Reflective Glass	0.25	21	0.48	0.35
4	Triple Pane Insulated Glass (standard clear)	0.125	74	0.36	0.67
5	Double Pane Insulated Glass (standard clear)	0.25	79	0.48	0.70
6	Pyrolytic Low-e Double Glass	0.125	75	0.33	0.71
7	Soft-coat Low-e Double Glass w/Argon gas fill	0.25	73	0.26	0.57
8	High Efficiency Low-e	0.25	70	0.29	0.37
9	Suspended Coated Film	0.125	55	0.25	0.35
10	Suspended Coated Film w/ Argon gas fill	0.125	53	0.19	0.27
11	Double Suspended Coated Films w/ Krypton	0.125	55	0.10	0.34

In the design with 100% window-to-wall ratio, the window height has a length of $h = 4.40$ meters, while for 75% window-to-wall ratio $h = 3.70$ m, for 50% $h = 2.85$ m and finally for 25% window-to-wall ratio $h = 1.70$ m. Sample images of the design change made as a result of different window-to-wall ratios is shared in Figure 3.3. The white part in the images represents the underground basement walls, the red-toned walls are exterior brick, the blue-colored ones are the windows, and the green color is the roof. To confirm the accuracy of the designed elements in the model and to distinguish the designed elements more easily, layers of different colors were preferred.

In the third step, objective functions have been defined. The study includes three different task functions, i.e., energy consumption, thermal comfort, and visual comfort. A multi-objective function has been used to minimize trade-offs between design parameters.

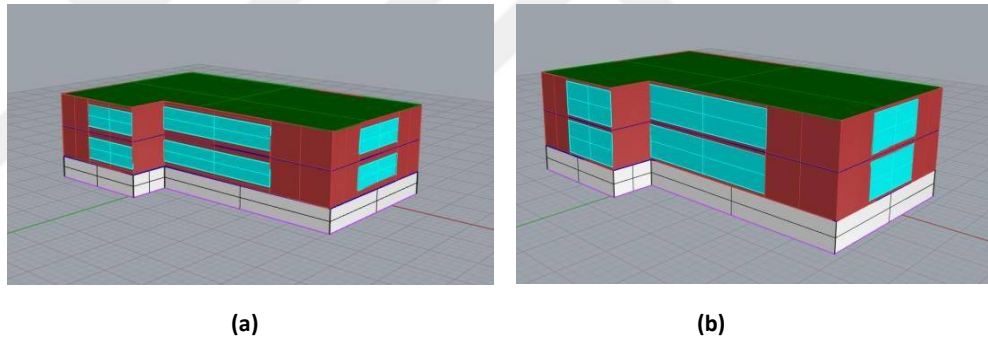


Figure 3.3 The w / w ratio in the building, a) 50%, b) 75%

Successful performance in building optimizations depends on the ability to distinguish, the solution for the relationships between multiple tasks, definition of different discrete variables (Sandberg and Mikkavaara, 2019). In Table 3.5, the list of objective functions used in the study can be observed.

Table 3.5 The summary of optimization objectives

Goal of Optimization	Objectives	Criteria
BIM-based Building Energy and Thermal/Indoor Comfort	Visual Comfort	sDA (Spatial Daylight Autonomy)
	Thermal Comfort	PMV (Predicted Mean Value)
		PPD (Predicted Percentage of Dissatisfied)
	Energy Consumption	Electric Lighting & Equipment Consumed
		Heating Energy
		Cooling Energy

The optimization problem introduced to the study is as follows (Eq. 6)

$$mi\{f_1(x)\}, max\{f_2(x), f_3(x)\}, x = [x_1, x_2, \dots, x_n] \quad (6)$$

Each $f(x)$ function in the equation represents each objective involved in the optimization. In other words, $f_1(x)$ defines the energy consumption of the building, $f_2(x)$ thermal comfort, and $f_3(x)$ visual comfort. Expressions such as $x_1, x_2, x_3 \dots x_n$ indicate design variables. In the Eq. 7, it can be observed how energy consumption is calculated. In Eq. 8 and Eq. 9, how thermal comfort and visual comfort can be obtained are shared respectively.

$$\begin{aligned} f_1(x) = \text{Energy Consumption} &= \text{Heating Energy} + \text{Cooling Energy} + \text{Equipment Energy} \\ &= \sum_{n=1}^r HE + \sum_{n=1}^r CE + \sum_{n=1}^r EE \end{aligned} \quad (7)$$

$$\begin{aligned} f_2(x) = \text{Thermal Comfort} &= \text{PPD} = \text{Predicted Percentage of Dissatisfied} \\ &= \sum_{n=1}^r (100 - 95 \cdot e^{-(0,03353 PMV^4 + 0,2179 PMV^2)}) \end{aligned} \quad (8)$$

$$f_3(x) = \text{Visual Comfort} = sDA_{\frac{x}{y}}\% = \frac{\sum(w_{fi} \cdot DA)}{\sum p} \quad (9)$$

After defining the objective functions, it is needed to identify which parameters or variables affect which objective functions. Except insulation material thickness and visual comfort objective function, each parameter affects each objective function. The reason why insulation material thickness does not affect the visual comfort is that, the visual comfort is related with the exterior layer of building elements. Since insulation material is inside of the building element, it does not have any direct interaction with light beams. In Table 3.6, the list of parameters and their effects on the objective functions can be observed.

Table 3.6 The list of parameters and the types of analysis they affect

No	Parameters	Visual Comfort	Energy Consumption	Thermal Comfort
1	Insulation Thickness	X	✓	✓
2	Window Types	✓	✓	✓
3	Surrounding Buildings	✓	✓	✓
4	Building Rotations	✓	✓	✓
5	Windows to Wall Ratio	✓	✓	✓

In the fourth step, different scenarios have been simulated. As mentioned above, both the designed office and the surrounding buildings were analyzed by rotation. It was examined in which situations the modeled office building analysis give the most ideal results. Four different cases were determined for the study. In the first case, only the existing office building has been analyzed without any surrounding conditions and the office building was rotated at 30 degrees each time. In the second case, the office building was analyzed with the surrounding buildings and it was rotated at an angle of 30 degrees for each analysis. The rest of the two cases are done for the hypothetical conditions. In those cases, not only the designed office is rotated but also the surrounding buildings were rotated. As explained in the above sentences, it is out of the question to position the surrounding buildings according to the current project. However, in the third case, the office building was kept fixed and the

surrounding buildings were rotated at 90 degree angles. Thus the importance of the facade effect can be examined. In the last and the fourth case, the office building was rotated at an angle of 30 degrees with the surrounding buildings as well. In this way, the effect of the surrounding buildings and building rotation could be observed. This means we can observe the effect of having a taller building on the west vs north side of the building as well as having the building the façade of the building with more windows looking at different directions with different surrounding buildings. A summary of four different situations is shared in Table 3.7 below.

Table 3.7 The four different cases applied for the study

Case	Surrounding Building Existence	Building Rotation (in degrees)	Rotation of Surrounding Building (in degrees)
1	☒	30,60,90,120...360	☒
2	✓	30,60,90,120...360	☒
3	✓	☒	90,180,270,360
4	✓	30,60,90,120...360	30,60,90,120,...360

The rotations were carried out in counterclockwise direction. As an example, the images of the surrounding buildings and how the building rotation is done is shown in Figure 3.4 below. In the first figure, the situation where there are no buildings around the office building is shown (Figure 3.4a). In Figure 3.4b, the office building is shown together with the surrounding buildings, and in Figure 3.4c the position where the office building is rotated 60 degrees is visualized. Further below, all possible rotation conditions are shared in Figure 3.5.

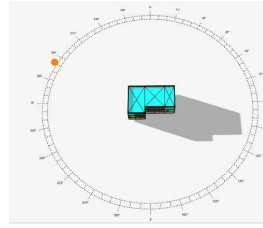


Figure 3.4a

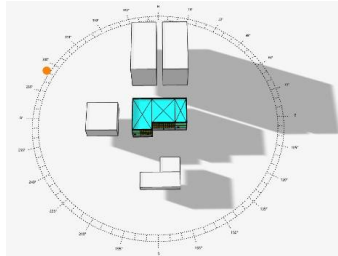


Figure 3.4b

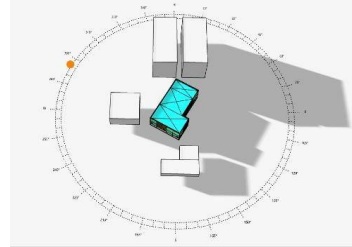


Figure 3.4c

Figure 3.4 Illustration of the office buildings in different scenarios

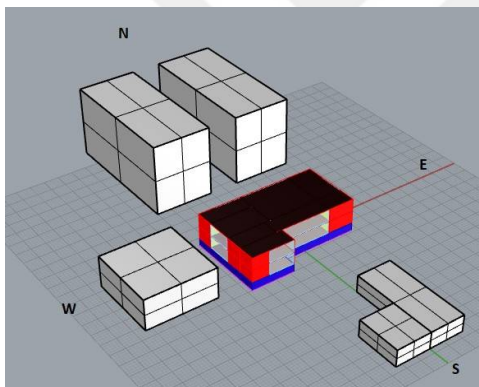


Figure 3.5a 0 degree

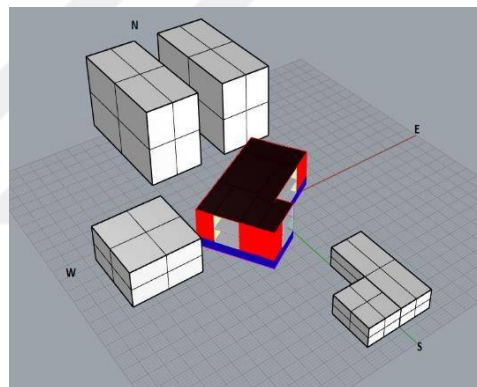


Figure 3.5b 30 degrees

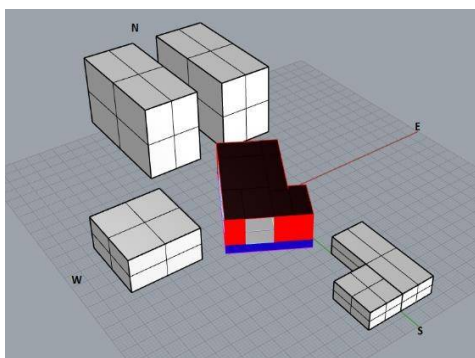


Figure 3.5c 60 degrees

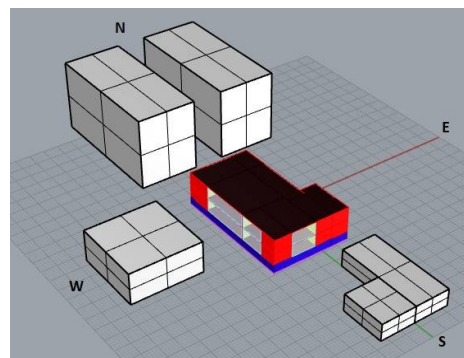


Figure 3.5d 90 degrees

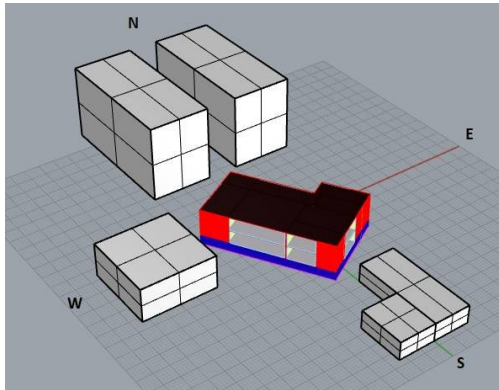


Figure 3.5e 120 degrees

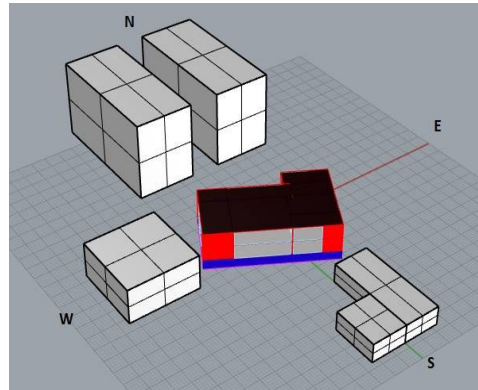


Figure 3.5f 150 degrees

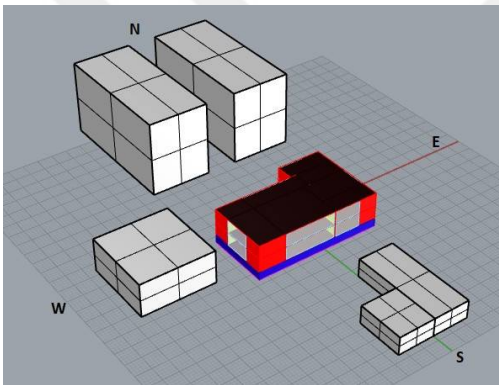


Figure 3.5g 180 degrees

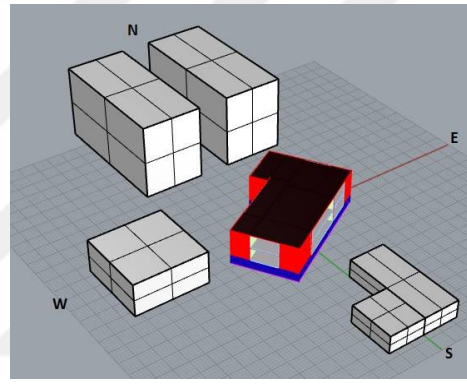


Figure 3.5h 210 degrees

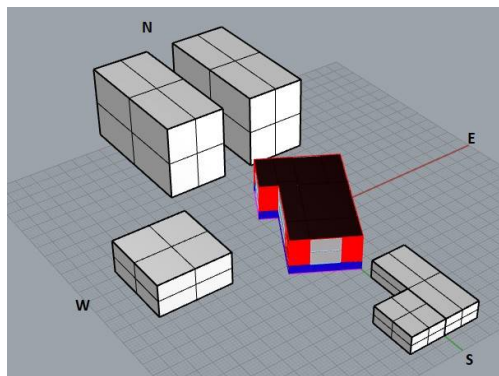


Figure 3.5i 240 degrees

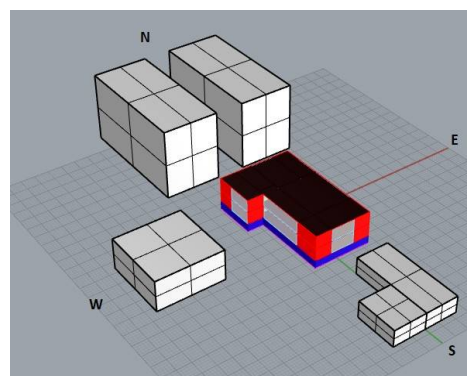


Figure 3.5j 270 degrees

Figure 3.5 All rotations of building starting from 0 degrees to 330 degrees

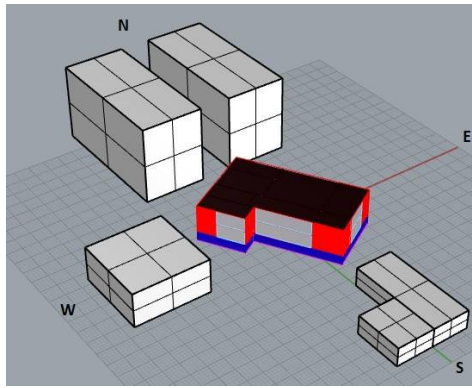


Figure 3.5k 300 degrees

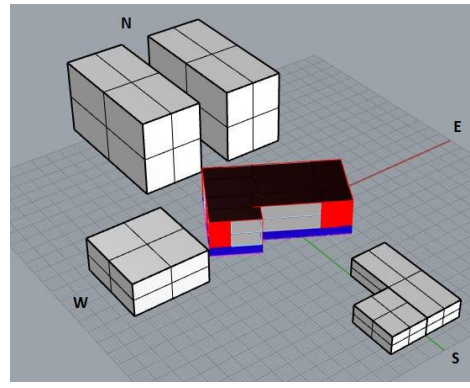


Figure 3.5l 330 degrees

Figure 3.5 Cont.'d All rotations of building starting from 0 degrees to 330 degrees

Finally, all different cases have been analyzed by using each parameter with each case in the fifth step. According to different scenarios, the results for energy consumption, visual comfort and thermal comfort simulations has been observed. Analysis results were examined and interpreted separately by considering different cases and different wall-to-window ratios. Previously, the results of a totally of 1760 different situations were analyzed without any additional filtering. Afterward, the results of the optimization study were subjected to a separate filtering process to observe the ideal situation easily since the results obtained after the optimization are various and so many. For example, the window type is said to be suitable if the results obtained from the sDA (spatial daylight autonomy) method used for visual comfort are 55% and above. Because, in cases where visual comfort is measured with the spatial daylight autonomy method, the acceptable minimum ratio determined by Indoor Environmental Quality (IEQ) in the LEED v4 category is 55 percent (Nezamdoost and Wymelenberg, 2016). ASHRAE55 standards can be taken as a reference for thermal comfort. ASHRAE stated that the PPD value, which is the criterion for thermal comfort, should be at a maximum of 20%, otherwise thermal comfort will not be provided. However, the value of 15%, taken from European standards was chosen in the case analysis, by doing so a separate elimination could be performed in the dominated solutions obtained after optimization. Therefore, the results which are higher than 15% for the thermal comfort and the results which are smaller than 55%

for the visual comfort were eliminated from the best cases for the study. In other words, a post elimination processes has been applied in order to limit finding results.

3.2. Objective Functions:

3.2.1. Visual Comfort Simulation

When the studies in the literature are reviewed, it is seen that the visual comfort includes parameters such as i) amount of light, ii) glare, iii) the quality of light, and/or iv) the rendering quality of light. When the details of these indicators, which can be considered as the main criteria, are examined, it is found out that there are also sub-analysis methods such as Daylight Factor (DF), Daylight Autonomy (DA) for the amount of light, Unified Glare Rating (UGR), and Predicted Glare Sensation Vote (PGSV) for glare, or Color Rendering Capacity and Color Quality Scale for the quality of light, and so on. It is possible to increase these example methods for each category. Spatial Daylight Autonomy (sDA) was preferred to measure the visual comfort in this study. The sDA method is a method of measuring amount of light and it is frequently preferred both in analysis tools and literature studies for calculating visual comfort. Spatial Daylight Autonomy (sDA) can be defined as the percentage of the area within the building that provides the targeted threshold value for each year, as well as defining the annual sufficient daylight level. To include any surface in the desired percentage of area, the analyzed surface must exceed the targeted threshold value for at least half of the one-year occupied hours (8 am to 6 p.m. of the local clock time) (Suk, 2019). The Spatial Daylight Autonomy formula is shared below (Eq. 10). This method is calculated on each surface in the area to be analyzed and adds only the surfaces that can exceed the threshold value.

$$sDA_{\frac{x}{y}}(\%) = \frac{\sum(wf_i x DA)}{\sum p_i} \in [0,1] \quad (10)$$

$$with wf_i = \begin{cases} 1 & if DA \geq DA_{limit} \\ 0 & if DA < DA_{limit} \end{cases}$$

In the equation Eq. 10, x represents the reference threshold value given, y represents the time fraction, pi represents the grids that will be included in the

calculation. sDA has positive features as well as negative features. It can also be said that the method has several advantages and disadvantages. Since only one result can be obtained from the analyzed area and since it is a method for long-term, the sDA method is advantageous. On the other hand, it is disadvantageous because, the amount of light in the region to be analyzed exceeds the threshold value, even if it is an extremely high level that causes glare or can negatively affect daily life, hence will contribute positively to the visual comfort index result since the method is a one- tailed equation (Suk, 2019). In the study, the data was analyzed by DIVA software and sDA method was used for visual comfort measurement. Among the main criteria, only the amount of light was analyzed. Another indicator of visual comfort such as glare or quality of light were not evaluated within the scope of the study. The reason for excluding the glare is the absence of a specification that answers questions such as which window should be selected, which distance from window should be taken or where the analysis should be done in the room. Although it is known how to interpret visual comfort according to the glare analysis result, it is not known how to calculate an average value for many rooms. However, thanks to the DIVA software, other indicators can also be analyzed. In DIVA software, the threshold value of visual comfort and the distance, how high from the ground the analysis should be done, can be defined by the user. While the threshold value suggested by the software to the user is specified as 300 lux, the height to be analyzed is foreseen as the height of the desk. Since there is no consensus which height should be selected for the analysis, an exemplary study should be performed in order to determine the height and the threshold value. As the target threshold value in the study is 351,6 lux (~ 352 lux), calculated by Suk (2019) for providing the visual comfort, the results of Suk's study reported and confirmed that this value should be at eye level (Suk, 2019). Therefore, the eye level defined at 44 inches (~ 110 cm) above the floor as was used for ergonomic studies. In the DIVA program, it is possible to define the area to be analyzed and its height. The area to be analyzed includes the entire sitting area on the second floor of the office building, which is preferred in the study. Therefore, areas are not only rooms with frequently used offices; but also other living areas such as kitchen, lobby,

corridor, toilets, and stairs. Thanks to the average value obtained with the help of the sDA method, the visual comfort index on a general floor could be obtained. It is sufficient to draw separate surfaces on the model, that can be converted from Revit to Rhino, that is another useful software that is compatible with DIVA, to define the area to be analyzed and how high it should be from the floor. The area to be analyzed was divided into grids and each small area can be evaluated within itself and the average value can be calculated. The 60cmx60cm grid area proposed by DIVA was chosen and analyzed. To be able to analyze in the software, it is necessary to define the geometry of the building that is planned to be analyzed in the software, to indicate which area at which height with the help of grids, and to define the location information. Since the information related to the grid is mentioned above, it is not included in the information in this section. The geometry information to be analyzed in the program can be easily defined thanks to the Revit- Rhino compatibility. Grasshopper software has two options for defining geometry in the DIVA tool. The first one is using the Rhino screen and the second is to manually specifying the desired geometry as an object. Since there are buildings that are going to be analyzed in the surrounding for this optimization study, the second option, the object definition has been preferred. Because it would be more useful since it contains different cases such as rotating the existing building or rotating the existing building together with the surrounding buildings, etc. Windows, floors, walls, basement walls, foundation slab, roof, exterior, and surrounding buildings are defined for the mentioned objects. Furniture in the office, computers, unnatural light sources such as lamps, and static elements such as columns and beams were not included. In this way, a significant shortening was achieved in the duration of the analysis and it was observed that there were no significant differences in terms of results for the case when all objects like computers, furniture, etc. is included or not. The properties of the objects to be defined in the software can be created with the reflection value of the light for the elements excluding windows and the transparent value of the light for the windows. Different types of windows, the buildings around the office, the rotation of the office with or without the surrounding buildings, the window-wall ratios affected the visual comfort analysis. Since the insulation material

thickness does not change the reflectance values of roof, exterior wall and so on, it is not included in the visual comfort simulations. Moreover, it is possible to apply the default materials of DIVA and its values (Table 3.8). Available materials of DIVA have been defined for building elements such as interior walls, facades, floors, etc.

Table 3.8 DIVA default materials assigned

Building Elements	Material Default Name	Reflectance Value
Interior Wall	White Generic Interior Wall	70
External Wall	Outside Facade	30
Ceiling	Generic Ceiling	80
Floor	Tile Floor	40

It is also possible to define and include non-default materials in the model such as window objects by defining necessary values such as visual transmittance, visual transmissivity, solar heat gain coefficient, U-value. Since the exterior of the office is designed as brick, floor type as oak, the default values of DIVA to be selected must be compatible with these material types. The default values used defined in the DIVA library were shown in Tables 3.8. The .epw extension files that work integrated with the energy plus software of the DIVA software can be used for any part of the world to provide require location information for the analysis to be made, the .epw files can be downloaded for the desired region via <https://energyplus.net/weather> link. Thus, the information for Ankara, Turkey location was downloaded and used in the study. After defining the grid information, object information (building geometry), and location information, the software can be run and visual comfort analysis can be performed for the desired area. It is shared visually how the program works in a relatively small area in Figure 3.6, (for two different office rooms used in the designed building) below, which is not included in the study. The red grids that appear in the image indicate the window edges where a lot of illuminances can be observed, while the yellow and even blue parts are areas away from the window and represent the wall edges where the light is relatively less collected. The result was found by using sDA method for the

selected area. In other words, the targeted threshold value was achieved for at least half of the building's occupied time.

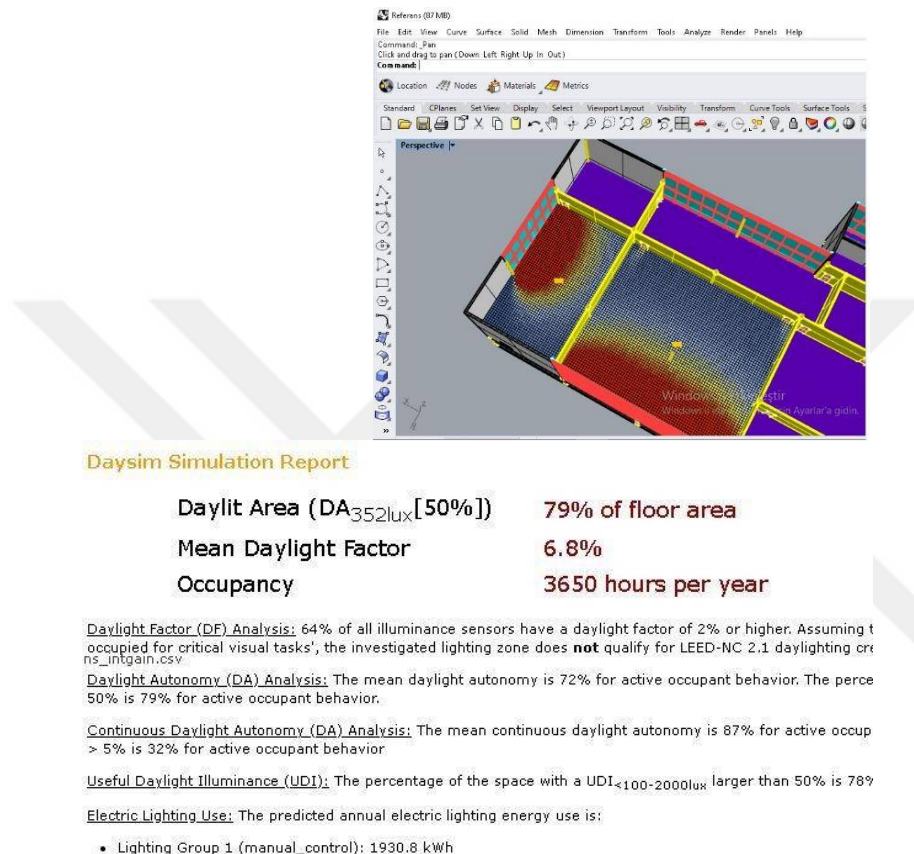


Figure 3.6 An illustration of DIVA software's daylight simulation result

Images were shared below for glare analysis, another main criterion that is not included in the study but can be calculated with the help of DIVA (Figure 3.7). Glare analysis can be performed at any special time of the day or can be analyzed throughout the whole year. However, it was not included in the scope of the study because the analysis results took too long and the result made the optimization very complex. For glare analysis, it is possible to obtain results in any part of the room, especially for

parts close to the glass edge. A glare analysis for a sample rendered room can be observed below. For this example, the study in Suk et al. (2013) was referenced. As mentioned in the article, the results were obtained at 30-minute intervals and even the day analyzed in the article was chosen to be the same (29 April from 07:00 am to 6:30 PM) (Suk et al, 2013).

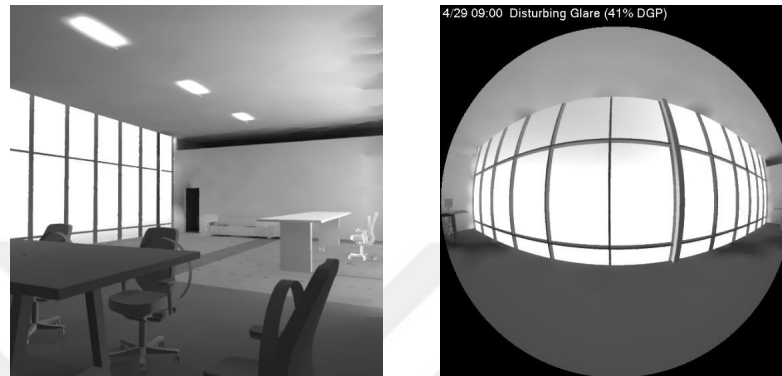


Figure 3.7 Rendered office and its glare analysis result

Also, the DGP value of 41% obtained at 09:00 p.m. in one of the office rooms, which is shown as an example, was different for another office room that has another facade; thus it confirms that the software works smoothly and accurately. DIVA software uses Discomfort Glare Probability (DGP) for glare analysis. The glare indicator which focuses on the contrast between the light source that causes glare and the average background brightness includes the brightness level perceived by the user with the help of the DGP method. Therefore, DGP offers a much stronger relationship in the glare perception of users (Carlucci et al., 2015). The equation X used for the DGP method can be observed below. The DGP value varies between 0.2 and 0.8. Not just for the DGP method but also for other methods can be observed in Table 3.9 below.

Table 3.9 Degree of glare in different glare index (Carlucci et al., 2015)

Degree of Perceived Glare	CGI	UGR	VCP	DGI	DGP
Imperceptible	<13	<13	80-100	<18	<0.35
Perceptible	13-22	13-22	60-80	18-24	0.35-0.40
Disturbing	22-28	22-28	40-60	24-31	0.40-0.45
Intolerable	>28	>28	<40	>31	>0.45

$$DGP = 5,87 \times 10^{-5} \times E_v + 0,0918 \times \left[1 + \sum_{i=1}^n \left(\frac{L_{s,i}^2 \times W_{s,i}}{E_v^{1,87} \times p_i^2} \right) \right] + 0,16 \quad (11)$$

In the Eq. 11, E_v represents vertical eye illuminance, L_s is the luminance of the source (cd / m²), w_s is the solid angle of the source seen by an observer, P represents the position index. The day of the year or the entire year should be selected after selecting the object and the region or point to be analyzed as in the sDA method.

3.2.2. Energy Consumption Analysis

It could be said that energy consumption is one of the issues that a lot of importance should be given in the last centuries. Factors such as the danger of running out of energy resources in the world and the risk of increasing cost of energy production can make this problem even worse. There is an increase in the need for sustainable energy resources. Therefore, it is important to find, use and promote sustainable energy resources, but it will be not be enough by itself. Efficiency should also be achieved in the consumption of energy obtained from nonrenewal sources such as natural gas, coal, or petroleum derivatives, so that it should be possible to save as much as possible. Precautions related to energy consumption should be carefully planned especially in the design phase, and by this way significant improvements can be achieved. In this study, attention was paid to the energy consumption of the designed office building, and design parameters effecting energy consumption was considered. In addition to parameters such as insulation material type, insulation thickness, and window types, parameters such as the location of the surrounding buildings, the presence or absence of the surrounding buildings, the location and

rotation of the existing designed office building, the wall-window ratio were also evaluated in the study. In Table 3.10 the layers of materials of the building elements used in this study is given. There is designable or not column is available in Table 3.10. It simply shows that which material thickness can be changed or which one is included in the design variables. The designable materials' lower and upper limits are given in Table 3.11 below.

Table 3.10 Building elements and material layers

Building Element	Materials (Outer Surface to Inner)	Thickness (cm)	Designable or Not
Exterior Floor	Oak	1,4	No
	Concrete	25	No
	Extruded Polystyrene (XPS)	5	Yes*
Exterior Wall	Gypsum Board	2	No
	Expanded Polystyrene (EPS)	5	Yes*
	Brick	23	No
Roof	Gravel	6	No
	Glass Wool	5	Yes*
	Membrane	0,5	No
	Membrane	0,5	No
	Concrete	20	No
	Gypsum Board	2	No

Table 3.11 Boundaries of insulating materials

Designable Variables	Lower Bound (m)	Upper Bound (m)
Extruded Polystyrene (XPS) for Exterior Floor	0.02	0.10
Expanded Polystyrene (EPS) for Exterior Wall	0.02	0.10
Glass Wool for Roof	0.02	0.10

Eleven different window types were used in the study. The windows and their properties are shared in Table 3.4 in the visual comfort section. Honeybee tool of Grasshopper software was preferred for energy consumption analysis. Thanks to Revit and Rhino integration, it is possible to perform energy modeling of a building model designed in Revit with Rhino and Grasshopper software. Two different methods can be followed to perform the energy analysis of the existing office project loaded into the Rhino software in the Honeybee component. The first is automatic identification and energy analysis of the building directly loaded into the software, while the second is to model each room of the existing building into the program by separating them into zones. In this study, individual modeling has been done to find more accurate results. Besides, each zone was grouped according to its area of use, and thus the correct energy consumption was applied in the rooms defined according to the purpose of the occupied area. Thanks to the 'List Zone Program' component offered by Honeybee as an option to the user, rooms can be separated according to different usage purposes such as kitchen, lobby, corridor, etc., and energy consumption can be estimated more accurately. The equipment energy consumption of the rooms that can be divided into different categories is presented in Table 3.12 below.

Table 3.12 Equipment energy consumption according to different zone types

#	Zone Types	Equipment Load	Number of People
		per Area (kW/m ²)	per Area (person/m ²)
1	Kitchen	48	0.05
2	Lobby	0.75	0.1
3	Toilet	0.75	0.1
4	Stairs	0	0
5	Office 2 (Open)	7.64	0.06
6	Hole	1.72	0.01
7	Office 1 (Closed)	6.89	0.05
8	Secretary Room	6.89	0.05

After the designed office building is modeled according to the zone, the material properties of building elements such as walls, floors, and roofs can be defined in the Honeybee library. New materials can be created in the software if the materials are not available in the Honeybee library. The properties of the materials used in the floors, roofs, and walls are given in Table 3.13 below.

Table 3.13 The properties of assigned materials

Properties of Materials	EPS	Oak	Concrete	Gypsum Board	Gravel	XPS	Membrane	Glass Wool	Brick
Roughness	Rough	Rough	Rough	Medium Smooth	Rough	Rough	Very Rough	Medium Smooth	Medium Rough
Thickness (m)	0,02-0,10	0,014	0,25	0,02	0,06	0,02-0,10	0,0095	0,02-0,10	0,23
Conductivity (W/mK)	0,035	0,17	1,5	0,16	1,442	0,035	0,16	0,04	0,7
Density (kg/m ³)	27	750	2384	800	1674	30	1121,29	18	1970
Specific Heat (J/kgK)	1300	2390	653	1090	881	1213	1460	657	800
Thermal Absorptance (Emissivity)	0,9	0,9	0,8	0,96	0,28	0,9	0,9	0,9	0,9
Solar Absorption	0,7	0,35	0,6	0,4	0,7	0,7	0,7	0,7	0,6
Visible Light Absorptance	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7

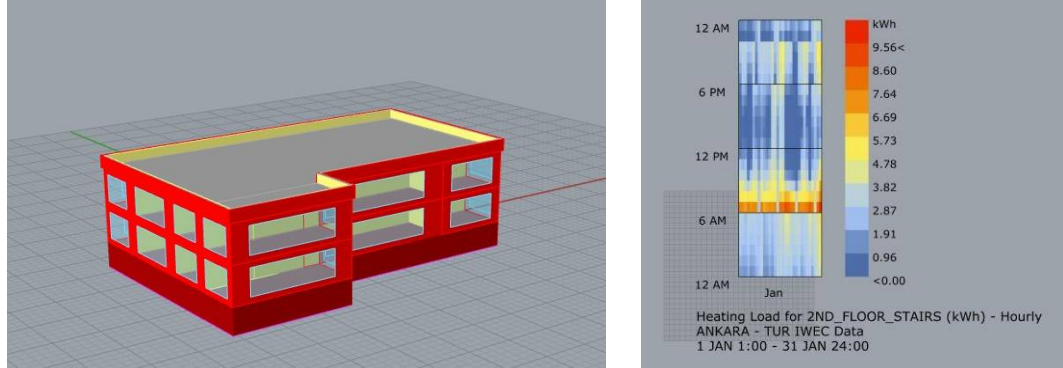
In the study, a set point value was determined to estimate the result of the simulation more accurately. The set point value of 20 degrees for heating and 24 degrees for cooling was selected. These set values were determined by considering the ASHRAE standard recommendations and these are shared below with a table (Table 3.14). One year was taken as a reference in the analysis. As a result of the analysis, the energy consumed for cooling, heating, electric lighting, and electric equipment varying according to the usage needs of the room for each zone was evaluated for the energy consumption calculation. By using the visualization of the software, it is possible to validate accuracy of modelling of the building, and energy consumption values of any zone such as heating and cooling at any time interval can be reported visually.

Table 3.14 Typical recommended indoor temperature and humidity in office buildings (ASHRAE, 2015)

Area	Indoor Design Conditions		Comments
	Temperature, °C/ Relative Humidity, %		
	Winter	Summer	
Offices, conference rooms, common areas	20.3 to 24.2 20 to 30%	23.3 to 26.7 50 to 60%	
Cafeteria	21.1 to 23.3 20 to 30%	25.8 50%	
Kitchen	21.1 to 23.3	28.9 to 31.1	No humidity control
Toilets	22.2		Usually not conditioned
Storage	17.8		No humidity control
Mechanical rooms	16.1		Usually not conditioned

In Figure 3.8b below, the total energy consumption for heating in the stair for second-floor in January is shown on an hourly basis. It is possible to see the distribution of the outputs obtained in energy consumption not only for one room but also in the whole building. Also, the operative temperature value in any room can be displayed for any specified time. In the left image (Figure 3.9a) below, how electrical

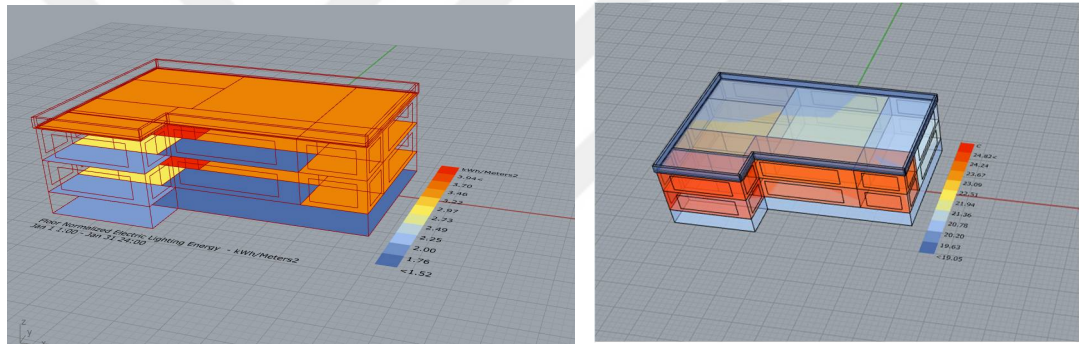
lighting energy consumed in the entire building can be seen in, while on the right one in Figure 3.9b, operative temperature data can be observed.



3.8(a)

3.8(b)

Figure 3.8 An illustration for heating energy consumption



3.9(a)

3.9(b)

Figure 3.9 An illustration of operative temperature result and PMV

3.2.3. Thermal Comfort Analysis

Ladybug Tool of Grasshopper software was preferred for thermal comfort analysis. Since Ladybug and Honeybee are compatible and integrated, it is possible to analyze the results. The predicted mean vote (PMV) and percentage of people dissatisfied (PPD) values, which are thermal comfort indicators, were obtained and analyzed in the optimization study. To obtain PMV and PPD results, mean radiant temperature, operative temperature, and relative humidity values, which are also defined and specified in Section 1.2, can be observed with the help of the Honeybee

tool used for energy consumption analysis for each zone at each floor. The met value is 1.175 (~68 W / m²), which is an average metabolic rate calculated by us using the estimated activity times of an office worker, according to ASHRAE standard met units for different activities. The activities and their met values are shared in Table 3.15.

Table 3.15 Calculated met value according to estimated office activities

Office Activities	Met Units (met)	Hours per Day (h)	(metxh)
Seated	1	2	2
Typing	1,1	3	3,3
Filing, seated	1,2	2	2,4
Walking about	1,7	1	1,7
Average			1,175 met

In Lin (2018), it was stated that the clothing value based on ASHRAE recommendations should be 1 clo for winter and 0,5 clo for summer. Therefore, these recommendations values were used in the study. Also, 0,6 clo value for spring and 0,7 clo value for autumn was estimated since there is no further information for in between seasons in the previous studies. For the analysis period, all days of the year were used, in other words, the analysis was completed annually. It was concluded by taking the average of the PPD data calculated separately for all zones. It is aimed to be close to 0 for PMV value, which is explained in detail in section 1.2.2, and close to 10% for PPD values. The visual results obtained from the simulations are given below. While the average surface temperature value is shown for all buildings in the Figure 3.10, in the Figure 3.11, the visual of the thermal comfort analysis made for January in the second-floor toilets are shared.

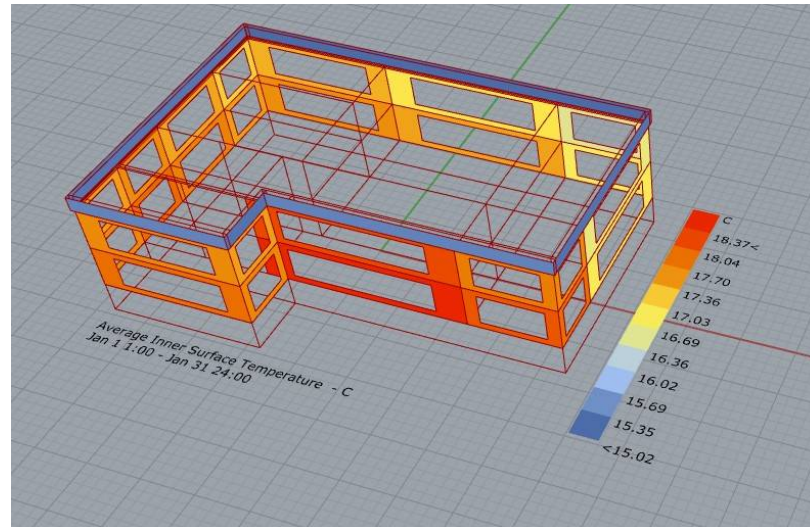


Figure 3.10 An illustration of results of PMV

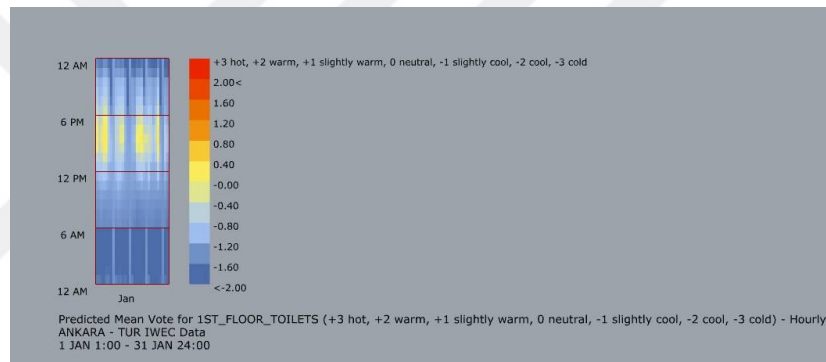


Figure 3.11 An illustration of results of surface temperature



CHAPTER 4

CASE STUDY AND RESULTS

It has not been observed that the value of an objective task increases while the value of other multi-objective tasks decreases in the sensitivity analysis between the insulation materials changing from 2cm to 10cm as stated in the discrete variable table. In other words, there has been an improvement in thermal comfort and energy consumption in direct proportion to the continuously increasing insulation material thickness instead of any trade-off relationship. The first data obtained are shared in Table 4.1 below. According to data, less energy consumption and lower PPD value has been observed as the insulation material is getting thicker. Therefore, it was determined that it would be wrong to make analysis with the insulation material thickness so it was not evaluated as a parameter, and it was removed from the design variables of the study.

Table 4.1 The initial results of the analysis for 6th Window type and for only January in the absence of any rotation and any buildings around

Insulation Thickness		Energy Consumption (kWh)	Predicted People Dissatisfied (%)
4	cm	46736	25.19
5	cm	45411	24.65
6	cm	44384	24.22
7	cm	43595	23.88
8	cm	42927	23.58
9	cm	42387	23.35
10	cm	41920	23.14
20	cm	39472	21.93
40	cm	38041	21.13

When the data obtained from the first analyzes shown in the table above are examined, it can be determined that there is no trade-off relationship. With the constantly increasing insulation material thickness, it can be seen that energy consumption decreases and thermal comfort improves. Since the analysis covers only the winter months, the PPD values obtained remained far from the ideal PPD value of 10. The insulation thickness, which was kept only between 2cm and 10cm in the study, was increased up to 40cm while the first results were obtained. The main purpose of the wide range of thickness values is to determine whether the analysis results change after a critical thickness value. It can be said that there is no such critical value as a positive result is obtained continuously. Therefore, the thickness of the insulation material was not included in the parameters list for the study, and the thickness values were taken at constant values instead of a certain range. The thicknesses of the insulation material were chosen following TS825 standards. The thickness of the insulation material on the wall, roof, and floor was determined according to the recommended U values according to the regions in Turkey specified in the standard. Accordingly, 6 cm EPS was used on the exterior walls, 7 cm XPS was used on the floors, and 12 cm glass wool was used on the roof. U value created by the materials used and the maximum acceptable U values shown in TS825 are shared in Table 4.2 below.

Table 4.2 The U values used in the case study

Building Element	U value (W/m²K)	U Value in TS825 (W/m²K)
Roof w 12 cm glass wall	0,29	0,30
Wall w 6cm EPS	0,46	0,50
Floor w 7cm XPS	0,44	0,45

Contrary to this study, the reason for using the thickness of the insulation material used in the literature studies is that it has a trade-off relationship between the multi-objective functions. Therefore, window types, another design variable, have been included in this study as the main parameter since they affect thermal comfort, energy

consumption, and visual comfort at the same time. Similarly, it has been tested whether there is a tradeoff relationship between window types and multi-objective functions. As can be observed from the data shared below, it is understood that the visual comfort of the windows with relatively good energy consumption and thermal comfort is lower (Table 4.3). Therefore, while improving thermal comfort and energy consumption by using different window types, it has been observed that visual comfort is sacrificed. Also, how the building, which is designed to improve thermal comfort, visual comfort, and energy consumption values, should be positioned with the surrounding buildings or in which direction it should be positioned with the surrounding buildings is taken as the design variable. Situations such as building rotation in the tables below or whether there is a building in the around are explained in the following sections.

Table 4.3 The results of the analysis in the absence of any buildings around (in January)

Window Types	Energy Consumption (kWh)	Predicted People Dissatisfied (%)	Visual Comfort (%)
1	58979	29.22	69.1
2	55699	28.06	77.1
11	38776	21.90	58.3

Table 4.4 The results of the analysis when the office building is oriented by 60° in the absence of any buildings around (in January)

Window Types	Energy Consumption (kWh)	Predicted People Dissatisfied (%)	Visual Comfort (%)
1	60098	29.57	72.6
2	57251	28.53	78.1
11	39668	22.24	59.9

Table 4.5 The results of the analysis when there are buildings on facades (in January)

Window Types	Energy Consumption (kWh)	Predicted People Dissatisfied (%)	Visual Comfort (%)
1	59026	29.26	52.9
2	56123	28.26	57
11	38986	22.02	47.9

Table 4.6 The results of the analysis when the office building is oriented by 60° and there are buildings on facades (in January)

Window Types	Energy Consumption (kWh)	Predicted People Dissatisfied (%)	Visual Comfort (%)
1	60156	29.59	58.3
2	57687	28.67	68.8
11	39881	22.32	51.4

Table 4.7 The results of the analysis when the surrounding buildings are oriented by 270° (in January)

Window Types	Energy Consumption (kWh)	Predicted People Dissatisfied (%)	Visual Comfort (%)
1	59390	29.32	55.2
2	56703	28.33	60.3
11	39263	22.08	49.5

For example, the 11th window type is advantageous if the energy consumption and PPD value are adopted as the main criteria for the 1st and 11th window types in

the last table, on the other hand, the 1st window type is advantageous if the visual comfort is the main criterion. The other parameter that can affect all three objective functions in the study is surrounding buildings. The surrounding buildings affect both the temperature of any building and the arrival of sufficient light into the building, as it affects the angle of incidence of sunlight. Therefore, thermal comfort, visual comfort, and energy consumption are affected. As can be seen from the first data obtained in Table 4.3 and Table 4.5, there is an increase in energy consumption and PPD values in the case of surrounding buildings, while there is a decrease in the visual comfort indicator. Besides, buildings of different heights were modeled on different facades of the office building to observe how the surrounding buildings affect the optimization results. DIVA software for visual comfort, Ladybug software for thermal comfort, and Honeybee software for energy consumption has been used. 1760 different situations formed by six different parameters explained were analyzed and all data were recorded. How the obtained data is evaluated is shown in the flowchart. (Figure 4.1).

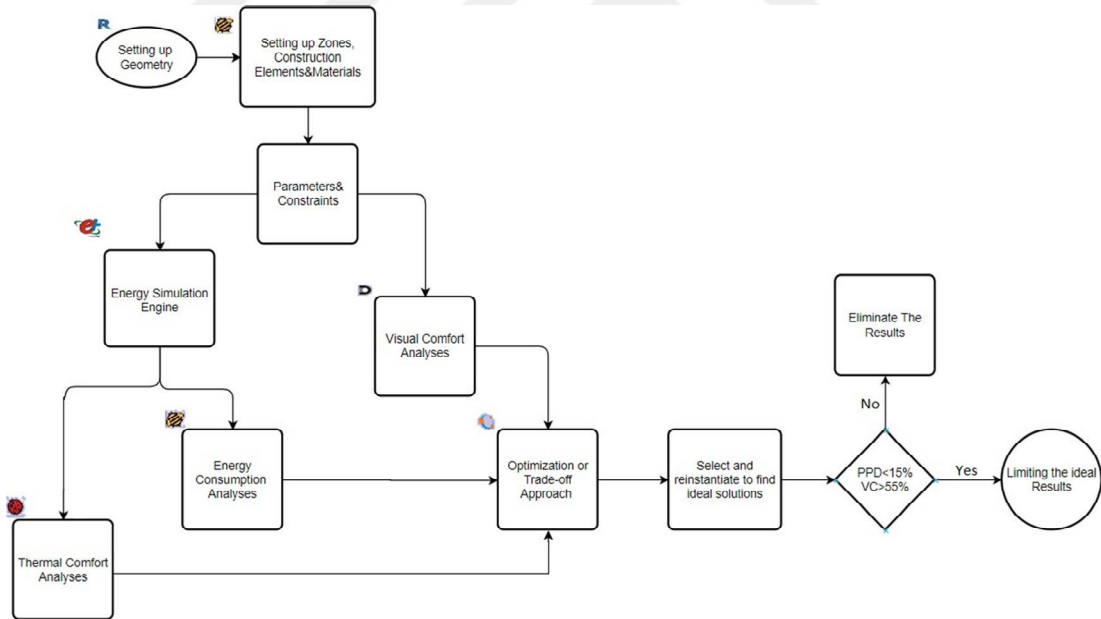


Figure 4.1 Flowchart of the case study

After determining the situations that give more ideal results by using the trade-off relationship, an extra post-elimination process was applied according to the

threshold values specified in the literature for visual comfort and thermal comfort. In this way, the ideal results obtained are limited and the decision stage is facilitated. The analysis phase of the modeled case study was carried out using the GNU Octave software. The data obtained from the simulation were resulted by considering the objective functions such as energy consumption, visual comfort, and thermal comfort, and dominated and non-dominated results were obtained. The input values for Octave comes from the simulation analysis that has been observed by software. The output is the dominated and non-dominated results based on Pareto front method. In the first stage, the existing office building was kept constant, in other words, the situations with and without buildings around it were interpreted without any rotation. In both cases, the window types to be used were the same. These window types were the 6th, 7th, and 11th window types with 75% or 100% window to wall ratios. However, the non-common results in the presence or absence of the surrounding buildings were the amount of energy consumed, the percentage of thermal comfort, and the visual comfort value. While there was an improvement, that is, a decrease in energy consumption when there are buildings in the environment, there was a small perceptible deterioration in thermal comfort. A dramatic decrease was observed when visual comfort was compared. As expected, the presence of buildings in the vicinity harmed visual comfort as the angle of entry of the sun rays into the designed building was affected. When the extra filtering process is applied to the obtained results (55% visual comfort, 15% thermal comfort), the desired criterion is not met in any window type or window-wall ratios when there are surrounding buildings. The reason for this is that visual comfort cannot be adequately provided. Therefore, it has been observed that the surrounding buildings should not be close to each other and horizontal architecture is an important element for city planning. When the data in the table 3.24 are examined, visual comfort is provided only in two cases, when the second and fifth window types are used. However, thermal comfort could not be provided. The reason for this can be explained by the decrease in sunlight entering the building in winter which decreases the temperature inside the building compared to the 1st case, hence the thermal comfort is worse in winter. Of course, this comment differs according to the location of the

designed building. Since Ankara is in the northern hemisphere, the PPD values and energy consumption is suitable for the climate condition. The result would be different for the southern hemisphere countries. In addition, the reason for the decrease in energy consumption can be explained as the low energy consumption for cooling due to the scarcity of sunlight entering the interior in summer. On the contrary, the increase in the energy consumption spent on heating in winter can be seen in the Table 4.8, but there has been a decrease in the overall total energy consumption as the energy spent on cooling outweighs energy spent on heating.

Table 4.8 Energy Consumption and PPD values according to a different season

	Window Type	Energy Consumption (kWh)	Predicted People Dissatisfied (%)	Cases	
Winter {(1,1)-(2,28)}	5	47874 (heating)	23.68	1	
		48788 (heating)	23.93	2	
Summer {(6,1)-(8,31)}		73499 (cooling)	9.56	1	
		67785 (cooling)	9.84	2	

The most ideal result is obtained with the use of 11th window type (#1331) with a 100% window-to-wall ratio if energy consumption or thermal comfort is a priority criterion for the designer, and the 6th window type with a 100% window-to-wall ratio is the best if the primary criterion is visual comfort (#1326) in the absence of surrounding buildings, that is the first case. In Table 4.9 shared below, the cells indicated with 'N' (Criteria Not Satisfied) indicate the situation where the required condition is not met after extra filtering, the cells marked with 'S' (Satisfied) indicate the conditions that meet the conditions. The cells also indicated in the following tables in italics represent the best state among the ideal results. The first shared table shows the 1st case that is without the surrounding buildings, while the second table shows the 2nd case that has surrounding buildings.

Table 4.9 Results of the first case w/o rotation of office building w/o surrounding buildings after filtration

#	X1:Case- #	X2: Rotation (°)	X3: Window Type	X4: Window- wall ratio (%)	Y1: minimize energy consumption (kWh)	Y2: minimize PPD (%)	Y3: maximize visual comfort (%)	Criteria Satisfied or Not
11	1	0	11	25	352684	16.29	40.00	N
451	1	0	11	50	354821	15.01	47.80	N
886	1	0	6	75	388021	14.00	62.20	S
887	1	0	7	75	376654	14.44	60.80	S
891	1	0	11	75	356986	14.30	53.70	N
1322	1	0	2	100	458247	16.89	77.10	N
1325	1	0	5	100	410082	15.02	73.30	N
1326	1	0	6	100	396025	13.98	70.70	S
1327	1	0	7	100	382150	14.23	69.10	S
1331	1	0	11	100	358991	13.88	58.30	S

Table 4.10 Results of the second case w/o rotation of office building with surrounding buildings after filtration

#	X1:Case- #	X2: Rotation (°)	X3: Window Type	X4: Window- wall ratio (%)	Y1: minimize energy consumption (kWh)	Y2: minimize PPD (%)	Y3: maximize visual comfort (%)	Criteria Satisfied or Not
143	2	0	11	25	351748	16.50	33.10	N
576	2	0	4	50	376533	15.18	50.20	N
583	2	0	11	50	353278	15.33	39.80	N
1018	2	0	6	75	383913	14.45	50.70	N
1019	2	0	7	75	373679	14.87	49.20	N
1023	2	0	11	75	354958	14.66	44.70	N
1454	2	0	2	100	453296	17.45	57.00	N
1457	2	0	5	100	405596	15.52	55.80	N
1458	2	0	6	100	390985	14.40	54.00	N
1459	2	0	7	100	378528	14.68	52.90	N
1463	2	0	11	100	356494	14.25	47.90	N

After the situation without any rotation in the designed office building, the orientation has been tried. Therefore, the office building was rotated counterclockwise direction with 30-degree angles and the results were examined, the effect of the building rotation was analyzed. The 1st case where there are no buildings on the facades was examined first. Just as in the condition that there is no rotation for the office building, the 6th, 7th, and 11th window types gave the most ideal results again as a result of the optimization. However, the 6th and 7th window types were more dominant than the 11th window types. For the window- to-wall ratio result, a smaller number of 75% also gave acceptable results, while the 100% window-to-wall ratio was dominant. The obtained results are also shared in Table 3.27 below. As a result of extra filtering, if energy consumption or thermal comfort quality is prioritized, the most ideal result was the 11th window type (#1452). On the other hand, the 6th window type (#1370) emerges as the most ideal option if visual comfort is designed as the primary goal. That result was observed when the building was rotated 330 degrees counterclockwise for the 11th window type and 120 degrees for the 6th window type. When the building rotation data are examined, it has been observed that ideal results could be obtained when 210, 240, 270, 300, and 330 degree counterclockwise rotations are available. If the Table 4.09 and Table 4.11 are examined, it can be said that the annual energy consumption, which varies between 359000 and 396000 kWh in the absence of any rotation, varies between 358000 and 407000 kWh with rotations. Although there is no serious difference and even an increase appears, it can be said that the reason for this result is actually due to the abundance of data due to the rotation of the building at twelve different angles. If the results are compared individually according to the window-wall ratios, it has been observed that the energy consumption has generally decreased and the visual comfort and thermal comfort values have been generally improved. It can be said that there is an improvement of approximately 1000 kWh in the most ideal result based on energy consumption, that is the 11th window type in case of 330 degrees rotation (from 358991 kWh to 357931 kWh).

Table 4.11 Results of first case with rotation of office building w/o surrounding buildings after filtration

#	X1:Case- #	X2: Rotation (°)	X3: Window Type	X4: Window- wall ratio (%)	Y1: minimize energy consumption (kWh)	Y2: minimize PPD (%)	Y3: maximize visual comfort (%)	Criteria Satisfied or Not
99	1	240	11	25	352730	16.17	41.10	N
132	1	330	11	25	349964	16.08	40.00	N
572	1	330	11	50	352777	14.89	48.80	N
886	1	0	6	75	388021	14.00	62.20	S
953	1	180	7	75	378290	15.23	68.60	N
964	1	210	7	75	379945	15.03	68.20	N
986	1	270	7	75	381650	14.70	65.30	S
996	1	300	6	75	393300	14.20	64.40	S
1007	1	330	6	75	389424	14.14	63.00	S
1012	1	330	11	75	355512	14.24	54.30	N
1322	1	0	2	100	458247	16.89	77.10	N
1326	1	0	6	100	396025	13.98	70.70	S
1327	1	0	7	100	382150	14.23	69.10	S
1333	1	30	2	100	464359	17.08	77.90	N
1337	1	30	6	100	401572	14.19	72.80	S
1338	1	30	7	100	386469	14.31	71.00	S
1344	1	60	2	100	470070	17.49	78.10	N
1347	1	60	5	100	420900	15.58	75.50	N
1355	1	90	2	100	470843	17.75	78.30	N
1358	1	90	5	100	421914	15.83	76.10	N
1359	1	90	6	100	407773	14.84	74.70	S
1360	1	90	7	100	392326	14.89	74.00	S
1366	1	120	2	100	470943	17.89	78.50	N
1369	1	120	5	100	421900	15.99	76.50	N
1370	1	120	6	100	407676	14.98	75.00	S

Table 4.11 (cont'd)

#	X1: Case- #	X2:	X3:	X4:	Y1:	Y2:	Y3:	Criteria Satisfied or Not
		Rotation (°)	Window Type	Window- wall ratio (%)	minimize energy consumption (kWh)	minimize PPD (%)	maximize visual comfort (%)	
1371	1	120	7	100	392055	15.09	74.20	N
1377	1	150	2	100	466328	17.92	78.40	N
1393	1	180	7	100	383880	15.06	73.50	N
1397	1	180	11	100	360599	14.62	63.90	S
1403	1	210	6	100	400650	14.71	73.90	S
1404	1	210	7	100	385736	14.86	73.00	S
1408	1	210	11	100	361897	14.45	63.70	S
1415	1	240	7	100	389418	14.55	73.40	S
1419	1	240	11	100	362597	14.07	61.30	S
1425	1	270	6	100	402921	14.44	74.30	S
1426	1	270	7	100	387898	14.57	73.80	S
1430	1	270	11	100	362524	14.11	60.70	S
1435	1	300	5	100	416206	15.27	75.20	N
1436	1	300	6	100	402116	14.25	73.50	S
1437	1	300	7	100	387042	14.39	72.00	S
1441	1	300	11	100	361952	13.96	59.80	S
1447	1	330	6	100	398304	14.18	72.40	S
1448	1	330	7	100	382763	14.33	69.60	S
1452	1	330	11	100	357931	13.87	58.70	S

In contrast to relatively small improvements in energy consumption and thermal comfort range, the actual jump was seen in the visual comfort data. The visual comfort value, which varies between 58 and 70 percent without any rotation, was increased up to 75 percent as in the 6th window type when the rotation occurs.

Table 4.12 Results of second case with rotation of office building with surrounding buildings after filtration

#	X1:Case- #	X2: Rotation (°)	X3: Window Type	X4: Window- wall ratio (%)	Y1: minimize energy consumption (kWh)	Y2: minimize PPD (%)	Y3: maximize visual comfort (%)	Criteria Satisfied or Not
264	2	330	11	25	349349	16.30	35.70	N
671	2	240	11	50	355874	15.31	49.20	N
704	2	330	11	50	351840	15.21	43.30	N
1085	2	180	7	75	376347	15.97	60.80	N
1096	2	210	7	75	378614	15.51	63.70	N
1100	2	210	11	75	358896	15.23	54.80	N
1106	2	240	6	75	394543	14.77	64.90	S
1107	2	240	7	75	381315	15.03	63.70	N
1111	2	240	11	75	358990	14.73	54.90	N
1117	2	270	6	75	392051	14.81	61.70	S
1118	2	270	7	75	380196	15.12	60.30	N
1128	2	300	6	75	390665	14.62	59.80	S
1144	2	330	11	75	354222	14.61	48.80	N
1509	2	150	2	100	463274	18.57	75.40	N
1520	2	180	2	100	456892	18.68	73.90	N
1525	2	180	7	100	381494	15.83	69.60	N
1529	2	180	11	100	359092	15.27	57.20	N
1531	2	210	2	100	460822	18.22	75.20	N
1534	2	210	5	100	412658	16.28	73.30	N
1535	2	210	6	100	398314	15.23	72.90	N
1536	2	210	7	100	384132	15.37	71.60	N
1540	2	210	11	100	360783	14.89	60.00	S
1542	2	240	2	100	466812	17.82	73.80	N
1546	2	240	6	100	403715	14.83	71.60	S
1547	2	240	7	100	387868	14.91	71.20	S
1551	2	240	11	100	361579	14.39	59.60	S
1557	2	270	6	100	400357	14.86	69.70	S

Table 4.12 (cont'd)

#	X1:Case- #	X2: Rotation (°)	X3: Window Type	X4: Window- wall ratio (%)	Y1: minimize energy consumption (kWh)	Y2: minimize PPD (%)	Y3: maximize visual comfort (%)	Criteria Satisfied or Not
1558	2	270	7	100	386168	15.00	68.30	S
1562	2	270	11	100	361382	14.48	56.80	S
1568	2	300	6	100	398865	14.64	67.70	S
1569	2	300	7	100	384763	14.82	65.90	S
1573	2	300	11	100	360533	14.35	55.90	S
1584	2	330	11	100	356333	14.25	52.30	N

Therefore, the effect of rotation on the results shows that the location of the surrounding buildings is important. Therefore, it is important to analyze and place the building also according to the surrounding buildings. When the rotation process of the designed office building in 12 different scenarios by 30 degrees' is examined, it is observed that the results are no different from the results in the 1st case and the 2nd case. The 6th and 7th window types were dominated after the post-optimization processes again. The only result that differs from the situation when there is no rotation for the 2nd case is that both thermal comfort and visual comfort provide the targeted threshold values. As can be seen in table 4.12, the results of which are shared below, it has been observed that the thermal comfort can be below 15% and the visual comfort can be above 55% in the counterclockwise rotations of office at 240, 270, and 300 degrees. These locations can be interpreted as the cases where the long facade of the designed office building faces empty surrounding in the east direction and other long facade faces the lower surrounding buildings. Like in the results of the first case of the rotation, the most ideal result is the 11th window type (#1573) when energy consumption and thermal comfort are prioritized, and the 6th window type when visual comfort is prioritized (#1546). While the energy consumption in the second case, where there is no rotation, varies between 351000 and 453000 kWh, it has been observed that it varies between 356000 and 466000 kWh in the case of rotation.

Contrary to the negative change in energy consumption, the PPD value was improved up to 14.35, while the percentage of visual comfort increased to approximately 72. After observing the effect of rotation, it was observed how the results differ based on the window wall ratio only. In the optimization phase, the window-to-wall ratio was filtered separately at 25, 50, 75, and 100 percent, and the results were obtained. For office buildings, the utilization of sunlight will increase, and a balance will be created between the energy spent for lighting and cooling systems as the ratio of window to wall increases. Also, the choice of window to wall ratio should be at an early stage decision of the designer, because once designed it is impossible or very difficult to change it later. The first table, shared below, illustrates the case where the window to wall ratio is 25%. According to the results obtained, window types 2, 5, 6, 7, and 11 gave the best results. However, the ideal result could not be achieved because both the target value of 55 percent for visual comfort and the thermal comfort value of 15 percent were not met in any case.

Table 4.13 Results of all cases according to 25% window wall ratio after filtration

#	X1:Case- #	X2: Rotation (°)	X3: Window Type	X4: Window- wall ratio (%)	Y1: minimize energy consumption (kWh)	Y2: minimize PPD (%)	Y3: maximize visual comfort (%)	Criteria Satisfied or Not
68	1	180	2	25	394453	17.26	51.90	N
71	1	180	5	25	373747	16.59	48.70	N
72	1	180	6	25	367136	15.98	48.10	N
73	1	180	7	25	362757	16.53	47.20	N
77	1	180	11	25	354186	16.71	41.20	N
79	1	210	2	25	395968	17.06	52.00	N
82	1	210	5	25	375144	16.41	49.80	N
90	1	240	2	25	396276	16.05	51.80	N

Table 4.13 (cont'd)

#	X1:Case- #	X2: Rotation (°)	X3: Windo w Type	X4: Window- wall ratio (%)	Y1: minimize energy consumption (kWh)	Y2: minimize PPD (%)	Y3: maximize visual comfort (%)	Criteria Satisfied or Not
93	1	240	5	25	374959	16.00	49.60	N
94	1	240	6	25	368369	15.38	48.20	N
95	1	240	7	25	362795	15.94	47.40	N
99	1	240	11	25	352730	16.17	41.10	N
110	1	270	11	25	354587	16.32	41.40	N
112	1	300	2	25	395854	16.55	50.60	N
116	1	300	6	25	368463	15.31	46.80	N
117	1	300	7	25	363470	15.93	45.90	N
127	1	330	6	25	364043	15.23	45.30	N
128	1	330	7	25	359044	15.85	44.80	N
132	1	330	11	25	349964	16.08	40.00	N
222	2	240	2	25	395444	16.97	50.00	N
226	2	240	6	25	367672	15.68	45.70	N
227	2	240	7	25	362245	16.18	44.90	N
259	2	330	6	25	362999	15.59	40.20	N
260	2	330	7	25	358265	16.15	40.40	N
264	2	330	11	25	349349	16.30	35.70	N
435	4	330	6	25	361563	15.66	37.80	N
440	4	330	11	25	348617	16.34	33.70	N

However, visual comfort can be improved with artificial light, and the 55 percent threshold determined by LEED criteria can be achieved. However, extra energy consumption is spent while providing visual comfort. Since this study is based on only natural light resources, an example analysis was not performed. It could be also said that the energy consumption value would be different according to artificial

light type and the usage time. It is also possible to meet the thermal comfort threshold value of 15%. By changing the set point of heating, it is manageable. For example, the thermal comfort would be 12,76 instead of 15,98 (#72) for the 6th window type with 180° rotations for the 1st case if the set point increased to 21° from 20°. On the other hand, the energy consumption would jump to 381022 kWh from 367136 kWh (#72). Therefore, thermal comfort and visual comfort can be achieved for the 25% window-wall ratio case. However, there will be a significant increase in energy consumption. The most important feature of an office with a 25 percent window-to-wall ratio is that it consumes much less energy than other window- to-wall ratios. The reason for this is that the U value of the wall of the designed office building is better than U value of windows. In window types with a better U value than U value of the exterior wall, there was a less increase in energy consumption compared to other window types. If the improved visual comfort and thermal comfort values are also included, it has become possible to obtain more ideal results with the increased window-to-wall ratio. After the window to wall ratio was increased to 50%, the targeted threshold values for thermal comfort and visual comfort began to be achieved, and the most ideal results began to be obtained. As can be observed from the tables 3.30 shared below, the 7th window type (#557) and the 6th window type (#446 for thermal comfort, #523 for visual comfort) are the most ideal window material if the energy consumption and thermal comfort or visual comfort are taken into consideration in the design phase respectively. However, it should not be forgotten that the rotation values of the 6th window type, which gives the most ideal results for visual and thermal comfort, are different. The situation where the sun rays can enter the office building more easily, that is the case when the rotation is 210 degrees, gave the most ideal result for visual comfort. The situation where the rotation was 0 gave the most ideal result for thermal comfort. To emphasize once again, it should not be forgotten that the ideal result may vary depending on the priority between the planned window-to-wall ratio or the prioritized objective functions during the design phase. In the case of a window-to-wall ratio of 75 (Table 4.15) , it was found that if the energy consumption value is the priority, the 11th window type (#957), and if thermal comfort or visual comfort is

prioritized, the 6th window type gives the most ideal results (Case #886 for thermal comfort and #952 for the visual comfort). Just like the 50% window-to-wall ratios (Table 4.14), thermal comfort was observed for the 6th window type when the rotation was 0, and for visual comfort, the rotation was 180 degrees. In the ratio of 100 windows to walls, it was seen that the results were no different from the results in the first evaluation, that is the evaluation of building rotation. When energy consumption and thermal comfort were the main factors for the design, the 11th window type was the most ideal material type, and if visual comfort was determined as the main criterion for the designer, the 6th window type was the most ideal material type. 120-degree rotation offers the user the best visual comfort this time unlike the rotation value in other window-to-wall ratios. The reasons why the 6th, 7th or 11th window types are the most ideal window types are discussed in the following sections. One of the interesting results obtained is that with the increase in the ratio of window to wall, energy consumption is also saved. While the energy consumption was approximately 373000 kWh at 50 window ratio, 358000 kWh at 75% window wall ratio (Table 4.15), this value was 357000 kWh at 100 percent window wall (Table 4.16).

Table 4.14 Results of all cases according to 50% window wall ratio after filtration

#	X1:Case- #	X2: Rotation (°)	X3: Window Type	X4: Window- wall ratio (%)	Y1: minimize energy consumption (kWh)	Y2: minimize PPD (%)	Y3: maximize visual comfort (%)	Criteria Satisfied or Not
446	1	0	6	50	377972	14.29	55.50	S
500	1	150	5	50	393796	16.05	60.70	N
508	1	180	2	50	423082	17.20	64.70	N
511	1	180	5	50	389908	16.00	60.60	N
512	1	180	6	50	379749	15.12	59.80	N
513	1	180	7	50	371313	15.63	58.70	N
517	1	180	11	50	356423	15.63	51.60	N
519	1	210	2	50	425270	17.00	64.40	N
522	1	210	5	50	392021	15.79	60.30	N
523	1	210	6	50	381830	14.93	59.40	S
524	1	210	7	50	372681	15.43	58.60	N
528	1	210	11	50	357333	15.47	51.60	N
530	1	240	2	50	428274	16.63	63.30	N
534	1	240	6	50	384137	14.56	57.80	S
535	1	240	7	50	373899	15.03	57.30	N
539	1	240	11	50	356501	15.05	51.00	N
541	1	270	2	50	426368	16.63	62.70	N
545	1	270	6	50	382963	14.56	57.20	S
546	1	270	7	50	373780	15.08	56.40	N
552	1	300	2	50	425736	16.47	61.50	N
556	1	300	6	50	382249	14.40	56.50	S
557	1	300	7	50	373139	14.93	55.90	S
561	1	300	11	50	357020	15.01	50.10	N
567	1	330	6	50	378197	14.35	55.70	S
568	1	330	7	50	368680	14.88	54.80	N
572	1	330	11	50	352777	14.89	48.80	N
578	2	0	6	50	375051	14.73	45.60	N
667	2	240	7	50	372983	15.36	55.60	N
671	2	240	11	50	355874	15.31	49.20	N
699	2	330	6	50	376287	14.80	50.10	N
704	2	330	11	50	351840	15.21	43.30	N
710	3	0	6	50	375051	14.73	45.60	N
754	4	0	6	50	375051	14.73	45.60	N
880	4	330	11	50	350843	15.26	40.90	N

Table 4.15 Results of all cases according to 75% window wall ratio after filtration

#	X1	X2: (°)	X3:	X4: (%)	Y1: (kWh)	Y2: (%)	Y3: (%)	Criteria
886	1	0	6	75	388021	14.00	62.20	S
887	1	0	7	75	376654	14.44	60.80	S
898	1	30	7	75	380485	14.49	62.00	S
915	1	90	2	75	453500	17.33	74.50	N
926	1	120	2	75	453572	17.50	75.20	N
937	1	150	2	75	449420	17.56	74.10	N
940	1	150	5	75	407064	15.96	71.90	N
948	1	180	2	75	444123	17.47	73.80	N
951	1	180	5	75	402262	15.86	71.70	N
952	1	180	6	75	389840	14.87	70.00	S
953	1	180	7	75	378290	15.23	68.60	N
957	1	180	11	75	358646	15.00	57.80	S
962	1	210	5	75	404773	15.67	71.50	N
963	1	210	6	75	392347	14.71	69.80	S
964	1	210	7	75	379945	15.03	68.20	N
968	1	210	11	75	359770	14.83	57.60	S
973	1	240	5	75	408673	15.34	71.00	N
974	1	240	6	75	396348	14.40	68.20	S
975	1	240	7	75	382578	14.67	66.60	S
979	1	240	11	75	359813	14.43	56.00	S
981	1	270	2	75	448393	16.96	73.80	N
985	1	270	6	75	394094	14.38	66.90	S
986	1	270	7	75	381650	14.70	65.30	S
992	1	300	2	75	447716	16.79	73.40	N
996	1	300	6	75	393300	14.20	64.40	S
997	1	300	7	75	380850	14.54	63.50	S
1001	1	300	11	75	359746	14.34	55.00	S
1007	1	330	6	75	389424	14.14	63.00	S
1008	1	330	7	75	376496	14.48	61.60	S
1009	1	330	8	75	376200	16.43	60.80	N
1012	1	330	11	75	355512	14.24	54.30	N
1085	2	180	7	75	376347	15.97	60.80	N
1111	2	240	11	75	358990	14.73	54.90	N
1144	2	330	11	75	354222	14.61	48.80	N
1320	4	330	11	75	352930	14.67	45.40	N

Table 4.16 Optimization results of all cases according to 100% window wall ratio after filtration

#	X1:Case- #	X2: Rotation (°)	X3: Window Type	X4: Window- wall ratio (%)	Y1: minimize energy consumption (kWh)	Y2: minimize PPD (%)	Y3: maximize visual comfort (%)	Criteria Satisfied or Not
1322	1	0	2	100	458247	16.89	77.10	N
1326	1	0	6	100	396025	13.98	70.70	S
1327	1	0	7	100	382150	14.23	69.10	S
1333	1	30	2	100	464359	17.08	77.90	N
1337	1	30	6	100	401572	14.19	72.80	S
1338	1	30	7	100	386469	14.31	71.00	S
1344	1	60	2	100	470070	17.49	78.10	N
1347	1	60	5	100	420900	15.58	75.50	N
1355	1	90	2	100	470843	17.75	78.30	N
1358	1	90	5	100	421914	15.83	76.10	N
1359	1	90	6	100	407773	14.84	74.70	S
1360	1	90	7	100	392326	14.89	74.00	S
1366	1	120	2	100	470943	17.89	78.50	N
1369	1	120	5	100	421900	15.99	76.50	N
1370	1	120	6	100	407676	14.98	75.00	S
1371	1	120	7	100	392055	15.09	74.20	N
1377	1	150	2	100	466328	17.92	78.40	N
1397	1	180	11	100	360599	14.62	63.90	S
1403	1	210	6	100	400650	14.71	73.90	S
1404	1	210	7	100	385736	14.86	73.00	S
1408	1	210	11	100	361897	14.45	63.70	S
1415	1	240	7	100	389418	14.55	73.40	S
1419	1	240	11	100	362597	14.07	61.30	S
1425	1	270	6	100	402921	14.44	74.30	S
1426	1	270	7	100	387898	14.57	73.80	S
1430	1	270	11	100	362524	14.11	60.70	S
1435	1	300	5	100	416206	15.27	75.20	N
1436	1	300	6	100	402116	14.25	73.50	S
1437	1	300	7	100	387042	14.39	72.00	S
1441	1	300	11	100	361952	13.96	59.80	S
1447	1	330	6	100	398304	14.18	72.40	S

Table 4.16 (cont'd)

#	X1:Case- #	X2: Rotation (°)	X3: Window Type	X4: Window- wall ratio (%)	Y1: minimize energy consumption (kWh)	Y2: minimize PPD (%)	Y3: maximize visual comfort (%)	Criteria Satisfied or Not
1448	1	330	7	100	382763	14.33	69.60	S
1452	1	330	11	100	357931	13.87	58.70	S
1525	2	180	7	100	381494	15.83	69.60	N
1551	2	240	11	100	361579	14.39	59.60	S
1584	2	330	11	100	356333	14.25	52.30	N
1606	3	90	11	100	357245	14.45	54.20	N
1760	4	330	11	100	354791	14.32	48.50	N

After examining and analyzing the main difference in the study, whether there are surrounding buildings or not, the 3rd case and 4th case, then the facade effect and the case where the surrounding buildings are rotated together with the office, were examined. It can be said that these two situations are not possible in reality. However, the results were interpreted by accepting the fact that the positioning of the surrounding buildings around the office and its rotation with the office building at the same time is possible theoretically. Initially, the facade factor was analyzed. In the first designed model, buildings that are taller than the office were placed on the north, a shorter building was placed on the south side, and the surrounding buildings which were placed on the west façade has equal height with the office. In the third case, these surrounding buildings were rotated counterclockwise direction by 90 degrees, and observations were made (Table 4.17).

Table 4.17 Results of the third case after filtration

#	X1:Case- #	X2: Rotation (°)	X3: Window Type	X4: Window- wall ratio (%)	Y1: minimize energy consumption (kWh)	Y2: minimize PPD (%)	Y3: maximize visual comfort (%)	Criteria Satisfied or Not
270	3	0	6	25	363798	15.67	37.30	N
271	3	0	7	25	359869	16.29	37.90	N
275	3	0	11	25	351748	16.50	33.10	N
277	3	90	2	25	391589	17.14	44.90	N
279	3	90	4	25	365717	16.26	42.20	N
280	3	90	5	25	371311	16.52	42.80	N
281	3	90	6	25	364491	15.88	41.90	N
282	3	90	7	25	360476	16.49	41.50	N
286	3	90	11	25	352248	16.68	37.00	N
308	3	270	11	25	352163	16.84	35.60	N
710	3	0	6	50	375051	14.73	45.60	N
711	3	0	7	50	367405	15.31	45.00	N
715	3	0	11	50	353278	15.33	39.80	N
717	3	90	2	50	418685	17.02	55.20	N
720	3	90	5	50	386208	15.83	52.50	N
721	3	90	6	50	375841	14.92	51.70	N
1150	3	0	6	75	383913	14.45	50.70	N
1155	3	0	11	75	354958	14.66	44.70	N
1157	3	90	2	75	438723	17.26	63.70	N
1160	3	90	5	75	397606	15.66	59.00	N
1161	3	90	6	75	384752	14.62	57.50	S
1162	3	90	7	75	374471	15.08	56.60	N
1166	3	90	11	75	355661	14.85	49.80	N
1590	3	0	6	100	390984	14.40	54.00	N
1595	3	0	11	100	356494	14.25	47.90	N
1597	3	90	2	100	454218	17.56	70.80	N
1600	3	90	5	100	406509	15.67	66.80	N
1601	3	90	6	100	391900	14.55	64.30	S
1602	3	90	7	100	379386	14.87	62.90	S
1606	3	90	11	100	357245	14.45	54.20	N

Table 4.17 shows which window type dominates the optimization result with which rotation angle, along with different window-to-wall ratio percentages. It can be seen that the degree of rotation should be 90 especially if the position, in which surrounding buildings are rotated 90 degrees in the counterclockwise direction, dominates the results. This represents the position where high-rise buildings are located on the facade, which is the narrowest part of the rectangular structure.

Since the position, where one of the longitudinally long facades is empty, increases the solar radiation efficiency, it offers high values in terms of visual comfort and also improves thermal comfort.

The positioning of 90-degree rotation is also shared below in Figure 4.2

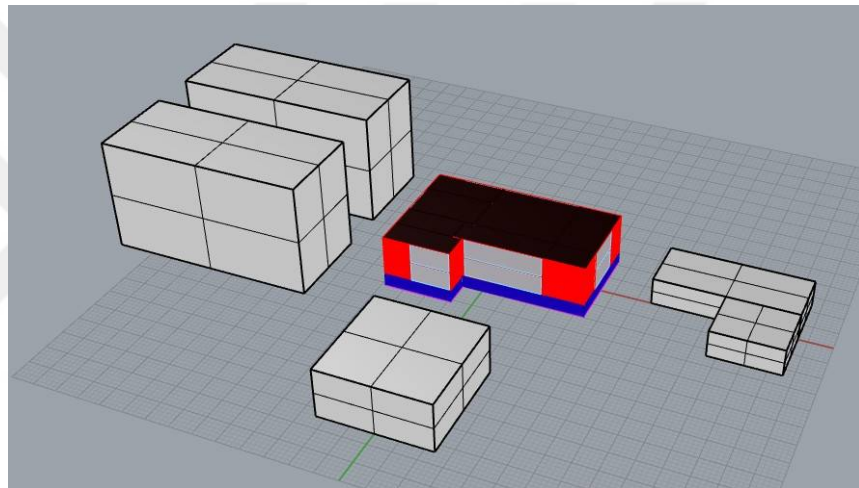


Figure 4.2 Best facade orientation according to results

As it can be understood, it has been observed that a building with a higher structure than the designed office building should be on the shortest facade to have a minimum effect on thermal comfort or visual comfort. Especially, the efficiency obtained from the results would be increased if the buildings, relatively short or have almost equal height with the designed office building, coincide with the empty facade or the relatively long facade of the building. In particular, the fact that the position, where the rotation is 180 degrees, that is, the position where the tall buildings coincide with the long facade, is not included in the results in the table, supports this interpretation. Moreover, as it is observed in 45th table, there is an improvement in thermal comfort

in vacant facades (when the long facade is empty), with the high amount of sunlight entering the building in winter. However, although tall buildings coincide with relatively short facades in the 270-degree rotation position, only one window type (#308) gave good results when the results were examined. Therefore, it is important not only whether the structures are positioned transversely or longitudinally to the designed building, but also in which direction the empty facade is. When the results are examined, it has been observed that the northern facade should be empty. Therefore, leaving the northern facades of the buildings empty with the support of environmental conditions during the design phase will be the most efficient situation in terms of providing important objective functions such as thermal comfort, visual comfort, or energy consumption of the building. It should be noted that the office building in the case study is not designed in the most ideal condition, therefore the results obtained in the first and second cases could be improved even better when optimization processes are repeated. It may even be possible to obtain the desired thermal and visual comfort threshold values in the 2nd case even without any rotation. However, the designed office structure offers the second-best option considering the results. It can be seen from the table that; the 7th window type gives the most ideal result when the ratio of window to the wall is 100 percent (#1602) if the energy consumption value is considered as a priority for the designer. If visual comfort or thermal comfort is aimed more primarily from the designer's point of view, the 6th window type with a 100% window-to-wall ratio should be selected (#1601). Unlike other cases, low energy consumption and thermal comfort could not be achieved in the same window type, and the 6th window type would be the first exception for being the best material for both visual and thermal comfort. Moreover, the 7th window type is the best material type for the first time in terms of energy consumption. As stated in the previous section, the obtained results can be varied depending on the purpose (visual comfort, thermal comfort, or energy consumption), and or conditions which the building modeled (1st, 2nd, 3rd, 4th Cases), as a result of this the most ideal material type would be diversified. After analyzing the effect of the facade on the objective functions, the last hypothetical case, the fourth case, which is the case of simultaneously rotating the designed office building with the surrounding buildings,

in the same direction has been examined. Again, as in the other cases, the rotations were performed counterclockwise direction, and a total of 12 cases were tested at 30-degree intervals. If the fourth case without any rotation is considered, as in the 1st and 2nd cases, it is seen that the data obtained in the 2nd case would be the same as the data obtained in the 4th case when there is no rotation. Because they have the same conditions. Therefore, the targeted visual and thermal comfort values could not be reached without any rotation process. Rotations of 270, 300 or 330 degrees in counterclockwise direction are mainly focused on the results just as in the cases in the 1st and 2nd cases. In cases where the rotation is at these degrees, there has been an improvement in the visual comfort value. However, there were no cases where both 15 percent target for the thermal comfort and 55 percent target for the visual comfort was achieved at the same time. 6th, 7th, or 11th window types provided the European standard of 15 percent in some cases but somehow failed to meet the 55 percent set by the LEED criteria. The data obtained are also shared below. When Table X is examined in general, it is observed that the 2nd window type stands out for the first time apart from the window types that generally give positive results (6th, 7th, 11th). It has been observed that this window type, which can provide sufficient visual comfort, failed to provide enough thermal comfort. Although the cost was not included in the scope of the case study, the 2nd window type is considered to be relatively more cost-effective than other window types, and it has also been observed that under the specific condition, such as the 4th case, the more economical material can give the good enough or reasonable enough result even though it is not the best. When the shared tables are examined, once again the cases with the 100% WWR dominates the results. Despite the cost that may increase due to increase in WWR, it can be said that the decrease in energy consumption can compensate for the increased cost in the long run, and the working personnel will perform better both psychologically and physically with the increased thermal comfort and visual comfort quality. However, one of the results obtained based on the whole situation is that rotating both the office building and the surrounding buildings at the same time does not give the ideal or the most efficient result. While the surrounding buildings were located at a certain angle, the office building to be designed at a different angle compared to the surrounding buildings

provided much better results. In addition to the fact that it is impossible to rotate or position the office building to be designed with the surrounding buildings at the same time, the fact that a new building to be designed which would be independent concerning surrounding building may not be suitable in terms of city architecture and aesthetics. Therefore, it is inevitable to consider other factors while designing. However, in terms of optimization, the contribution of the rotation process to the results is undeniable. Finally, the ideal result, which cannot be obtained in the 4th case (Table 4.18), can be achieved with the better thermal comfort quality that can be improved with different window type materials, different building geometry, different window-wall ratio, or different insulation materials selection.



Table 4.18 Results of the fourth case after filtration

#	X1:Case- #	X2: Rotation (°)	X3: Window Type	X4: Window- wall ratio (%)	Y1: minimize energy consumption (kWh)	Y2: minimize PPD (%)	Y3: maximize visual comfort (%)	Criteria Satisfied or Not
440	4	330	11	25	348617	16.34	33.70	N
880	4	330	11	50	350843	15.26	40.90	N
1194	4	0	6	75	383913	14.45	50.70	N
1195	4	0	7	75	373679	14.87	49.20	N
1304	4	300	6	75	386410	14.66	51.30	N
1305	4	300	7	75	375936	15.05	50.50	N
1316	4	330	7	75	372343	15.03	50.20	N
1320	4	330	11	75	352930	14.67	45.40	N
1630	4	0	2	100	453296	17.45	57.00	N
1633	4	0	5	100	405596	15.52	55.80	N
1634	4	0	6	100	390985	14.40	54.00	N
1635	4	0	7	100	378528	14.68	52.90	N
1639	4	0	11	100	356494	14.25	47.90	N
1729	4	270	2	100	457624	18.16	58.80	N
1740	4	300	2	100	456299	17.80	58.80	N
1744	4	300	6	100	394056	14.67	54.50	N
1745	4	300	7	100	381317	14.90	53.80	N
1749	4	300	11	100	358002	14.40	49.00	N
1755	4	330	6	100	391715	14.73	54.40	N
1756	4	330	7	100	377828	14.90	53.60	N
1760	4	330	11	100	354791	14.32	48.50	N

After evaluating the optimization results in different situations and under different conditions, it was examined why certain window types dominated the optimum results. First of all, to repeat which window types give better results in which conditions and for what purpose, the window types that can serve the designer best according to the design purpose are summarized below and shared in Table 4.19. In addition to the evaluation in the table, two cases were taken from the table as an example and the results were graphed according to different window types. In addition,

the estimated annual energy consumption amount, visual comfort, and thermal comfort values for each window type are given in the graph. While the 1st case whose having 100 WWR and 330 degrees rotation was shared in the first example graph, the 2nd case having 100 WWR and 240 degrees rotation was shared in the second example graph.

Table 4.19 Summary of trade-off analysis results of all cases after filtration

#	Case	Rotation	Window Wall	Window	Priority
		(°)	Ratio (%)	Type	
446	1	0	50	6	Thermal Comfort
523	1	210	50	6	Visual Comfort
557	1	300	50	7	Energy
886	1	0	75	6	Consumption
952	1	180	75	11	Thermal Comfort
957	1	180	75	11	Visual Comfort
1326	1	0	100	6	Energy
1331	1	0	100	11	Consumption
1370	1	120	100	6	Thermal Comfort & Visual Comfort
1452	1	330	100	11	Thermal Comfort & Energy
1546	2	240	100	6	Consumption
1573	2	300	100	11	Visual Comfort
1601	3	90	100	6	Thermal Comfort & Energy
1602	3	90	100	7	Visual Comfort
					Energy
					Consumption

As can be observed from the shared graphs, the percentage of visual comfort resulted in direct proportionality with the visible transmittance (VT) values of the

window types. Visible transmittance is a criterion with a value ranging from 0 to 1, which defines how much sun rays penetrate the building (Carmody & Haglund, 2012). It is not concerned if the sun's rays retain heat or not while passing through the window. It simply tells how much the building will benefit from the sun, which is a natural light source. Therefore, the visual comfort values of the window types with higher VT values in the graph were higher than the others. If the 2nd window type is analyzed as an example, it ranked first with 76.9 percent and 73.8 percent in the first and second charts respectively. (Figure 4.3 and Figure 4.4) On the other hand, the 3rd window type which has the lowest VT value presented the worst visual comfort result in both graphs and all analyzed conditions. The high VT value of the window types has been important in the study to reach the targeted threshold value of visual comfort, and it directly provides visual comfort in which can be improved with artificial lighting by consuming extra energy in case the visual comfort percentage is not enough.

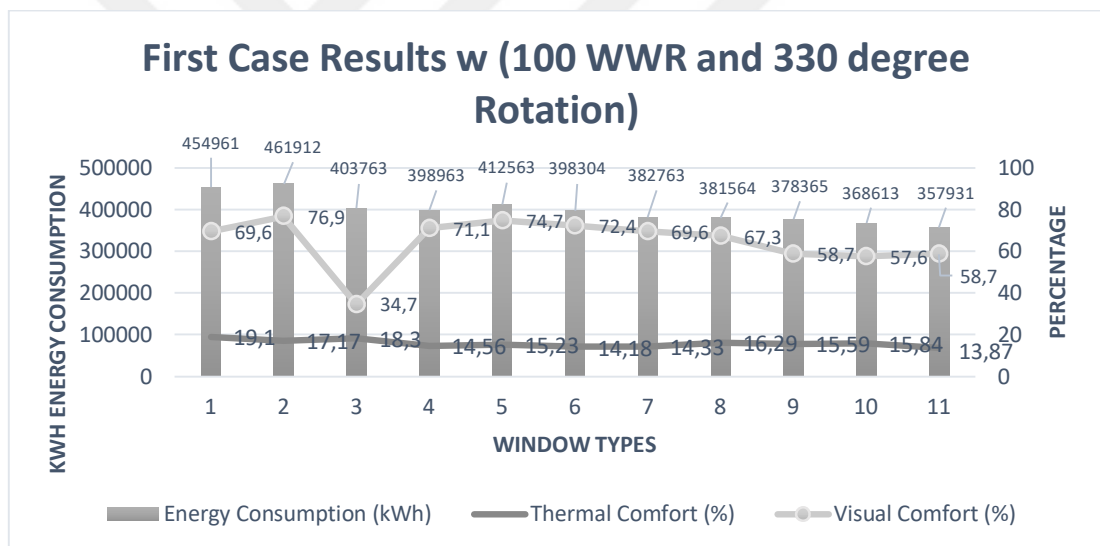


Figure 4.3 100 WWR and 330-degree rotation of the first case

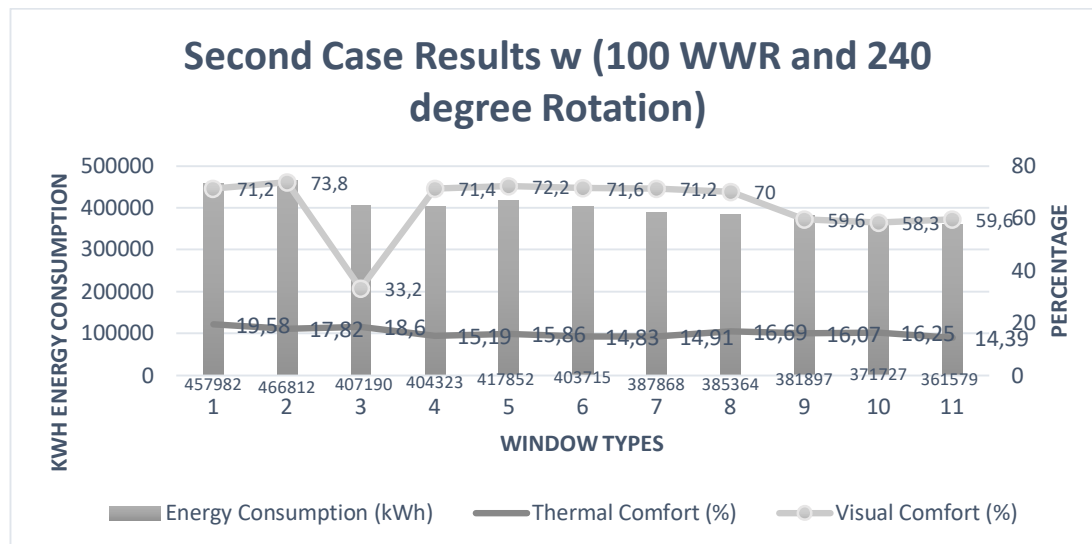


Figure 4.4 100 WWR and 240-degree rotation of the second case

Another feature of the window types used is the Solar Heat Gain Coefficient, SHGC. Like VT, SHGC is also a criterion ranging from 0 to 1. SHGC is a percentage expression that indicates how much heat is retained while the sun's rays passing through the window. Windows with high SHGC values are the types of materials that transfer more heat to the interior (Carmody & Haglund, 2012). Especially in climatic regions where air conditioning is not a problem, window types with high SHGC values can be preferred. However, considering that it will give a lot of heat inside the building during the summer days for hot climate regions, it may cause problems in terms of thermal comfort and may cause extra energy consumption to provide thermal comfort (Paulus, 2014). Therefore, depending on the type of climate in which the building is located, the energy consumption desired to be spent for heating or cooling, or the number of days in summer or winter climate, window types with different SHGC values can be preferred. Considering that the currently designed office building is located in Ankara, Turkey, it will not be easy to comment on keeping the SHGC value high or low. Because in Ankara, which has very harsh winter conditions, window type with high SHGC value will help to reduce the energy consumed for heating, while for the region with very hot weather in summer days, this time the energy spent for cooling will increase. Therefore, it would not be correct to make a sharp and clear comment. The correct result can be reached by using different window types in different

situations, as in the case analysis in this study. The last of the window properties used in case analysis is the U value. The U value shows how well the window's thermal insulation is (Carmody & Haglund, 2012). As the U value decreases, the insulation quality in the window also increases. In addition, with the decreasing U-value, energy consumption is also saved with the help of insulation. Thermal comfort can be improved with both the U value and the SHGC value. If evaluations are made on shared graphics, for example, the following comments can be made for the 1st and 2nd window types. The energy consumed for the 1st window type is lower than the energy consumed for the 2nd window type because the U value is lower for the 1st window type. However, if the thermal comfort values are compared, it is seen that the second window type is much more comfortable. The reason for this is that the SHGC value of the 2nd window type is higher, and therefore the thermal comfort for the winter months is higher due to the relatively high amount of heat entering the building. It would be insufficient to explain all the results in this way. Because although some window types have a higher SHGC value when compared, it may be in a situation where thermal comfort is worse. For example, if the 4th and 5th window types are compared graphically, the SHGC value of the 4th window type was lower than the SHGC value of the 5th window, but the thermal comfort result was better. The reason for this is that the 4th window type has a lower U value, in other words, it has better insulation and keeps the indoor environment warmer in the winter and cooler in the summer months. Therefore, it is not wrong to say that the thermal comfort quality of a window type with both a smaller U value and a higher SHGC value will be better. However, in window types that do not fulfill both conditions, that is, with a better U value or SHGC value, which window type will be better can be evaluated as a result of the analysis. In particular, the results may vary depending on many parameters such as building geometry, window height, window wall ratio, and the climate of the city where the designed building is located. However, if the analyzed case study is examined, comments can be made without making generalizations. When the most ideal result tables shared above are examined, it will be seen that the ideal result is obtained in the 6th window type for visual comfort. This result is not surprising, because, among the dominant window types 6, 7, and 11, the window type with the highest VT value is the

6th Window type. When the energy consumption is examined, the 11th window type gave the most ideal result. The reason for this is that the 11th Window type is very advantageous when U values are compared. But, there are no always window type for the thermal comfort objective function. Because it depends on the situation, it was the 6th Window type or the 11th Window type. While the 6th window type is very advantageous in terms of the SHGC value, the 11th window type was able to provide thermal comfort thanks to its robust insulation due to its U value. The results of these two window types in the summer and winter months are also examined separately in the 1st case where rotation is 330 degrees.

As expected, the window type with a higher SHGC value provided more ideal thermal comfort in winter thanks to the heat of the sun rays, while the 11th window type with a better U value insulation provided a more ideal thermal comfort in summer, thus keeping the air cool inside (Table 4.20)

Table 4.20 The PPD Values in winter and summer respectively

Window Types	Predicted People Dissatisfied in Winter (%)	Predicted People Dissatisfied in Summer (%)
6	19.85	8.23
11	19.93	7.37

In summary, according to the findings obtained from the case analysis, the window type with a relatively low SHGC value can be tolerated with a low U value, or the window type having a higher U value can be tolerated with window type with a higher SHGC value. It should also be noted that these small percentage differences may not be felt by human. It should give just an perspective for the designer.

CHAPTER 5

CONCLUSIONS

A thesis study was completed by considering three different objective functions. While the energy consumption value in the building is minimized, it is aimed to maximize the visual and thermal comfort values. Different window types, different window wall ratios, buildings around the designed office, rotation of the office and surrounding buildings, and insulation material thicknesses were selected as parameters to analyze and a tradeoff relationship was examined in between them. According to data, it was observed that both the energy consumption and thermal comfort value has improved with similar parameters while the visual comfort is observed to be the opposite. In cases where visual comfort is good, there has been a decrease in the values of thermal comfort or increase in the energy consumption. Therefore, a trade-off relationship has been observed. The parameters were analyzed using different scenarios. Post elimination processes was applied over the dominated and non-dominated solutions found by using multi objective functions. According to the determined threshold values, window types that do not meet the criteria of thermal comfort and visual comfort have been eliminated, thus the options proposed for the design have been limited. According to the designer's preference in terms of visual comfort, thermal comfort, or energy consumption objective function; window type, window-wall ratio and rotation values are suggested. Thus, the thesis study is aimed to be a method for the designer, to set an example and to broad a different horizon. The parameters used were analyzed and given using different scenarios. There are some shortcomings in the study. The most important of these is that the cost is not included in the objective functions. Contrary to literature studies, it was not included in the thesis due to the inability to provide sufficient financial data and the fluctuating pricing of material types. Another missing objective function is acoustic comfort that can be included in indoor comfort. It was not included in the study because there is an inability to determine the effect of the currently used parameters on acoustic comfort. In addition, an input that may directly affect thermal comfort, such as ventilation, is

not included in the scope of the study. The main reason for that the ventilation calendar to be uploaded to the Honeybee software is not in accordance with a certain standard. Therefore, other parameters such as cost, glare, ventilation, acoustic comfort can also be included in the future studies, and a trade-off relationship can be investigated for new scenarios to help designers in future design decisions.



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