EFFECT OF NATURAL WALL MATERIALS ON ENERGY CONSUMPTION IN CONTINENTAL AND MEDITERRANEAN CLIMATES

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by
Ekin Gamze YÖNEY

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We approve the thesis of **Ekin Gamze YÖNEY**

Examining Committee Members:

Assoc. Prof. Dr. Mustafa Emre İLAL
Department of Architecture
İzmir Institute of Technology

Prof. Dr. Tahsin BAŞARAN
Department of Architecture
İzmir Institute of Technology

Assist. Prof. Dr. İlker KAHRAMAN
Dept. of Int. Architecture & Environ. Design
Yaşar University

17 July 2019

Assoc. Prof. Dr. Mustafa Emre İLAL
Supervisor, Department of Architecture
İzmir Institute of Technology

Prof. Dr. Koray KORKMAZ
Head of the Department of
Architecture

Prof. Dr. Aysun SOFUOĞLU
Dean of the Graduate School of
Engineering and Science

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ABSTRACT

EFFECT OF NATURAL WALL MATERIALS ON ENERGY CONSUMPTION IN CONTINENTAL AND MEDITERRANEAN CLIMATES

Concern on earth and other natural building materials has been increased by rise of energy shortage and environmental problems. Not only the speed, quality and standardization in the production process of natural building materials should be improved, but also energy consumption of buildings constructed with these materials should be on acceptable levels in order to expend their usage. This study investigates the relationship between natural wall materials and energy consumption on two adobe buildings from Continental and Mediterranean climates.

Totally 20 different wall options, composed of adobe, vertical hollow brick, limestone, hempcrete and strawbale with 0.30- and 0.50-meter thickness without and with flax thermal insulation material are tested with different combinations of direction and climate. The digital models of case buildings in Continental and Mediterranean climates are created to examine the question of in what climate and which direction a wall material is appropriate for energy efficient design.

Consequently, strawbale enables the minimum annual energy consumption both for Mediterranean and Continental climates, while adobe shows better energy performance in summer period of Continental climate. Besides, it is observed that the energy consumption for cooling in case building of Mediterranean climate is 10 times more than of Continental one for whatever material is tested. The quantitative research conducted with different natural wall materials makes it a logical choice in terms of opening the path of industrialization that is supported by the aim of this thesis.

ÖZET

KARASAL VE AKDENİZ İKLİMLERİNDE DOĞAL DUVAR MALZEMELERİNİN ENERJİ TÜKETİMİ ÜZERİNE ETKİSİ

Giderek artan enerji darlığı ve çevre problemlerine bağlı olarak kerpiç ve diğer doğal yapı malzemelerine olan ilgi de artmıştır. Doğal yapı malzemelerinin kullanımının yaygınlaşabilmesi için üretim sürecinde hız, kalite ve standardizasyonun iyileşmesi kadar bu malzemeler ile üretilen binalarda enerji tüketiminin kabul edilebilir ölçülerde olması gereklidir. Bu çalışmada, Karasal ve Akdeniz iklimlerinde bulunan iki kerpiç yapıda doğal duvar malzemeleri ile enerji tüketimi ilişkisi incelenmiştir.

Kerpiç, düşey delikli tuğla, kalker taşı, kenevir tuğla ve saman balyasının 0.30 ve 0.50 metrelik kalınlıkta, yalıtımsız veya geri dönüşümlü keten yünü yalıtımdan oluşan toplam 20 farklı duvar seçeneği farklı yön ve iklim kombinasyonlarında test edilmiştir. Bir duvar malzemesinin, hangi iklim ve ne yönde konumlandırılırsa minimum enerji tüketimi sağlayacağı sorusunu irdelemek amacıyla Karasal ve Akdeniz iklimlerinde yer alan örnek yapıların dijital modelleri hazırlanmıştır.

Sonuç olarak saman balyası her iki iklim için de minimum yıllık enerji tüketimi sağlarken, kerpicin karasal iklimde yaz boyunca daha iyi enerji performansı gösterdiği görülmüştür. Bunun yanında, Akdeniz ikliminde yer alan binada hangi malzeme test edilirse edilsin, soğutma amaçlı tüketimin Karasal iklimdeki binadan yaklaşık 10 kat daha fazla olduğu tespit edilmiştir. Farklı doğal duvar malzemeleri ile gerçekleştirilen bu nicel araştırma, tezin amacı olarak da desteklenen malzemelerin sanayileşme yollarının açılması bakımından da mantıklı bir seçim haline geldiğini göstermektedir.

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LIST OF ABBREVIATIONS

.csv	: Comma Separated Values
.dxf	: Drawing Exchange Format
.epw	: EnergyPlus Weather File
ASHRAE	: The American Society of Heating, Refrigerating and Air Conditioning Engineers
c	: Specific Heat
C	: Thermal Capacity
CV-RMSE	: Root Mean Square Error
d	: Density
DB	: DesignBuilder
DHW	: Domestic Hot Water
HVAC	: Heating, Ventilating and Air Conditioning
IPMVP	:International Performance Measurement and Verification Protocol
k	: Thermal Conductivity
m	: Mass
M&V	: Measurement and Verification for Federal Energy Projects
MBE	: Mean Bias Error
MDF	: Modified Decrement Factor
NTV	: Night Time Ventilation
mtoe	: Million Tons of Oil quivalent
PVEF	: Pastoral Valley Eco Farm
RH	: Relative Humidity
SŞV	: Sonsuz Şükran Valley
T	: Temperature
TSE	: Turkish Standard Institute
U-Value	: Heat Transfer Coefficient
VHB	: Vertical Hollow Brick

CHAPTER 1

INTRODUCTION

1.1. Problem Statement

Earth, as one of the oldest building materials, constitutes one-third of the building stock over the world today or nearly 1,500,000,000 human beings live in earth houses, and the majority of them are remarkably the new buildings, shown in Figure 1.1 (Blondet, 2003; Houben, Guillaud, Gompers, and Schilderman, 2014). The main reason why earth is preferred as a building material in old buildings is that it can be easily accessed in the local area, whereas in new buildings new parameters have been included due to rising awareness toward sustainable architecture.

Most of the new earth buildings are of sustainability concern. These constructions minimizing environmental damage and dealing energy with more efficient ways can be shown as examples of theory of sustainability in architectural practice. The earth which has been a widely used building material in sustainable architecture provides energy efficiency especially because, it has less embodied energy, accordingly, reduces environmental damage, and does not cause sick building syndrome.

Chronologically, the development of earth construction dates back to 4000s BC by the Sumerians, Akkadians, and Babylonians from the Mesopotamian tribes, which used earth material in the walls, sewage system, and writing tablets. The ruins of cities, made entirely of earth material, have also been found during the excavations in ancient China, India and Central Asia (Kafesçioğlu, 1980).

Looking into the middle ages, earth buildings in the Central Europe are usually found in regions with little wood. In the Eastern Europe, specifically in Poland and Ukraine, the earth construction is still widely used as local material.

In the 18th and 19th centuries, the earth construction was revisited in France and efforts were made to develop it. In the same period, studies on the utilization of earth as a building material in Germany were accelerated in the theoretical sense; institutes were established and a large educational campaign was organized for public use (Kafesçioğlu, 1980). According to estimated adobe statistics until 1980, in the continental America, there is a total of 175,925 earth buildings in the USA, 97% of which are in New Mexico, and around 1,500 new ones are added to this amount each year (Gerbrandt, 1981).

Figure 1.1. World distribution of adobe
(Source: Houben et al., 2014)

As a result of the innovations and development of technology after the Industrial Revolution, earth has been replaced by mass-produced and industrialized building materials. These new materials, such as concrete and steel, which have the most common use in today's world, have brought many innovations and convenience in the construction sector. However, the high level of energy needed especially during the production and construction phases has also brought about the environmental pollution side due to the fact that this energy is mostly derived from fossil fuel sources and it emits toxic fumes and smoke.

Interest in earth structures increased again with two events in the 20th century. Firstly, with the commencement of the First and Second World Wars, construction materials such as iron and brick imported by many countries could not be supplied and people had to build their buildings with the building materials within their own country's capabilities. The second is the energy crisis in the 1970s. With the embargo of oil-exporting Arab countries, oil prices increased at a time and depending on this price rise, the stock market collapsed in 1973-74. After this crisis, which was the first energy crisis on a global scale since the crisis of 1929, the concept of passive solar design emerged as a thought that offered rationality and considered buildings in harmony with nature (Gürbüz, 2005). With this concept, it has been aimed at using solar energy in an efficient way, therefore, the use of earth as a building material has gained interest again for its high thermal mass by storing and releasing thermal energy obtaining from the sun for decreasing heating and cooling consumption.

The sustainable architectural practice, which has been growing building stock due to the energy shortage and environmental problems that we have been experiencing today, has led us to use not only earth and but also alternative natural building materials. Natural building materials such as adobe, reed, flax based materials, hempcrete are defined as materials that have undergone less processing than conventional synthetic building materials. They consist of renewable and easily available sources in the local area. Therefore, the fossil fuels used during the transportation process and material production are used less and the carbon footprint can be reduced accordingly. Depending on these, the end product is more environmentally friendly, healthy and compatible with nature. In this context, even in the most developed countries, researches and studies on the possibilities of utilizing the most effective form of earth and alternative natural building materials have gained importance.

The major issues that need attention in sustainable building design are, local climate, local methods of construction, and local availability of building materials. The parameters such as the thermal mass of the building, wall thickness, the amount of insulated used, and whether or not night ventilation takes place are among secondary parameters.

It is necessary to interpret traditional earth construction techniques, update them according to today's construction techniques that rely on mass-production and industrialization. Speed, quality and standardization are important for sustainable and healthy buildings. Therefore, it is necessary to reconsider the conservative traditional earth construction practices and to answer the question of which natural building materials should be used in which combination. These rethinking and responses will lead us to produce more efficient buildings in terms of material use, location, and energy consumption. Today, the same material is used on all four walls of a building. Materials are not determined according to the orientation of the wall. This neglect of the direction causes the walls occupying a large area in the building to be used inefficiently in terms of building energy consumption. It ignores the question of in what climate and which direction a wall material is appropriate for energy efficient design. In this study, wall options based on natural building materials were tested with different combinations of direction and climate.

1.2. Aim and Method of the Research

The general aim of this study is to examine energy efficiency of buildings with natural wall materials in different climates such as Mediterranean and Continental. Different natural wall materials are evaluated in terms of the adobe structure in two different climates and the relationship between energy efficiency and climate is examined according to the material.

The study is based on the calculation of annual energy consumption. It utilizes an optimization tool focusing on three main parameters of wall options (vertical component of envelope), façade orientation (direction) and natural (night-time) ventilation. In the determination of these parameters research questions considered were:

- Do adobe buildings provide enough energy performance for Mediterranean and Continental climates? Is the adobe an appropriate material selected for energy performance in Mediterranean and Continental climates?
- What is the most energy efficient natural wall material for the case buildings in Mediterranean and Continental climates?
- Is it possible to make combinations of materials on different wall directions of the building?
- Which combination of wall options provide the least energy consumption?
- How does the material with high thermal mass behave in buildings in summertime? How does thermal mass affect energy consumption while night-time ventilation on or off? In which way?

- What is the effect of night-time ventilation on energy consumption, and is the night-time ventilation effective on discharge accumulated daytime heat due to thermal mass?
- What is the effect of climate on energy consumption?
- Considering the U-Value and thermal mass, which is the most effective on energy consumption?
- How does the thickness insulation and material choice effect the energy consumption?

The questions led into the determination of the explored parameters. The parameters investigated are:

1-Wall options:

- Exterior wall material: adobe, vertical hollow brick (VHB), limestone, hempcrete, strawbale
- Exterior wall thermal insulation material: without thermal insulation and with flax as a thermal insulation material (0.05-meter thickness)
- Thickness of exterior wall: 0.30-meter and 0.50-meter

2- Night-time ventilation: night-time ventilation for summer period (on or off)

3- Building façade positioning: Orientation of walls.

The reasons behind selecting adobe, VHB, limestone, hempcrete and strawbale as wall materials, and flax as an insulation material are;

- Adobe; is the main wall material for the case buildings
- VHB; is the most common wall material in Turkey.
- Limestone; is abundant around Konya, Turkey where one of the case building located.
- Hempcrete; is not common in Turkey. It is used as an example of new materials that is being researched in Turkey.
- Strawbale; is an increasingly popular building material.
- Flax (wool, reused); is selected as a reused building material that is mass-produced in Turkey.

1.3. Limitations and Assumptions

In this research, there have been some assumptions and limitations in several sections. These are:

- The use of natural materials only in vertical elements of building envelope was studied. Roof, foundations, slab on grade were left out of scope.
- The occupancy data for the case building in Muğla have not been collected properly during the measurement campaign. Thus, it is assumed that case building was unoccupied. The internal gains due to occupancy are neglected.
- For both case buildings in Muğla and Konya, adobe material's of thermal properties is selected with the same features for comparison in the same conditions.
- For hempcrete and strawbale, a wood framing skeleton system was planned, and these two materials were used as a filling. In the model in DesignBuilder, the wood framing was not considered in the calculation, its effect on energy consumption was neglected. The wood framing system was not modelled.
- In Muğla case building, there is a building attached to its bedroom, an adjacent space. In 3D model, therefore, this adjacent building was treated as adiabatic and its material was selected as adobe, as well.
- As an assumption, strawbale infill blocks are produced by compressing into 0.30-meter and 0.50-meter thicknesses with the same density.

1.4. Thesis Outline

This study comprises of six chapters. In the first chapter of the thesis, the general framework is drawn. The retrospective evaluation on usage and development of earth as a building material and inclusion of natural building materials into the sustainable construction are introduced in the context of sustainable architectural practice. After the problem statement is expressed, the general aim, objectives, and method of the research are determined. Limitations and assumptions are stated for this study.

In the following part, the literature review exposes the basic terminology related to the thesis study. It includes the definition of sustainable, natural and renewable building materials in literature. Then, an overview of earth as a building material and natural building materials used in this research is provided. Scientific studies and empirical analysis conducted on earth and natural building materials are presented. Lastly, the research regarding wall orientations is examined.

In the third chapter, two case buildings are explained in detail and their local climates are described.

The methodology of thesis is examined in the fourth chapter. The methods of on-site measurements, generation of .epw (EnergyPlus weather file) files, dynamic modelling, calibration process, calculation of thermal capacity and time constant ,and modified decrement factor and time lag are mentioned. The parameters, then, belonging to optimization process are determined and explained.

In the fifth chapter, the results of thermal capacity and time constant, monitoring, calibration, data taken from optimization processes are indicated. The remarks and interpretations are clearly conducted as the conclusion in the sixth chapter.

CHAPTER 2

LITERATURE REVIEW

In this chapter, all terminology regarding the thesis aim and scope is explained. It generally presents the scientific research on energy efficiency in buildings with different wall orientation of wall option with a different climate, natural building materials, its production process and method of usage in building as a component and its usage area. The main aim of this chapter is to provide a summary of the studies in the literature that guided this thesis.

Three main headings exist in this literature review. Firstly, the definition of natural, sustainable or renewable building materials have been gathered together. Under the second heading, the literature survey on natural building materials explored in this research is presented under two sub-headings: materials that were used as a wall material and thermal insulation material. The natural building materials explored are adobe, VHB, limestone, hempcrete, strawbale, and flax. The material selection was explained, and selected materials are discussed one by one in terms of production processes, usage as building materials, research on their energy efficiency and their thermal properties. The third heading covers research on energy efficiency implications of wall orientation, and research on the effects of night-time ventilation and thermal mass.

2.1. Definitions of Natural, Sustainable, Renewable Material

Construction design is a complex process that does not focus solely on aesthetics. User comfort and environmental impacts are two of the most important factors that need to be considered. Considering the environmental aspect, it is estimated that the building sector is responsible for consuming approximately 40% of the overall energy in Europe (EU, 2018). Building materials are being discussed due to the high consumption of non-renewable materials and the problems associated with the disposal phase at the end-of life of these products.

Considering the physical aspect in terms of material choice in construction design, embodied energy of building materials has been searched by various researchers (Suzuki, Oka, and Okada, 1995). Ashok Kumar, Chani, and Deoliya (2015) calculated the embodied energy content of building materials. The results convey that 16% of the total energy is used by raw materials, 8% by industrial raw materials for manufacturing, 16% by manufacture of products, 10% by product transportation and people, 10% by human energy mainly workers' food, and 30% by heating.

Sustainability in the building sector slowly causes the production of building materials that are made of natural or recycled material. In the literature, the definition of natural, sustainable or renewable building materials has been investigated with different perspectives.

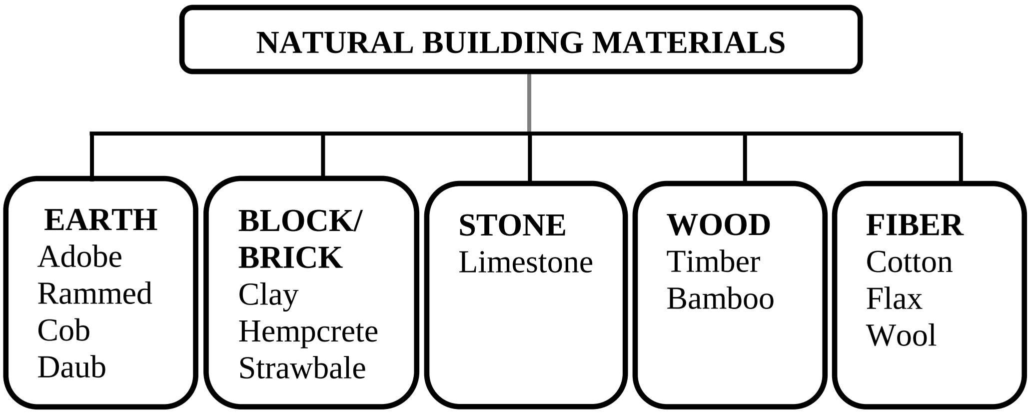


Figure 2.1. Classification of some of the natural building materials

Hussain and Kamal (2015) describe sustainable materials as minimizing the use of resources and environmental impacts, securing human health risks, assisting with sustainable site design strategies and production by companies following sustainable social, environmental and corporate policies. Bignozzi (2011) defines sustainable materials as recycling of appropriate waste which can replace natural materials deriving from non-renewable resources due to their own characteristics. Chihaoui, Khelafi, and Mouli (2015) describe natural building materials that are locally produced and sourced, reducing transportation costs and CO_2 emissions including recycled materials making use of renewable resources. Fernea et al. (2018) express that the new thermal insulation materials produced with waste or raw materials show similar performances with synthetic materials, so the construction industry should offer these new materials.

The building materials can be classified according to what they are produced from: Raw materials, recycled materials, or synthetic materials. As an example of natural building materials, earth, masonry bricks, stone, strawbale, hempcrete, flax have been used in this research. Bamboo, cotton, wool, reed or timber are also included as examples of natural building materials that are classified in Figure 2.1.

2.2. Natural Building Materials

In this section, natural wall materials selected as alternatives in the optimization study are examined. These are adobe, VHB, limestone, hempcrete, strawbale, and flax. First, the general framework of these materials is explained. Second, their usage as a building material is explained and last, thermal and physical properties are given.

2.2.1. Earth as a Building Material

Earth as a building material is one of the oldest materials known by human beings. Earth is still commonly used in this century mostly in rural areas because of the economic shortcomings, financial problems, availability, energy conservation easiness and low cost in production. Contrary to other construction materials, earth does not harm the environment. It can easily be reused or returned by grinding and wetting.

Earth provides bioclimatic comfort for all living creatures. It stores heat with its high thermal mass since it is used in dense forms. It keeps indoor temperature cool in summer and warm in winter with a convenient humidity and balance for indoor climate (Değirmenci, 2005).

Earth as a building material may have various make-ups. Its content consists mostly of gravel, fine sands, silt, and clay, which can be determined with sieve analysis. According to ISO 14688-1:2002, earth types was classified and named by size range, shown in Table 2.1. Sidibe (1985) classified the earth with sieve analysis and determined that soils with particles 0.05 mm or less in diameter are classified as silt and clay, over 0.05 mm as sand or gravel, and particles less than 0.005 mm is the finest clay. Earth can be used in buildings with methods such as rammed, cob, daub or adobe. One of the most common methods is the earth blocks named adobe.

Table 2.1. Characterization and identification of soil
(Source: ISO 14688-1:2002, 2002)

Name				**Size range [mm]**
Very coarse soil		**Large boulder**	LBo	>630
		Boulder	Bo	200–630
		Cobble	Co	63–200
Coarse soil	**Gravel**	**Coarse gravel**	CGr	20–63
		Medium gravel	MGr	6.3–20
		Fine gravel	FGr	2.0–6.3
	Sand	**Coarse sand**	CSa	0.63–2.0
		Medium sand	MSa	0.2–0.63
		Fine sand	FSa	0.063–0.2
Fine soil	**Silt**	**Coarse silt**	CSi	0.02–0.063
		Medium silt	MSi	0.0063–0.02
		Fine silt	FSi	0.002–0.0063
	Clay		Cl	≤0.002

Production of Adobe

Adobe is a building material that is traditionally produced in Anatolia by mixing clay-based earth, straw or fiber and water by mixing and drying in the sun. It is preferable in summer months when it is not rainy but not too hot to dry completely. The area where the adobe is applied is also smoothed. After drying, a thin layer of sand should be laid on the ground surface in order to remove the adobe easily and without breaking. The wooden adobe moulds are cleaned with a cloth in the water pool before and after each use so that the adobe patterns take regular shape. Generally, four-chamber mould is used in the production of adobe. Although it varies from region to region, the most used adobe components in our country are 30-40 cm in length, 18, 19, 25, 30 cm in width and 12 cm in height.

The adobe mixture is prepared by sieving the clay-based earth material through 4 mm sieves and mixing with some straw and water. The straw is distributed homogeneously into the earth. According to TSE-2514 (1977), the mortar should be rested for at least one night (12 hours). In the next day, the mixture is mixed again, the mixture placed in the mould is squeezed with the hands or feet of the adobe master; the top surface is polished with a wooden trowel. The mould is then carefully pulled upwards to remove it. The adobes removed from the mould are allowed to dry for a few days. It is then lifted from the floor in a vertical position and dried vertically for a few days to allow homogenous drying on all surfaces of the adobe. Finally, adobe bricks are stacked in a triangular form and made ready for use.

Some rules must be followed for the proper use of naturally produced adobe material without any burning process in building construction. First of all, the time for construction should be chosen correctly. Climatetic conditions should be taken into consideration as it is a material that can be affected by water. Where necessary, moisture insulation should be done, and the wall surfaces inside and outside must be protected with plaster.

Stone above 3 cm diameter must be absent in adobe that is made of clay earth. Approximately 40% of a good adobe should pass the sieve with diameter of 0,063 mm. It is accepted that the clay amount in adobe is 20% - 70% but 30% - 40% is the most convenient amount. Sand, pieces of stones, pieces of bricks or clinker can be added for preventing shrinkage and for easing kneading in the earth containing over clay (Çavuş, Dayı, Ulusu, and Aruntaş, 2015; Değirmenci, 2005; Gür, Deniz, and Ekinci, 2012; TSE-2514, 1977).

One of the most important disadvantages of adobe is its lack of compressive strength and durability. Research in the literature explores this problem to eliminate it.

Research for Compressing Strength and Durability

Earth as a building material has lots of advantages in terms of indoor air quality. However, it experiences a few disadvantages in mechanical properties. Constraint as low compressive quality and strength against weathering prevents its utilization on a large scale (Ngowi, 1997). These constraints combined with issues of successive and repetitive maintenance of earth structures forms the reason for the improvement of this material with cement, lime, rice, fiber and so on.

Alavéz-Ramírez, Montes-García, Martínez-Reyes, Altamirano-Juárez, and Gochi-Ponce (2012) investigated the utilization of lime and sugar stick bagasse ash (SCBA) as concoction stabilizers in compacted earth blocks. The tests were performed at 7, 14 and 28 days of age to assess the impacts of the expansion of lime and SCBA on the mechanical properties of the compacted earth blocks. The outcomes demonstrate that blocks produced with 10% of lime in blend with 10% of SCBA indicated better performance than those containing only lime.

Arvind Kumar, Walia, and Mohan (2006) examined compressive strength with the mixture of plain and crimped by polyester, coconut and sisal fiber. Polyester fibers and the increase of pressure polyester fibers were blended with delicate earth to search the relative quality increase as far as unconfined pressure. Tests were tried in unconfined pressure with 0%, 0.5%, 1.0%, 1.5% and 2.0% plain and pleated polyester fibers. The outcomes demonstrate that the level of compaction influenced the overall advantages of fiber reinforcement for the subject earth. Tests compacted in the wake of blending different extents of sand into clay were likewise tried. It was seen that unconfined compressive quality of clay increments with the expansion of fibers and its further increments when fibers are blended in clay and sand blend. The other research regarding durability and compressive strength of adobe is tabularized below, shown in Table 2.2.

The standards for adobe construction are developed based on researches. In Turkey, TS-2514 is used for construction with adobe. Table 2.3 presents the standards for various countries regarding earth buildings. Apart from these, the committee of the German Institute for Standardisation (DIN) has three norms regarding factory-produced earth products. These are as follows:

- DIN 18945 Earth Masonry – Definitions, Requirements, Testing Procedures
- DIN 18946 Earth Masonry Mortars – Definitions, Requirements, Testing Procedures
- DIN 18947 Earth Plaster Mortars – Definitions, Requirements, Testing Procedures

Table 2.2. Literature regarding durability and compressive strength of adobe (Source: Sharma, Marwaha, and Vinayak, 2016)

Literature	**Improvement**	**Treatment**		**Results**
		Stabilizer	**Reinforcement**	
1- (Vilane, 2010)	Compressive strength	Ordinary Portland Cement	Molasses, cow-dung, sawdust	Soil samples with molasses and Ordinary Portland Cement showed improved compressive strength
2- (Ngowi, 1997)	Strength of earth construction	Cement, lime, bitumen	Fibers, cow-dung	Specimen of lime and cement show improved strength
3- (Alavéz-Ramírez et al., 2012)	Durability, compressive strength, flexural strength	Lime	Sugarcane bagasse ash (SCBA)	Specimens with 10% lime + 10% SCBA showed improved properties
4- (Ren and Kagi, 1995)	Durability of adobe	Sodium silicate solution, siloxane and silicone	-	Treated specimens show better durability than untreated samples
5- (Muntohar, 2011)	Compressive strength	Lime	Rice husk ash	Specimens with 1:1 lime: rice hush addition showed improved compressive and flexural strength
6- (Arvind Kumar et al., 2006)	Compressive strength	-	Plain and crimped polyester fiber Coconut and sisal fiber	Fibers reinforced samples showed improved compressive strength
7- (Guettala, Abibsi, and Houari, 2006)	Durability, strength	Cement, lime, resin	-	Samples stabilized with 5% cement and resin showed better durability

Table 2.3: Standards for earth construction in each country guidelines/codes

S. No.	Country	Relevant guideline/code
1	Spain	AENOR: Spanish Association for Standardization and Certification 2008 (UNE 41410:2008-12-10)
2	France	AFNOR: 2001 (AFNOR:XP P13-901)
3	United States	ASTM International: 2010 – Standard Guide for Design of Earthen Wall Building Systems (ASTMD 559-57)
4	New Mexico	State Regulations "Rammed Earth and Adobe Based Construction" – 1999 (CID: NMAC 1474)
5	Australia	Australian Regulations "Bulletin 5" – 1952 by CSIRO Replaced by "Australian Earth Building Handbook" 2002
6	Turkey	Adobe Blocks and Production Methods (TS 2514)
7	Germany	DIN 18945 Earth Masonry – Definitions, Requirements, Testing Procedures DIN 18946 Earth Masonry Mortars – Definitions, Requirements, Testing Procedures DIN 18947 Earth Plaster Mortars – Definitions, Requirements, Testing Procedures

Thermal Properties

In this section, thermal properties of adobe are presented based on the investigation in the literature, summarized in Table 2.4. Kafesçioğlu (1980) carried out several experiments for the improvement of adobe. The abundant and widespread use of gypsum in Turkey and the fact that the earth-gypsum-lime mixture is known and used as plaster mortar in Anatolia has revealed the idea that the earth can be stabilized with gypsum. In the research carried out in 1980 as a TÜBİTAK MAG 505 project at ITU Faculty of Architecture, properties of mixture of gypsum and adobe were investigated, and a test house was built. The test house is still in service on the Istanbul Technical University in Ayazağa campus in İstanbul. For wall material to be produced in the traditional adobe form, the structure of (earth in granulometry) 10% gypsum added mixture gives the best results. According to the results of the experiment, the normal unit weight for adobe is 1,70-1,80 kg / lt, while the unit weight for gypsum-added adobe is 1.45 kg / lt. Shrinkage of 5% in normal adobe, and 1.8% in plaster added have been observed. Results showed that the gypsum added adobe has a heat conductivity of 0.40 W/mK. Its heat capacity was 1250 J/kgK when the density was 1500 kg/m^3.

Another research was conduted in Peru. Different adobes coming from several Peruvian regions have been performed in terms of experimental and numerical characterizations (Ginés et al., 2017). Effective thermal conductivity and heat capacity were measured by means of a hot parallel-plate method. Density was estimated using a pycnometer and measuring the physical dimensions and mass of each sample. Results showed that the heat conductivity varied from 0.25 W/mK to 0.33 W/mK, and the heat capacity range was 460 J/kgK – 620 J/kgK, shown in Table 2.4.

Table 2.4. Thermal properties of adobe in literature

Reference	**Conductivity [W/mK]**	**Specific Heat [J/kgK]**	**Density [kg/m^3]**
(Kafesçioğlu, 1980)	0.40	1250	1500
(Obafemi and Kurt, 2016)	-	1260	1540
(Ginés et al., 2017)	0.25-0.33	460-620	-

2.2.2. Vertical Hollow Clay Brick as a Building Material

Clay bricks or blocks made with hollow cores are commonly used as a construction material for building envelope walls for its good thermal characteristics (Roberto and Paolo, 2014). It is easy to use due to its reduced weight with its hollow core.

Clay is a plastic material that includes water captured in its structure. When water is added, the plasticity of the clay allows the bricks to be shaped and molded. After drying and firing process, clay loses its plasticity and turns into a hard and crunchy material (Rguibi, Baraka, and Khaldoun, 2018). After preparing a mixture made of 70% of clay and 30% of sand, an appropriate amount of water is added to the mixture to make it viscoelastic. Following that, the mixture is shaped, dried then fired. The main advantage of fired clay material from unfired material is its strength. There is also research regarding clay brick strength. These are explained in the following sections.

Production of Brick

Clay brick production process generally involves forming of clay into rectangular blocks of standard size, followed by firing to temperatures ranging from 900 - 1200°C. It is made of clay or shale and after it is given a desired shape it is dried and fired into a durable ceramic product. For hollow brick, the brick machines are used. Horizontally hollow generated block is then divided multiple times according to machine capacity to create hollow clay brick.

Research for Clay Brick with Binding Materials

According to literature, for comparison of the quality of fired bricks; values of porosity, bulk density, water absorption, and linear drying shrinkage are used, according to Goel, Kalamdhad, and Agrawal (2018). The improvement in quality is investigated by using many binding materials such as fly ash, or kraft pulp (Bolattürk, 2006; Canbaz and Albayrak, 2014; Demir, Serhat Baspınar, and Orhan, 2005; Monteiro and Vieira, 2014; Naganathan, Subramaniam, and Mustapha, 2012).

When fly ash is used in the production of bricks, it is observed that brick strength is reduced almost by 10% but carbonation is prevented with fly ash (Monteiro and Vieira, 2014). Perlite and diatomite are investigated in the production of clay brick and mechanical properties have been improved by using 20% diatomite (Bideci and Bideci, 2016). For a good insulation in bricks, fly ash, sand and lime were mixed in different proportions and used in brick production. This mixture is resulted with high heat insulation and a light brick (Sütçü, Alptekin, Erdogmuş, Er, and Gencel, 2015)

Thermal Properties

The way of improving thermal properties of hollow clay brick have been researched in various studies such as varying porosity or geometric configurations. These studies suggest that thermal conductivity of bricks is associated with bulk density. This suggests that higher porosity means increased thermal insulation. However, bulk density alone is not a significant factor for thermal conductivity of materials especially for bricks. Microstructural variables such as open, closed and total porosity, mean pore size, pore selection are all related to the thermal conductivity statistically according to the serial tests made by researcher. (Dondi, Mazzanti, Principi, Raimondo, and Zanarini, 2004). Table 2.5 shows the thermal properties of hollow clay bricks examined in literature.

Table 2.5. Thermal properties of vertical hollow clay brick in literature

Reference	**Conductivity [W/mK]**	**Specific Heat [J/kgK]**	**Density [kg/m^3]**
(Ulu, 2018)	0.45	850	1000
(Arsenovic, Lalic, and Radojevic, 2010)	0.35 - 0.52	-	800
(Arsenovic et al., 2010)	0.52 - 0.76	-	1600

2.2.3. Limestone as a Building Material

Limestone, which is situated in karst landscape, is the sedimentary rock soluble in water similar to mineral salt or chalk. It consists of calcium carbonate ($CaCO_3$) and crystalline minerals. Crystalline limestone is composed of minerals of calcite and aragonite. It is known that limestone take their shapes and are formed by inorganic chemical sedimentation with the help of organic processes and organisms (Küçükkaya, 2003). It is used in lots of sectors such as medicine, food, cosmetics and construction. In the construction sector, limestone can be used directly by cutting. In addition, it can be used as a mortar and plaster since it is beneficial to the lime content in clay.

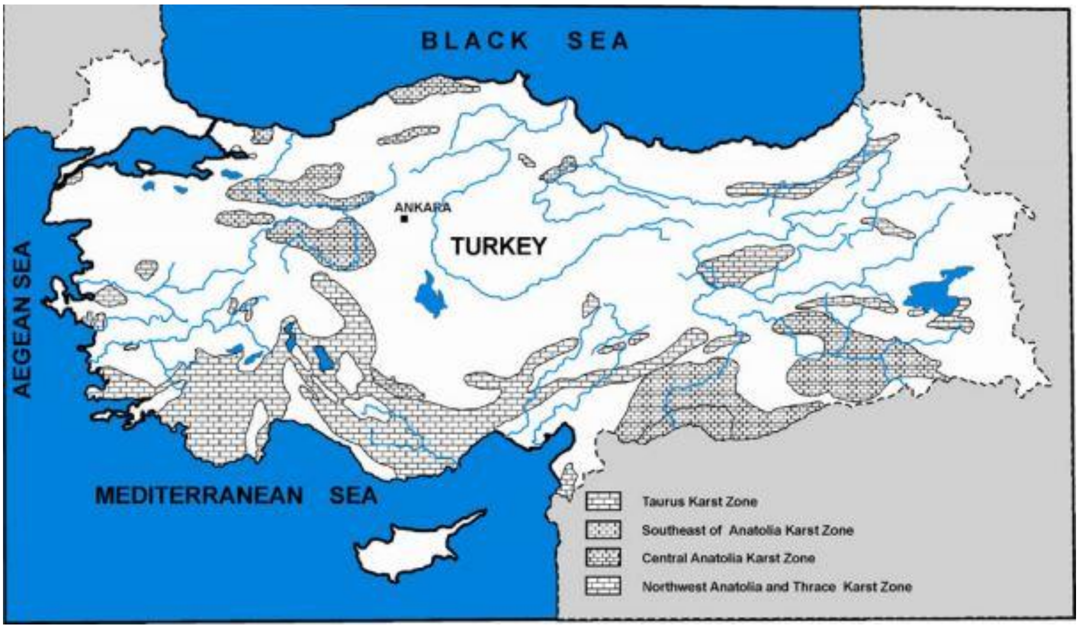


Figure 2.2. Karst zones in Turkey
(Source: Baba and Tayfur, 2011)

Karst landscape is widely distributed throughout Turkey as shown in Figure 2.2. Limestone, therefore, has been used since the beginning of history for monuments and for constructions because of its high thermal properties and the fact that it can be cut easily.

Limestone as a building material

Limestone is used as a construction material in many areas such as concrete aggregate, highway construction, building façade stone, etc. Its usage in buildings is generally as a block in masonry due to its high strength and high insulation properties (Agan, 2016). It can easily be sharpened with a hand-held saw or a rock-cutting machine for its high porosity, and it is suitable for building masonry walls (Smith B, 2010). Limestone has been widely used in historic structures. However, limestone tends to absorb water, and this has an impact upon its physical and mechanical properties. Water absorption is triggered by precipitation and by surface runoff.

Thermal Properties

Thermal properties of limestone founded in investigated literature are shown in

Table 2.6. In Gaziantep region, limestone was investigated and its thermal conductivity was found to have a range from 0.926 W/mK to 2.968 W/mK (Çanakci, Demirboğa, Burhan Karakoç, and Şirin, 2007). Thermal conductivity of limestone samples increased with increasing density for oven dried, partially saturated and fully saturated conditions. Thermal conductivity was between 0.926 W/mK and 2.516 W/mK for oven dried, 1.790 W/mK and 2.821 W/mK for partially saturated and 1.973 W/mK and 2.968 W/mK for fully saturated densities. Another research for limestone was conducted in Şanlıurfa. The results for thermal conductivity and specific heat were found to be approximately 1.42 W/mK and 1.041 J/kgK, respectively. Apart from these results, thermal conductivity, specific heat and density of limestone are indicated in dynamic simulation tool DesignBuilder's library as 1.1 W/mK, 1000 J/kgK and 1800 kg/m^3, respectively.

Table 2.6. Thermal properties of limestone in literature

Reference	**Conductivity [W/mK]**	**Specific Heat [J/kgK]**	**Density [kg/m^3]**
(DB, 2019)	1.1	1000	1800
(Turgut, Yeşilnacar, and Bulut, 2008)	1.42 ± 0.09	1.041 ± 0.94	-
(Çanakci et al., 2007)	0.93 - 2.97	-	-

2.2.4. Hempcrete as a Building material

Hemp named cannabis sativa is a plant that grows mostly in the northern hemisphere in the same manner as all plants. Hemp can be used both as a wall and insulation material. Shive, also known as hurd shown in Figure 2.3, is the wood part of hemp with a lower density and a porous structure that provides low thermal conductivity and less mass, compared to wood used as a building material especially on the walls.

Before its utilization, hemp is exposed to a three-step process. This process includes cutting, drying under the sun for two weeks and decortication. This process has been aimed at reaching the layer of hemp made of fibers inside the bast and shive, which is the inner part of the bast. Hemp does not involve protein in itself therefore, the insects or moths do not attack it (Benfratello et al., 2013).

Figure 2.3. Hemp stalk showing the fiber and core
(Source: Leskard, 2015)

The most common hemp-based material is hemp-concrete, shortly hempcrete. It is formed with hemp shives and a binder such as cement or lime (Piot et al., 2017). Hempcrete has good vapor permeability, it can easily absorb or release water by means of their structure of open pore. These features provide control of better relative humidity conditions for indoor environment of the building. Due to the presence of the practice of lime, hemp shives mineralize slowly so fungi or rot risk is reduced (Arrigoni et al., 2017; Walker and Pavía, 2014).

Production of Block

Hempcrete is formed with hemp shives. Hemp shives, binder (generally lime), and water is precisely dosed and mixed. Then this mixture is moulded into a block using a special press that creates blocks between 6 and 30 centimetres wide. After that hempcrete is shaped, they are taken for air drying that takes between 6 and 10 weeks depending on the width of the blocks produced. Once this period is over, the block is ready to use.

Thermal Properties

The factors that affect hempcrete performance and properties are: 1) The binder type and content, 2) the length and quality of the hemp shives 3) ratio in the mixtures and 4) production technology. According to these factors, hempcrete can be used as a filling material in infill walls, prefabricated panels, roof or floor insulation material or plaster (Arrigoni et al., 2017; Ingrao et al., 2015)

Collet and Prétot (2014) investigated the effects of hempcrete production methods on thermal conductivity. Hempcrete specimens which involve lime as a binder were produced as ones which are moulded using commercial fibered hemp shive with 1:2 hemp-shiv ratio, ones which are sprayed using commercial defibered hemp shive with the 1:2 hemp-shive ratio, and ones which are precast using defibered hemp shive with the 13:20 hemp-shive ratio. In Table 2.7, 3rd, 4th and 5th references are the results regarding sprayed hempcrete specimens. The research concluded that hemp shive type (fibered or defibered) affects thermal conductivity.

Benfratello et al. (2013) examine both hemps alone and bio composite materials. For the first analysis they used only the bast for preparing the specimens and for the second, they used shives with the inorganic chemicals. For the first specimens' group thermal conductivity results range from 0.077 W/mK to 0.0830 W/mK while density ranges from 212 kg/m^3 to 237 kg/m^3. This first group is generally used as insulation material because of their thickness and density. The second group of specimens composed of shives. Shives were chopped to granulometry in the range of 2 mm to 8 mm for homogeneous mixture and hydraulic lime was used for mixture. The results regarding thermal conductivity shows that increase in weight in shives causes thermal conductivity to increase as well. Thermal conductivity results are in the range of 0.085 W/mK - 0.14 W/mK while the density range is from 370 kg/m^3 to 610 kg/m^3.

Fernea et al. (2018) investigated thermal conductivity and sound absorption properties of hemp, binder and volcanic rocks mixtures. The study prepared mixtures of white cement, gypsum, perlite, vermiculite and water to create six specimens. According to study, the specimen with cement and vermiculite has good sound absorption; specimen with gypsum and perlite shows better thermal properties; specimen with cement and vermiculite shows the best performance against bending; specimen with cement, perlite and vermiculite is selected for compressive strength. The thermal properties examined in this section is tabularized and shown in Table 2.7.

Table 2.7. Thermal properties of hempcrete in literature

Reference	**Conductivity [W/mK]**	**Specific Heat [J/kgK]**	**Density [kg/m³]**
(Šedivý, 2019)	0.09	1600	330
(Nováková, 2018; Šedivý, 2019)	0.12	Not Reported	390 (light)
(Collet and Prétot, 2014)	0.14	Not Reported	425 (medium)
(Collet and Prétot, 2014)	0.15	Not Reported	460 (heavy)
(Collet and Prétot, 2014)	0.089	Not Reported	377 (light)
(Benfratello et al., 2013)	0.14	Not Reported	603 (heavy)

2.2.5. Straw Bale as a Building Material

Straw is a secondary product of growing crop. Straw has been used generally as a construction material derived from wheat cultivation. It is used for garages, small offices and generally one storey buildings such as summer houses and office buildings. It is used in Canada, the USA, Mexico, Australia, Europe and Asia. The first usage of straw in buildings was in mixtures of adobe bricks, for the purposes of stabilization, durableness and adding tensile strength. In the early part of nineteenth century, straw bales were used as a building material (Binici, Aksogan, and Shah, 2005).

In the study conducted by Ashour, Georg, and Wu (2011), in a test house in Germany constructed with straw bale, compressive strength, moisture content, thermal stability of bales, and pH values were investigated. The results show that the test house with straw bale provides hygienic living conditions according to relative humidity. Straw bale can be used for both load-bearing walls and infilling. According to the research of Marian (2010), straw bale building projects are mainly in Canada especially in Toronto where, with the purpose of encouraging this building material, large real estate projects were launched. In England, in LILAC (2013) project, straw bales were used as loadbearing walls as shown in Figure 2.4. However especially, strawbales are mostly used as infill materials in buildings.

Figure 2.4. The strawbale construction, Lilac project, UK, 2013
(Source: LILAC, 2013)

Production of Walls with Straw Bales

Strawbale construction is used as a building method. It uses bales of straw (commonly wheat, rice, rye and oats straw) as structural wall elements. This construction technique has been dated back to the late 19th-century following the invention of mechanical baling machines in the USA (King, 2006). Following World War II, straw was used as compressed panels for walls and short-span roofs (Harries and Sharma, 2016).

Figure 2.5. Fabrication of prefabricated straw bale panels
(Source: Harries and Sharma, 2016)

Straw bale wall construction is generally formed of individual bales which are laid horizontally in walls as the lightweight masonry units. They are coated inside and outside for protection and additional strength using plasters. Generally, bales are used for stockbreeding with the size is 100x45x35 cm and weight of around 20 kg. They are settled into walling systems as a bale or as a prefabricated panel compressed under pressure in timber framing, shown Figure 2.5. Both forms provide excellent thermal insulation on external walls.

Thermal Properties

Physical properties of strawbale have been investigated by many researchers (Goodhew and Griffiths, 2005; Leonardo, Matteo, and Massimo, 2016; Marian, 2010; Shea, Wall, and Walker, 2013) The results change from 0.048 W/mK to 0.084 W/mK in thermal conductivity and from 60 kg/m^3 to 133 kg/m^3 for density. Thermal properties examined are tabularized and shown in Table 2.8.

Table 2.8. Thermal properties of straw bale in literature

Reference	Conductivity [W/mK]	Specific Heat [J/kgK]	Density [kg/m^3]
(Goodhew and Griffiths, 2005)	0.0670	600	60
(Marian, 2010)	0.053	Not Reported	76.6
(McCabe, 1993)	0.032-0.042	Not Reported	133
(McCabe, 1993)	0.20	1000	750
(Ashour, 2003)	0.0414-0.0486	Not Reported	Not Reported
(Christian, Desjarlais, and Stovall, 1998)	0.0570	Not Reported	81

2.2.6. Flax (Reused Wool) as a Thermal Insulation Material

Thermophilic, insulation materials for good performance have small closed pores (Barkauskas and Stankevičius, 2000). In this context, flax that is a bio-based material is selected as a thermal insulation material.

Flax is a plant that is cultivated for food and fiber in cooler regions climates, shown Figure 2.6. Flax can absorb CO_2 more than other plants such as tree. Mostly, flax is used as a thermal insulation material with its fiber parts. The fiber parts of flax are obtained by scutching stalk part, surrounded by a fine layer of bast.

Production of Wall Insulation with Flax

Recycled wool produced with flax is used for insulation batt. As a thermal insulation material, wool products that are made from flax fiber are reused materials. In Turkey, some firms collect flax and hemp wools which gathered wools undergone a process that involves washing and adding boron minerals for preventing infestation or moisture accumulation (Kubilay, 2019).

Figure 2.6. From flax to linen
(Source: Santry, 2019)

Thermal Properties

The thermal properties of flax as an insulation material is taken from the firm named Eci, is the Turkish company, which produces natural building materials in Akhisar, Turkey, shown Table 2.9 (Eci, 2019).

Table 2.9. Thermal properties of flax in literature

Reference	**Conductivity [W/mK]**	**Specific Heat [J/kgK]**	**Density [kg/m^3]**
(Eci, 2019)	0.038	1600	76.5

(a) (b)

Figure 2.7. Flax wools before mixture with boron mineral (a), end-product (b) (Photography: Ekin G. Yöney, (2019), Location: Eci Company-Akhisar/Manisa)

2.3. Literature on Materials Applied Different Wall Orientation

Energy conservation has become a prominent worldwide energy policy especially, after energy crises of 1973 affected many countries. This is especially significant for Turkey since it imports the vast majority of the energy it uses. Energy utilization is quickly expanding because of the population increase and urbanization. Turkey's energy utilization has expanded annually by 4.4%. It is a reality that Turkey isn't extremely wealthy regarding energy assets. 60-65% of the energy prerequisite is imported from outside. Furthermore, this needs to increase roughly 4.4% each year (Demirbaş, 2001). Owing to the very restricted indigenous energy assets, Turkey needs to import about 52% of the energy from abroad to address its issues (Bolattürk, 2006). Turkey's last utilization of essential energy is assessed to be 130 mtoe (million tons of oil equivalent) in 2005, 171 mtoe in 2010 and 298 mtoe in 2020. Then again, in 1999, indigenous energy creation met 36% of the all-out essential energy request and will most likely meet 28% in 2010 and 24% in 2020 (Hepbaşlı and Özalp, 2003).

A significant portion of Turkey's energy resources is spent on heating and cooling buildings to ensure thermal comfort. The limitation of available energy sources and environmental pollution caused by energy consumption made energy conservation compulsory. Energy conservation can be achieved by reducing energy consumption in buildings. One way to achieve this is to investigate exterior walls of buildings. There are a couple of approaches to lessen heat loss, one of which is to apply an optimum insulation material to external walls. Walls and rooftop protection can create energy investment funds up to 77% (Mohsen and Akash, 2001). The other way is to investigate the optimum material in terms of orientation for external wall. Researches made regarding orientation are shown in Table 2.10.

Table 2.10. Literature on materials applied on different wall orientations (Y: Yes)

Literature	**Orientation**	**Climate**	**Thickness**	**Wall Material**
1- (Özel and Pıhtılı, 2007)	Y	Three different climates	Searched	Constant
2- (Yu, Yang, Tian, and Liao, 2009)	Y	Constant	Searched	Five Insulation Materials
3- (Özel, 2011)	Y	Constant	Searched	Two Insulation Materials
4- (Dongmei, Mingyin, Shiming, and Zhongping, 2012)	Y	Three different climates	Searched	Constant
5- (Kaynaklı, Özdemir, and Karamangil, 2012)	Y	Constant	Searched	Constant
6- (Kameni, Ricciardi, Reiter, and Yvon, 2017)	Y	Two different climates	Searched	Two Different wall structure

Özel and Pıhtılı (2007) considered externally insulated walls, and numerically examined the effect of wall orientation on insulation thickness in terms of gains and losses. The research was conducted for three different insulation materials in different locations Elazig, Izmir and Kars in Turkey. As a result, it was found that the insulation applied to the walls in the east and west orientations should be thicker than the insulation of the south facing walls. Yu et al. (2009) searched life cycle cost for five insulation materials in terms of climate, wall orientation, surface colours and optimum thickness.

Four cities, Shanghai, Changsha, Shaoguan and Chengdu were chosen to represent A, B, C and D subzones of hot summer and cold winter climate in China. Expanded polystyrene, extruded polystyrene, foamed polyurethane, perlite and foamed polyvinyl chloride were invesitgated on residential façades. Solar-air cooling, heating degree-days analysis, P1 (the life cycle energy model related to ratio of market discount) and P2 (the ratio of life cycle expenses incurred) economic models were used. Afterwards, life cycle costs, life cycle savings and restitution periods were determined dependent on life cycle cost investigation. Thinking about various orientation, surface colours, insulation materials and climates, optimum thicknesses of five insulation materials shift from 0.053 to 0.236 m, and the recompense time frames change from 1.9 to 4.7 years over a lifetime of 20 years. The most extreme life cycle savings are 54.4 $/m^2$ in Shanghai, 54.8 $/m^2$ in Changsha and 41.5 $/m^2$ in Shaoguan (with a deep-coloured north east external wall), and 39.0 $/m^2$ in Chengdu (with a light-colored northwest external wall).

Özel (2011) performed a comprehensive financial examination of the optimum thickness of insulation materials for different external wall orientation. The total cooling and heating consumption of façades were determined by use of implicit finite-difference method taking into account steady periodic conditions under the climatic conditions of Elazıg, Turkey. A financial model including expenses for insulation material and estimation of energy utilization cost over a lifetime of 10 years was utilized to determine the optimum insulation thickness, energy investment funds and compensation time for all external wall orientations. Extruded polystyrene and polyurethane have been considered as an insulation material in the investigation. Subsequently, the optimum insulation thickness of extruded polystyrene was observed to be 5.5 cm for south oriented wall and 6 cm for north, east and west oriented walls. Also, the least estimation of the optimum insulation thickness and energy investment funds were gotten for the south oriented wall while recompense period was practically same for all orientations.

Dongmei et al. (2012) investigated the impacts of external wall insulation thickness on annual cooling and heating energy utilization under various Chinese climates. A model space having four different exterior zones confronting four unique orientations for a place of business was chosen and the settings of the model space depicted. Annual cooling and heating energy utilization for the four different exterior zones with different external wall insulation thicknesses under three unique atmospheres in China, Guangzhou, Shanghai and Beijing, are accounted for. The outcomes suggested that energy efficiency improved dramatically when external wall insulation thickness was increased in outside zones confronting all orientations under Beijing's climate, since heating energy use was dominant and can be significantly reduced with the increase in insulation thickness. Under Shanghai's climate, increasing outside zone insulation thickness to over 26 mm would not lessen the aggregate of annual heating and cooling energy utilization in the south-facing exterior zone, however, would help save energy in outside zones confronting the other three orientations. For every single outside zone under Guangzhou's climate, it was, nonetheless, barely conceivable to lessen the total annual heating and cooling energy utilization by increasing the external wall insulation thickness.

Kaynaklı et al. (2012) focused on the optimization of the thermal insulation thickness applied to external walls of a building, considering the orientations of the walls. Different from similar studies in the literature, solar radiation on the exterior walls were considered, and optimum thermal insulation thicknesses have been resolved for various orientations of a building's external walls (east, west, north, south). The life cycle cost investigation, which takes into account lifetime, discount and expansion rates, and depends on the degree-days (DD) has been utilized. Thus, while the all-out DDs dependent on just the outside air temperature data is 1827, the complete DDs considering solar radiation are 1633, 1628, 1719 and 1535 for east-, west-, north-, and south-facing vertical surfaces, respectively. The optimum insulation thicknesses for these surfaces have been determined as 4.8 cm, 4.8 cm, 5.2 cm and 4.3 cm, respectively.

Kameni et al. (2017) explored the ideal insulation thickness, energy savings, and recompense period for buildings in Yaounde and Garoua, situated in two climatic regions in Cameroon. The financial model involved the cost of insulation material and the current value estimation of energy utilization ,and the expenses over a lifetime of 22 years. As insulation material extruded polystyrene was picked and utilized for two common wall constructions: Concrete block (HCB) and compressed stabilized earth block (CSEB). The cooling losses and level of radiation blocked were determined for each wall orientation. It was discovered that the west-and east-facing walls are unfavourable in the cooling season. While wall orientation significantly affected the optimum insulation thickness, it had an even more significant impact on energy expenses. In Yaounde, representing the equatorial climate, for south orientation, the optimum insulation thickness was found to be 0.08 m providing an energy savings of 51.69 $\$/m^2$. In Garoua which has a tropical climate, for north orientation, the optimum insulation thickness was determined to be 0.11 m resulting in an energy savings of 97.82 $/m^2.

CHAPTER 3

CASE STUDIES IN MUĞLA AND KONYA

3.1. Case Building in Muğla

3.1.1. Case Information and Location

The selected case building is one of the guest houses situated in Pastoral Valley Eco Farm (PVEF), Yanıklar, Fethiye, Muğla-Turkey, 18 km far from the centre of Fethiye, shown in Figure 3.1 and Figure 3.2. The PVEF was established in 1999 by the architect Ahmet Kizen on 43 decare of land for ecological tourism purposes. PVEF is laid alongside the Kargı River and Red pine Forest with the distance to the sea of approximately 3.4 km.

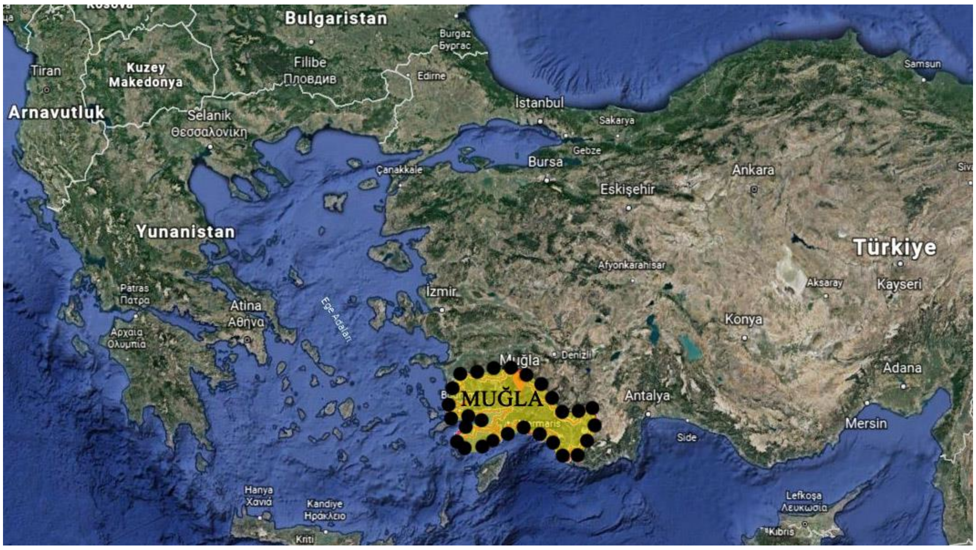


Figure 3.1. Location of case building in Fethiye, Muğla-Turkey
(Source: Google Earth, 2019)

The farm includes more than 900 fruit trees such as mandarin, olive, date palm, plum, peach and others. It has also a greenhouse, funded by the South Aegean Development Agency for growing seedling and vegetables, poultry house for chickens, stable for goats, two halls made up of wood and adobe for concert, yoga and meditation.

All buildings in the farm are constructed with adobe, stone or wood surrounded with orchard and pine forests. The site plan schema of PVEF is indicated in Figure 3.3.

Case building’s orientation is 328^{o} to the North according to main entrance of the case building, located at 36^{o}43’52’’ latitude and 29^{o}03’16’’ longitude in coordinates with the altitude of 48-meter.

Figure 3.2. PVEF in Yanıklar village
(Source: Google Earth, 2019)

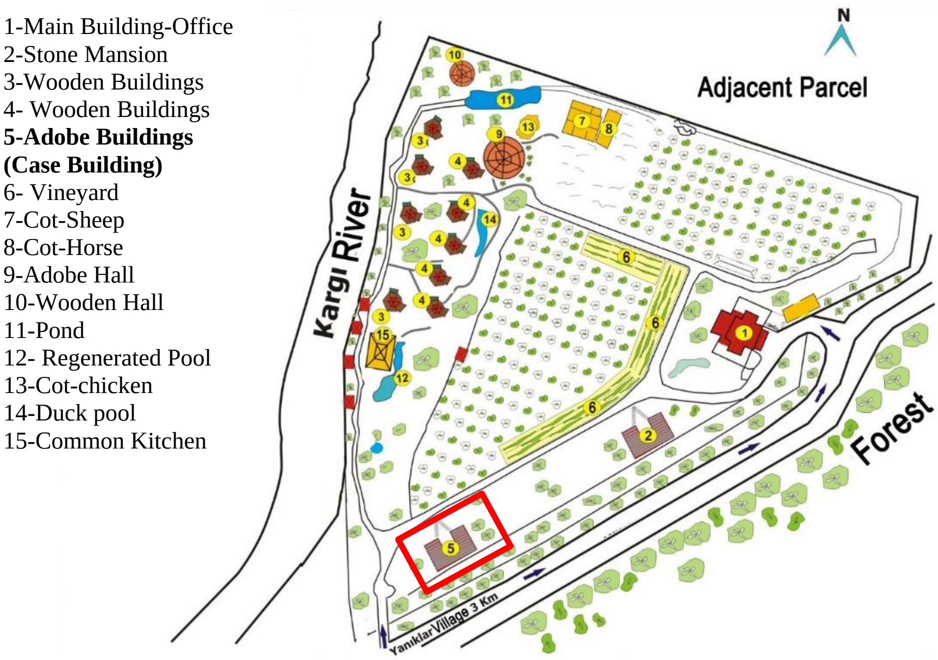


Figure 3.3. Plan schema of PVEF and case building indicated within red rectangle
(Source: Kizen, 2017b)

3.1.2. Building Component and Technique of Case Building

The case building is 61 m^2. The general view is indicated in Figure 3.4. As can be seen in the plan drawings in Figure 3.5, it has two bedrooms, one bathroom and one hall (sometimes used as a bedroom) with the kitchen. The adjacent building has with the same plan schema. The building specifications, specific to case building house, are indicated in Table 3.1.

Figure 3.4. Northeast view of the case building
(Photography: Ekin G. Yöney, (2019), Location: Fethiye, Muğla)

Table 3.1. Building specifications of the case building in Muğla

Feature	Value
Floor area (m^2)	61
Ceiling height in the lowest point (m)	2,5
Ceiling height in the highest point (m)	3,6
Volume (m^3)	180
Surface area of the façades (m^2)	100
Roof area (m^2)	66
Glazing area (m^2)	7.2
Glazing ratio (%)	0.072

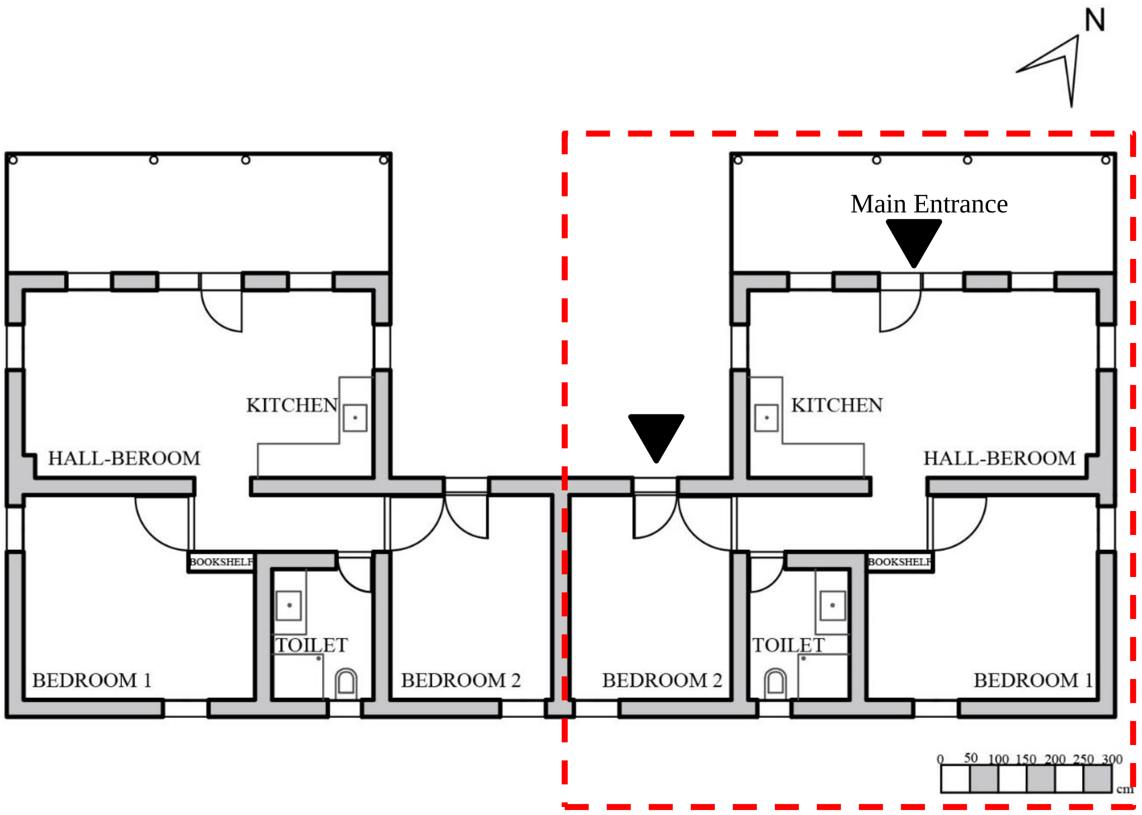
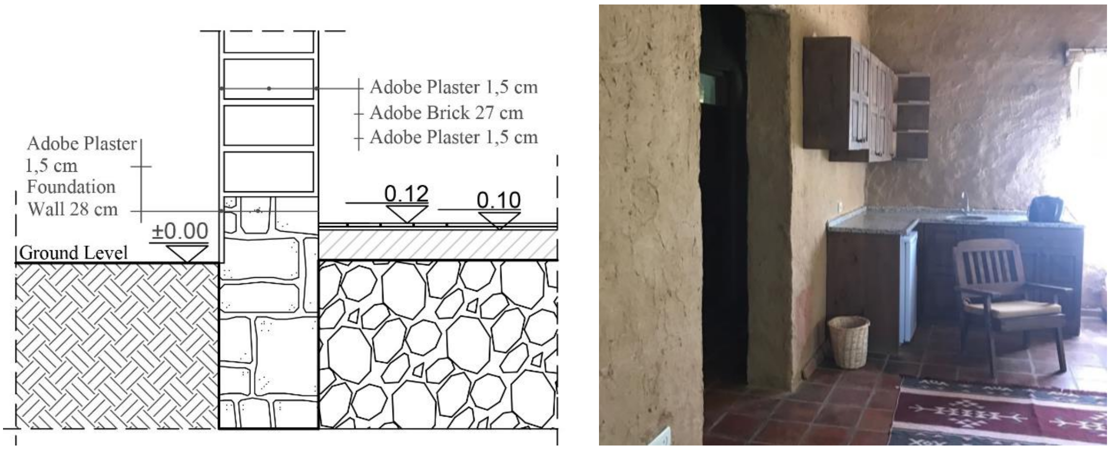


Figure 3.5. Plan of the case building study in Fethiye, Mugla

3.1.2.1. Exterior and Interior Walls

According to the building survey and interview with the owner of the case building, it was seen that all exterior and interior walls of the case building were comprised of adobe bricks. The thickness of all exterior and interior walls is the same of 0.30-meter. The adobe bricks are bonded with adobe mix based mortar as the adhesive material of approximately 2 cm horizontally and vertically. Adobe mix was also used as the plaster approximately 1 or 1,5 cm both inside and outside of the walls. According to Kizen (2017a), the thickness of adobe wall was planned as 30 cm (for more information see Chapter 4.4.).

The adobe bricks were prepared in Başmakçı, Afyonkarahisar, Turkey with three adobe masters, and transferred into Muğla for construction. The adobe brick has 25 cm in length 27 cm width and 12 cm in height as mother. According to Ahmet Kizen, the adobe-based building is high costly because of transportation expenses of adobe bricks from Afyonkarahisar to Fethiye (Kizen, 2017a). Thermal specifications of adobe wall are shown in Figure 4.2.



(a) (b)

Figure 3.6. Section of exterior wall (a) and outer wall from inside (b) (Photography: Ekin G. Yöney, (2019), Location: Fethiye, Muğla)

3.1.2.2. Foundation and Ground Floor

The foundation walls were laid under the adobe walls reaching 0.50-meter below the grade level. The walls and the base were constructed with stone subtracted from the quarry in chrome pit in Fethiye, Dalaman, Köyceğiz region, one of the six chrome pits in Turkey. The ground floor level is 0.10-meter over the garden level and composed of 0.50-meter hardcore with rubble stones, 0.10-meter concrete slab on grade and 2 cm mortar and terrakota tile.

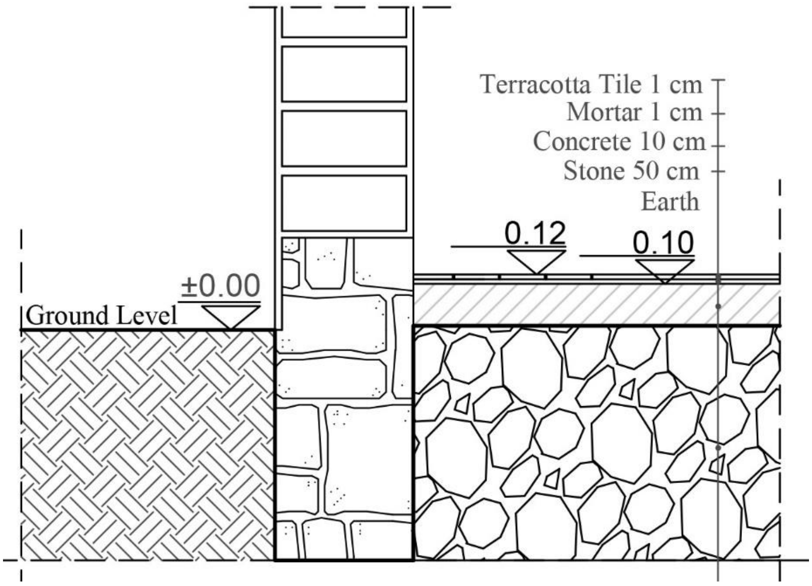
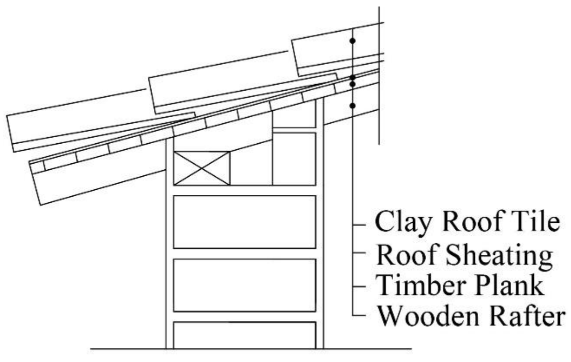


Figure 3.7. Section of ground floor in the case building

3.1.2.3. Roof

The building has the gable roof with wooden rafters covered with timber plank, roof sheathing for water insulation and clay roof tile from inside to outside, respectively (Figure 3.10). The highest point of the ceiling is 3.60 meters while the lowest point is 2.70 meters.

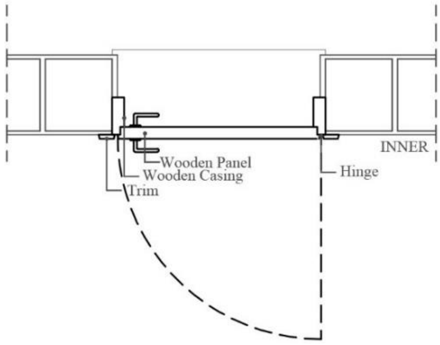


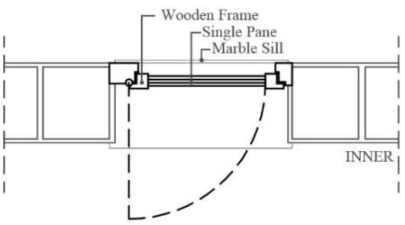
(a) (b)

Figure 3.8. Section of the roof (a) and downside view of the roof (b)
(Photography: Ekin G. Yöney, (2019), Location: Fethiye, Muğla)

3.1.2.4. Door and Windows

The case building has nine single pane windows, two external doors and three interior doors. All doors and windows frame were made of wood with the same connection details, produced by carpenter worked in PVEF. They are single glazing with simple pane. The windows and doors are covered up with the white cotton curtains. Detailed drawings of window and door are indicated in Figure 3.9 and Figure 3.10.





(a) (b)

Figure 3.9. Plan of the door (a) and window (b) of the case building

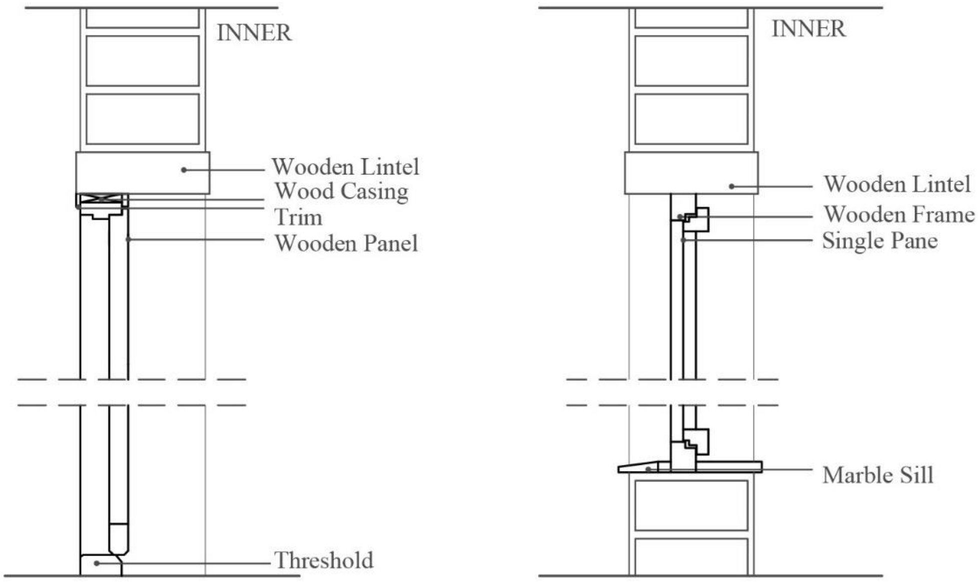


Figure 3.10. Section of the door (a) and window (b) of the case building

3.1.3. Occupancy Pattern, Heating, Cooling, Lighting, Electrical Equipment

The case building is a guest house rented for ecological tourism activities, for a family with four persons. It is heated with coal stove in winters. There is no electrical equipment for cooling. Every single space has a lamp, but the hall has two lamps. Every lamp is led type and six watts, which makes a total of 24 watts. The domestic hot water is provided by grid sourced water heater installed in bathroom. Otherwise, the building utilizes solar collector sourced hot water on the roof.

3.1.4. Microclimate

The climate data for Fethiye, PVEF is the Mediterranean climate, labelled with Csa, expressed with hot dry summer Mediterranean climate in the Köppen climate classification (Köppen, 2019).

The microclimate information specific to in case the case area in Fethiye, Muğla was generated by Meteonorm[1] software based on interpolation method from surrounded

[1] For Further information about Meteonorm software, see Chapter 4.3

meteorological stations (Meteotest, 2018). The presented data in Table 3.2 conveys that the microclimate of PVEF is very hot and humid.

Table 3.2. Monthly mean dry bulb temperatures, relative humidity wind direction and wind speed in PVEF

Muğla-PVEF	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Dry Bulb Temperature (°C)	8	8	10	14	20	24	27	30	25	16	11	9
Relative Humidity (%)	80	71	73	67	58	55	48	57	53	64	66	73
Wind Direction (°)	120	60	330	120	120	0	0	330	0	0	0	330
Wind Speed (m/s)	4	5	4	3	3	3	5	4	3	4	4	5

The annual mean outdoor temperature is 16.8°C. The highest temperatures are 30°C, 27°C and 25°C in August, July and September, respectively. For the coolest months, January, February and December are of 8°C, 8°C and 9°C, respectively.

The annual relative humidity is 63.8%. The highest relative humidity values are 80%, 73% and 71% in January, December and March, and February, respectively. The lowest relative humidity values are of July, September and May with 48%,53% and 58%, respectively.

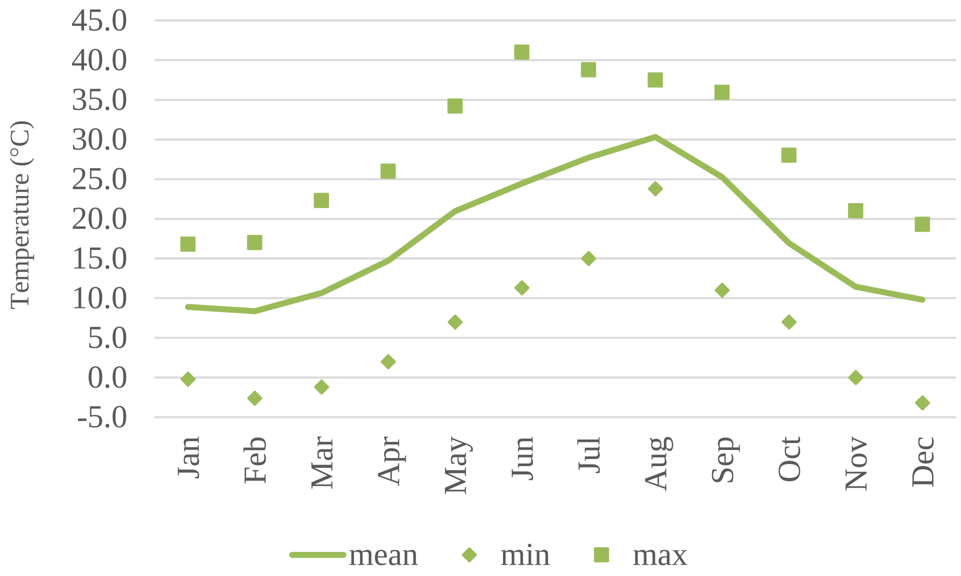


Figure 3.11. Monthly mean maximum, mean minimum and mean outdoor temperature values in PVEF

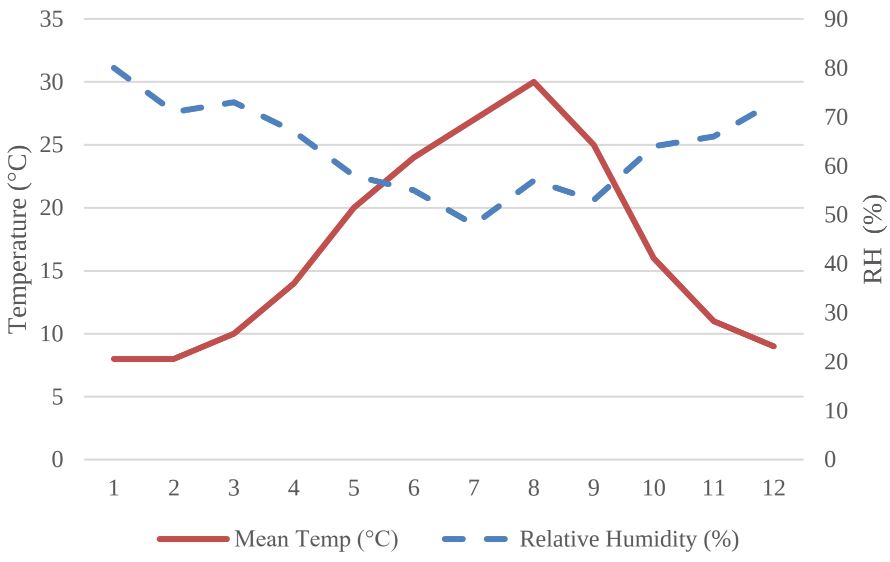


Figure 3.12. Outdoor temperature and relative humidity for PVEF

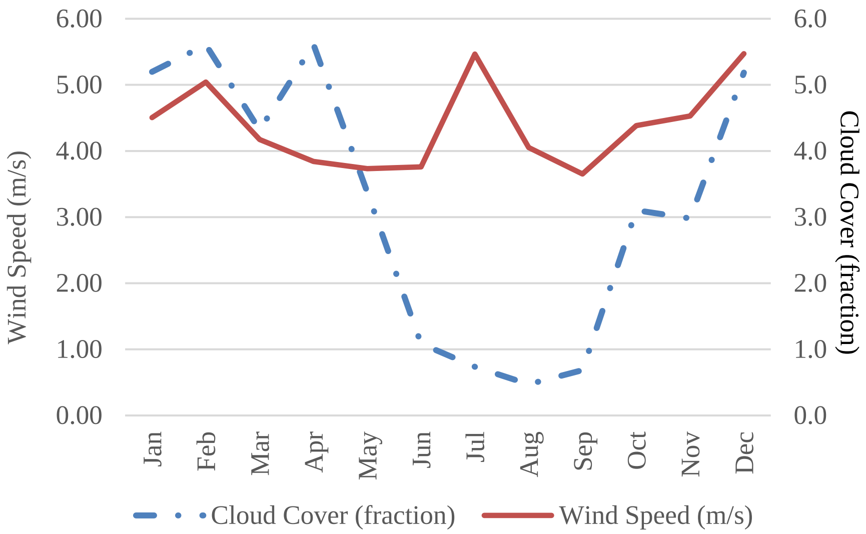


Figure 3.13. The relationship monthly mean wind speed and cloud cover in PVEF

The case building is located in a windy area, where the monthly mean wind speed does not drop less than 3m/s. The prevailing wind direction is the Northeast for Fethiye. Especially in winter season, when the Siberian cold air stream affects Anatolia, the wind direction in PVEF is determined by northern cold winds from December to February surrounded with mountains at an altitude of 2000 meters to the coastal plain.

Besides, there is an increase in the hot southern winds, especially in July with higher wind speed, due to the temperature difference between sea and mainland in the summer months (MGM, 2014). The clouds cover fraction has the lowest value from 1 to 0.47 from June to September.

3.2. Case building in Konya

3.2.1. The Case Information and Location

The selected case building is a house generally used in summer, situated Sonsuz Şükran Village (SŞV), Hüyük, Konya, 10 km far from the Hüyük, shown in Figure 3.14 and Figure 3.15. The Sonsuz Şükran village was established in 2010 by Mehmet Çiğdem who is the mayor of the Çavuş Village. The village was led by the founder Mehmet Taşdiken who is director and producer also the founder of French street project in Beyoğlu, Istanbul. The village has 25-30 house which used generally in summer.

Figure 3.14. Location of the province Konya, Turkey where the case building is located (Source: Google Earth, 2019)

In this area, both the village and the region taking into account the historical and social accumulation structure is realized. The activities, workshops and living spaces are created by competent artists both nationally and internationally. The village is considered as a project that will make a significant contribution to the cultural and economic life of the region. Therefore, the village is organized the festival named ‘Meeting on Gratitude to Anatolia’ every year since 2009 under the leadership of the Mehmet Taşdiken to convey the gratitude to Anatolia, which has raised many artists by her culture.

Figure 3.15. Sonsuz Şükran Village
(Source: Google Earth, 2019)

Figure 3.16. Plan schema of SŞV
(Source: Sonsuz Şükran, 2017)

The master plan of SŞV is SŞV has two ponds, one of them is in the centre of the village and other is in corner, with the distance to the Beyşehir lake of approximately 6 km, shown Figure 3.16.

Case building's orientation is 171° to the North according to main entrance of the case building, located at 37° 97' 56'' latitude and 31° 53' 54'' longitude in coordinates with the altitude of the 108-meter.

3.2.2. Building Component and Technique of Case Building

The case building is 82 m^2. As can be seen in the plan drawings in

Figure 3.18, it has two bedrooms, one bathroom, one hall (with a niche that is used as a working place) ,and a kitchen. The building specifications are indicated in Table 3.3.

Figure 3.17. Exterior view of the case building
(Photography: Ekin G. Yöney, (2019), Location: Hüyük, Konya)

Table 3.3. Building specifications of the case building in Konya

Feature	Value
Floor area (m^2)	82
Ceiling height in the lowest point (m)	2,7
Ceiling height in the highest point (m)	2,9
Volume (m^3)	170,1
Surface area of the façades (m^2)	100
Roof area (m^2)	82
Glazing area (m^2)	9,6
Glazing ratio (%)	0,096

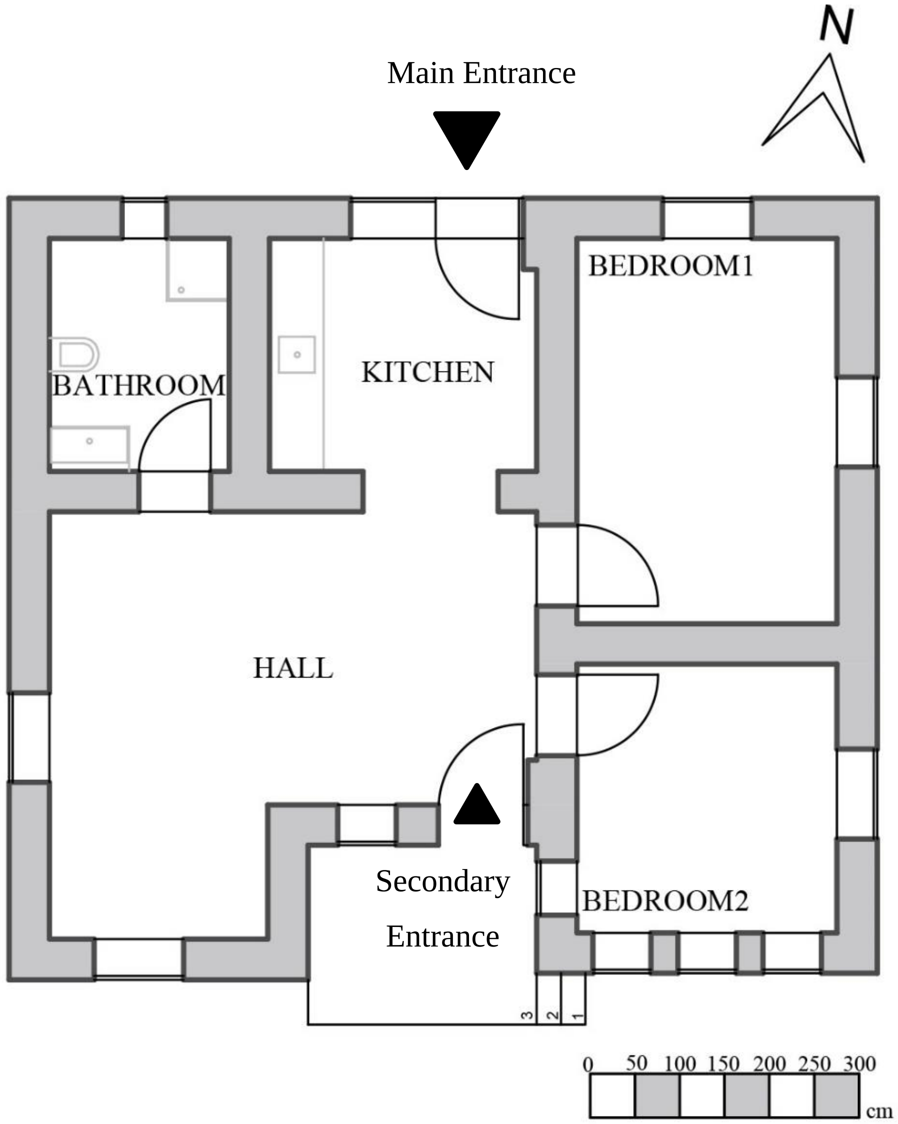


Figure 3.18. Plan of the case building in Hüyük, Konya

3.2.2.1. Exterior and Interior Walls

According to the building survey and interview with Craftman (2017), it was seen that all exterior and interior walls of the case building were comprised of adobe bricks. The thickness of all exterior and interior walls is the same of 0.50-meter. The adobe bricks are bonded with adobe mix based mortar as the adhesive material approximately 2 cm horizontally and vertically. Adobe mix was also used as the plaster approximately 1 or 1,5 cm both inside and outside of the walls (for more information see Chapter 4.4.). Figure 3.19 shows the section of the walls.

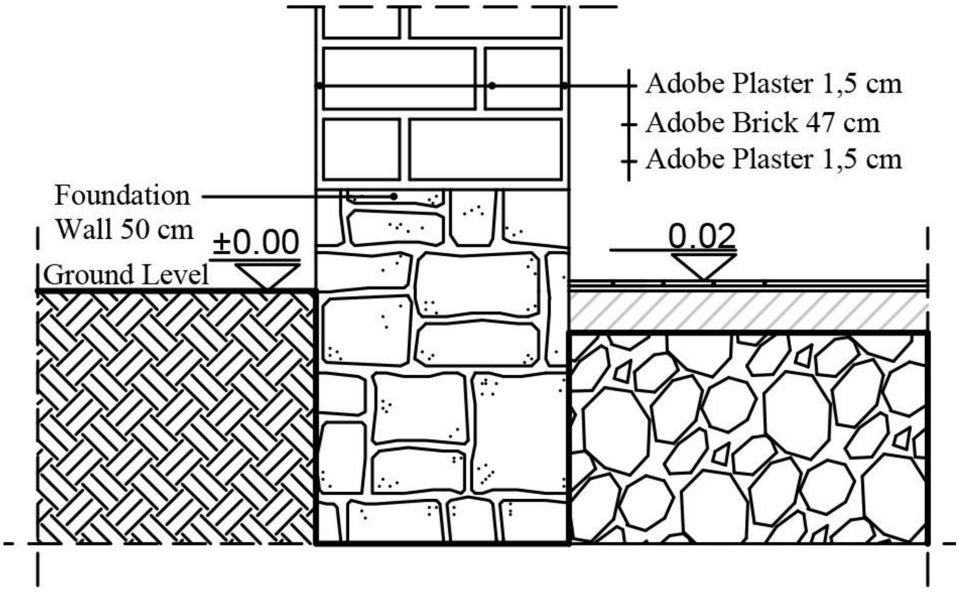


Figure 3.19. Section of the external wall of the case building

3.2.2.2. Foundation and Ground Floor

The foundation walls were laid under the adobe walls reaching 0.50-meter below the grade level. The walls and the base were constructed with stone collected from region. The ground floor level is 0.02-meter over the soil and composed of 0.40-meter hardcore with rubble stones, 0.10-meter hardcore with sand and pebble stones mix and concrete slab on grade and 2 cm wooden parquet. Figure 3.20 shows the section of the foundation.

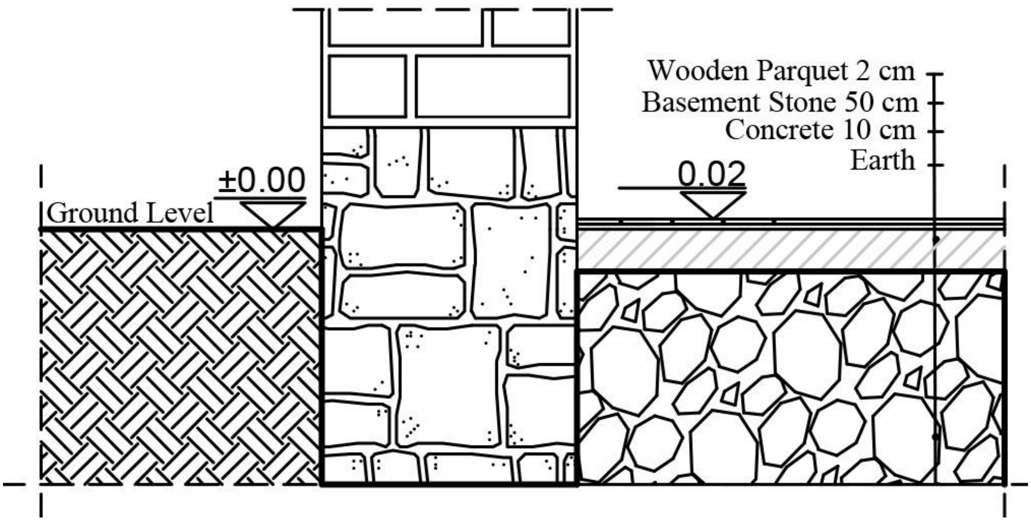
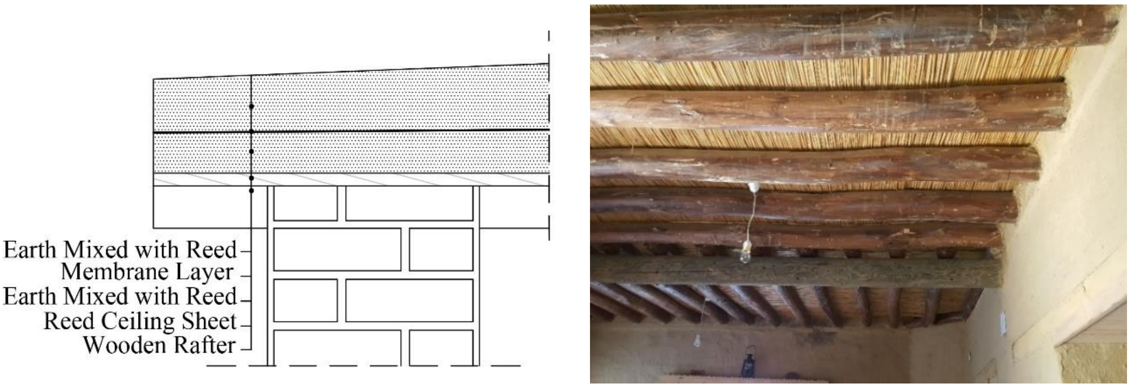


Figure 3.20. Section of the foundation of the case building

3.2.2.4. Roof

Firstly, the roof was constructed with the wooden rafter (poplar tree) with the diameter of 10 cm at 35 cm spacing. The reeds knitted by the women of that region was laid perpendicularly over the wooden rafter for aesthetic appearance of ceiling. Over these, 3,5 m length reed was laid with the same orientation of wooden rafter then the earth was put between and over the reed with the 3,5-m length for locking the reed, approximately 0.10-meter thickness. Over these, membrane was covered, and the roof has waited for two years for the earth and reed to interlock each other. Then the same process is repeated over the membrane. During these two processes, salt poured between the earth to keep the plant from growing and keep rigid. 30 or 40 tone earth was needed for roof. Figure 3.21 and Figure 3.23 shows the section and view of the roof.

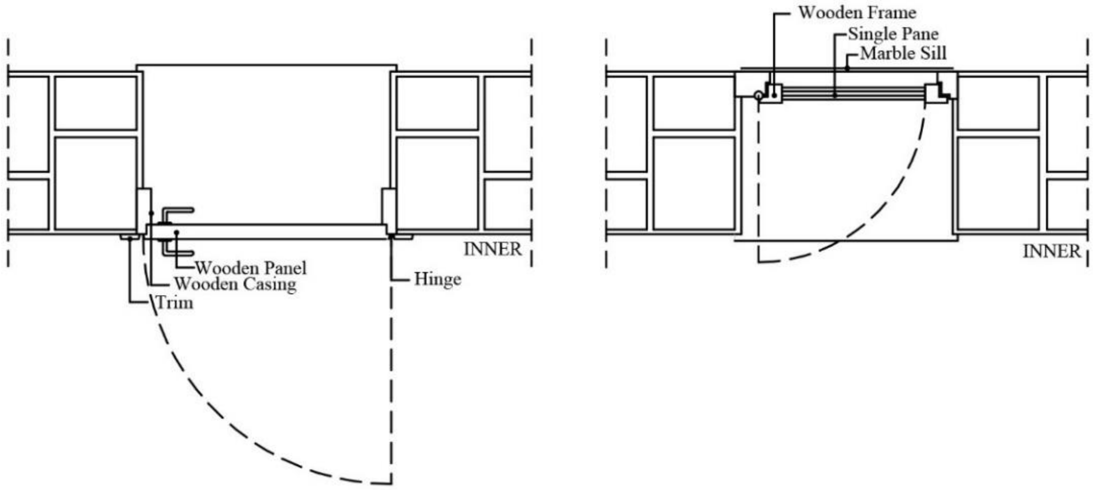


(a) (b)

Figure 3.21. Section of the roof (a) and view of the roof (b) of the case building (Photography: Ekin G. Yöney, (2019), Location: Fethiye, Muğla)

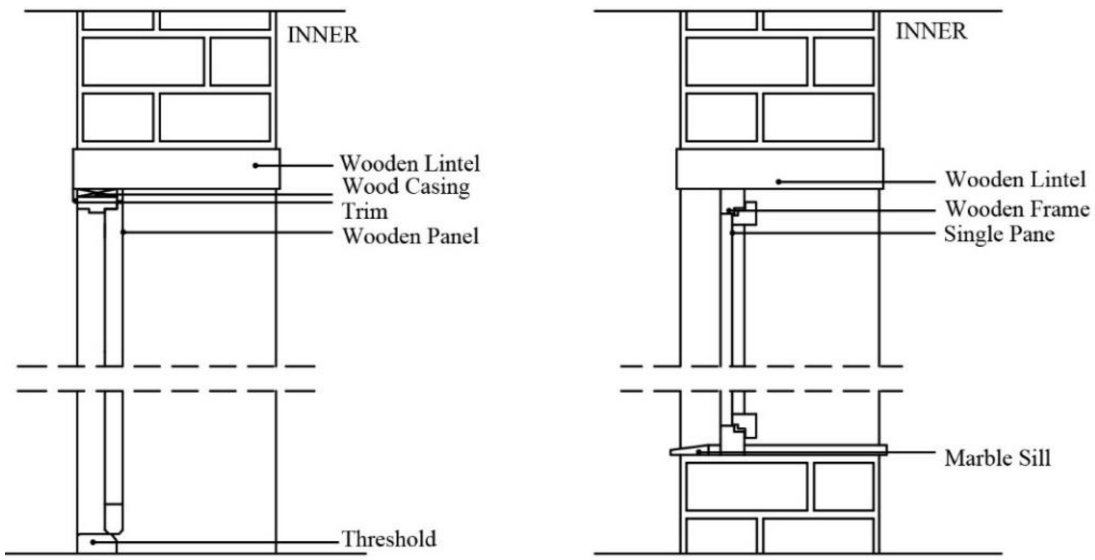
3.2.2.3. Door and Windows

The case building has twelve single pane windows, two external doors and three interior doors. All doors and windows frame were made of wood and use the same connection details and they are single glazing with simple pane. The windows and doors are covered up with the white cotton curtains. Detailed drawings of window and door are indicated in Figure 3.22 and Figure 3.23.



(a) (b)

Figure 3.22. Plan of the door (s) and window (b) of the case building



(a) (b)

Figure 3.23. Section of the door (a) and window (b) of the case building

3.2.3. Occupancy Pattern, Heating, Cooling, Lighting, Electrical Equipment

The case building has never been used in winter season. In the summer season, it is not cooled by the any electrical equipment. It has a water heater for getting the hot water. It has also the lamp every single space, but the hall has three lamps. Every lamp is led and six watts, totally 36 watts.

3.2.4. Microclimate

The climate data for Konya, SSV is continental climate, labelled with Csb, expressed as a cool dry summer Mediterranean climate in the Köppen climate classification (Köppen, 2019).

The microclimate information specific to in case the case area in Fethiye, Muğla was generated by Meteonorm[2] software based on interpolation method from surrounded meteorological stations (Meteotest, 2018). The Table 3.4 presents the data convey that the microclimate of SŞV is cool and dry.

Table 3.4. Monthly mean dry bulb temperatures, relative humidity wind direction and wind speed in SŞV

Konya-SŞV	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Dry Bulb Temperature (°C)	0	1	5	10	15	19	23	25	20	11	6	2
Relative Humidity (%)	74	74	68	65	64	55	46	44	44	57	69	75
Wind Direction (°)	60	50	10	50	30	20	30	340	0	20	20	30
Wind Speed (m/s)	5	6	5	4	4	4	5	5	5	4	5	5

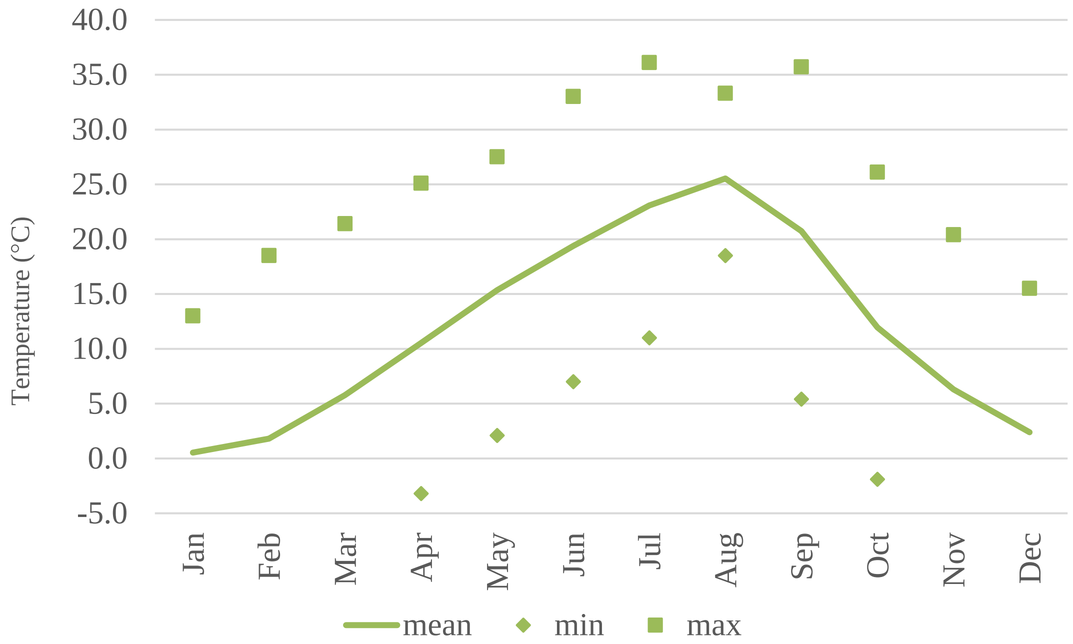


Figure 3.24. The maximum, minimum and mean temperature, annual in SŞV

[2] For Further information about Meteonorm software, see Chapter 4.3

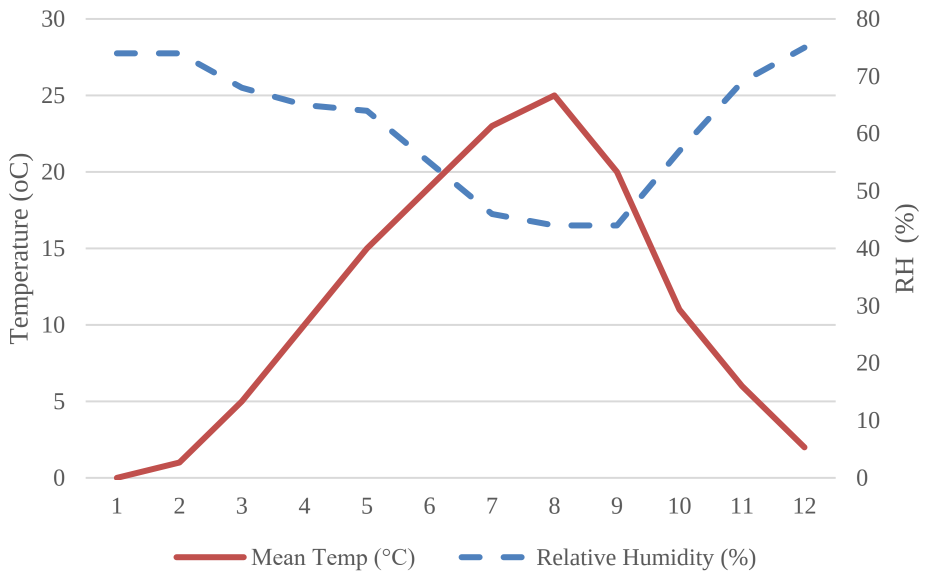


Figure 3.25. Temperature and relative humidity graph for SŞV

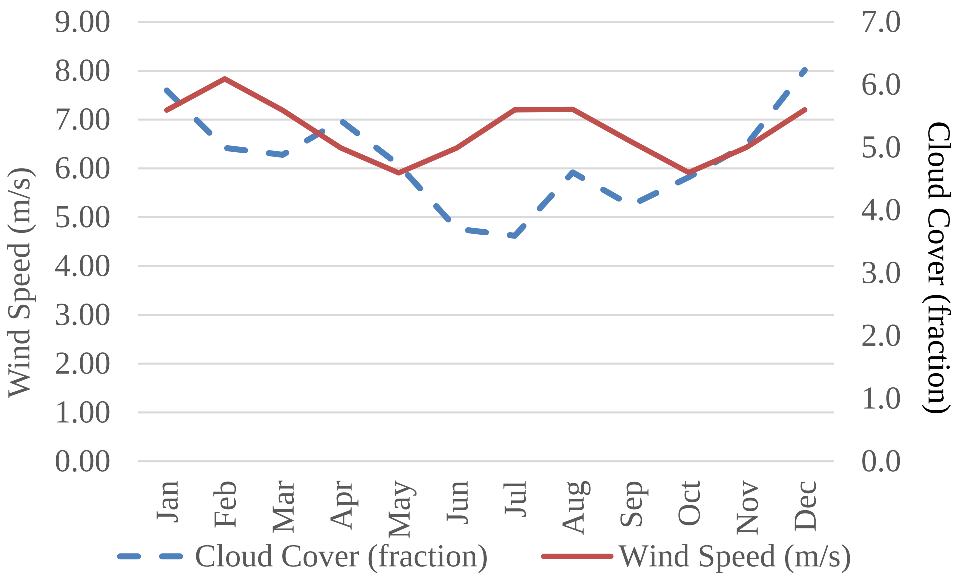


Figure 3.26. The relationship between wind speed and cloud cover in SŞV

The annual mean outdoor temperature is 11.4°C. The highest temperatures are 25°C, 23°C and 20°C in August, July and September, respectively. For the coolest months, January, February and December are of 0°C, 1°C and 2°C, respectively.

The annual relative humidity is 61.3%. The highest relative humidity values are 75%, 74% and 74% in December, January and February, respectively. The lowest relative humility values are 44%,44% and 46% on August, September and June, respectively.

CHAPTER 4

METHODOLOGY

In this chapter, the framework of research process is expressed in a detailed way. Methodology is visualized from selection of the case buildings through to the results. Each step is explained in further sections.

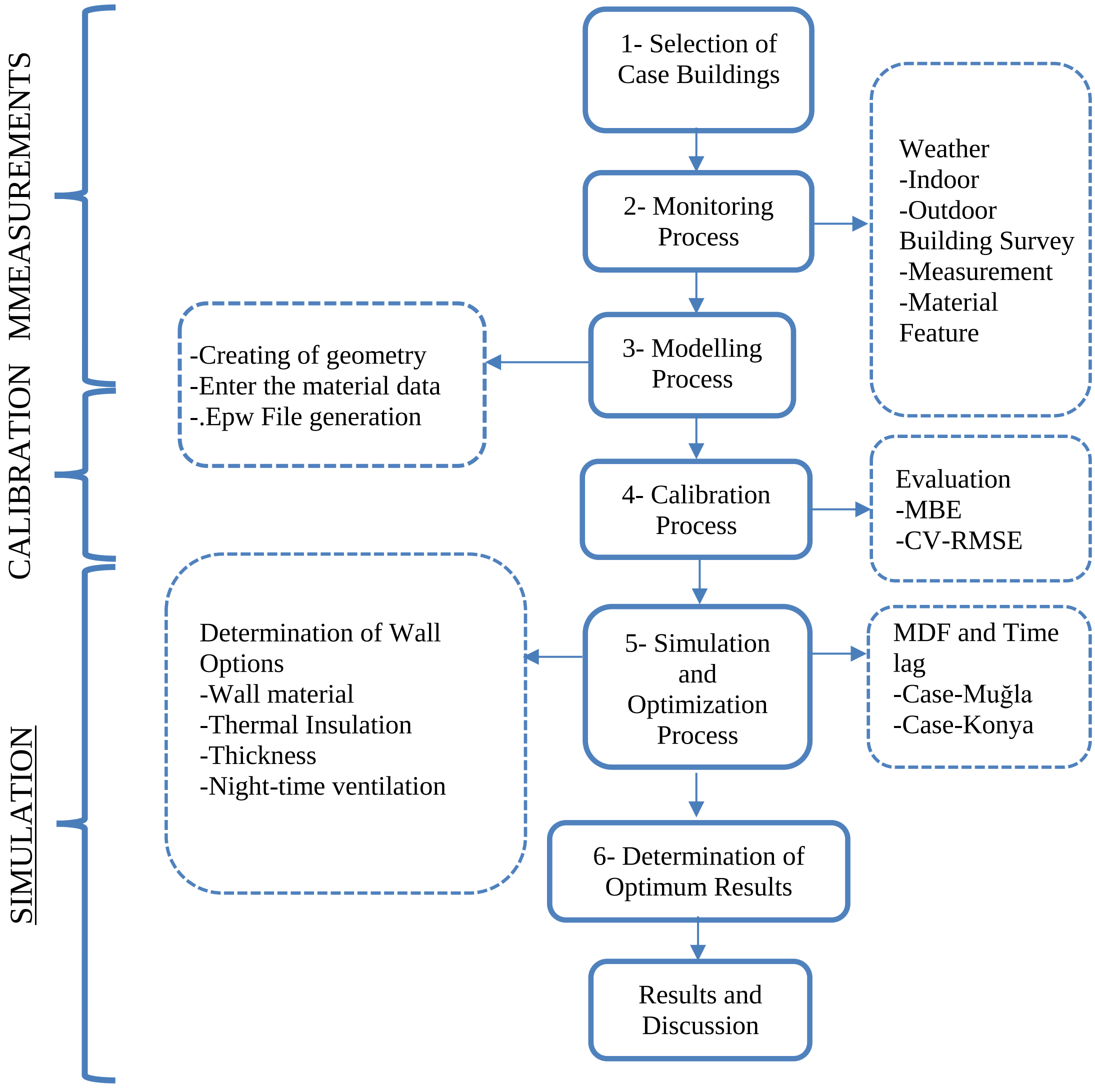


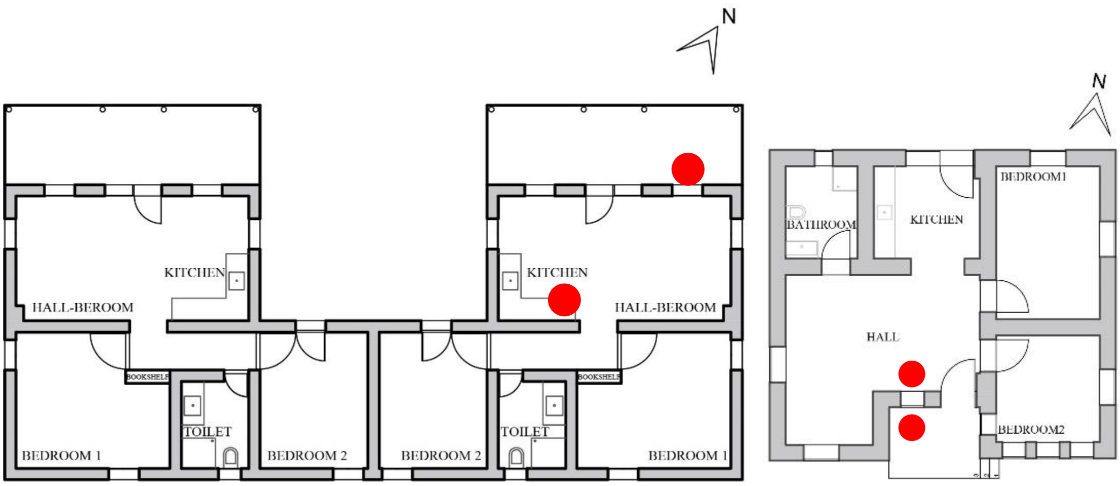
Figure 4.1. Methodology flowchart

4.1. Selection of Case Buildings

The case buildings were determined in line with the aim of this research. Two buildings located in different climatic conditions with traditional adobe construction were selected and considered for the aim of evaluating sustainable building materials. The buildings' climates are Mediterranean and Continental climates labelled as Csa and Csb according to Köppen climatic conditions, respectively for Muğla and Konya (Köppen, 2019). Essential criteria to select these two buildings is that the owners of buildings preferred adobe as a natural building material and traditional load-bearing construction technique.

4.2. Monitoring Process

The case buildings located in Mugla and Konya were equipped with diagnostic equipment. Data loggers (HOBO U12-012) were used between 28th of July 2017 and 10th of September 2017 for a total of 45 days both externally and internally to measure temperature and relative humidity every 10 minutes. During monitoring of these two case buildings, all windows and doors were kept closed. There were no occupants and no electrical equipment while monitoring campaign.



(a) (b)

Figure 4.2. The location of dataloggers of Muğla (a) and Konya (b)

One Hobo data logger located in Muğla was placed internally on the kitchen counter at a height of 0.90 m from the floor. The second data logger was placed externally on the window upper trim at a height of 2.40 m from the floor. The internal data logger in Konya was placed on the shelf at a height of 1.50 m from the floor and the external data logger was placed on the window upper trim at a height of 2.40 m from the floor, as shown in Figure 4.2.

The resolution of the Hobo data loggers is 0.03°C at 25°C and 0.05% relative humidity. The accuracy is ± 0.35°C from 0° to 50°C and ±2.5% from 10% to 90%, respectively, as shown in Table 4.1. By means of external measurements, climate data was transformed to be used in the analysis. The interior temperatures that were recorded during the monitoring period were later used to compare against simulation results.

Table 4.1. Technical specifications of data loggers
(Source: (Onset, 2018)

Data logger	**HOBO U12, T/RH/light/external data logger**
Measurement range	T: –20°C to 70°C, RH: 5% to 95%
Accuracy	T: ±0.35°C from 0°C to 50°C RH: ±2.5% from 10% to 90%

The case buildings' dimensions were measured on-site as the data loggers were installed. The buildings' inside and outside, windows' and doors' heights, widths and thicknesses were measured. Pictures were taken. The building materials were surveyed with the architects of the buildings. All building information was presented in Chapter 3.

4.3. .Epw (EnergyPlus weather file) Generation

Designuilder simulation tool requires specifying the location of the building being modelled and appropriate climate information in .epw format. The coordinates of the case buildings in Hüyük district of Konya and Fethiye district of Muğla were determined. Then these coordinates were entered into Meteonorm software (Meteotest, 2018). Meteonorm v7.2 database offers meteorological data measured from 1991 to 2010. The data are obtained through several solarimetric stations. One-year climate data of those coordinates were obtained by means of Meteonorm. Hourly data were taken from Meteonorm was combined with 45-day on-site measurements. Then, the file was saved in .csv (comma separated values) format which was converted into a .epw file using ‘energy statistics and conversion’ program, which works as an extension to EnergyPlus (EnergyPlus, 2018).

4.4. Modelling Process

The digital modelling of two case buildings in Muğla and Konya are presented. DesignBuilder has been selected as the tool for an assessment of building energy performance. Digital modelling process have been conducted by educational version v4.6.0.015, and simulation and optimization process have been conducted by educational version v6.01.019 (DB, 2019). DesignBuilder dynamic simulation software enables architects, engineers, energy assessors to analyse energy consumption, lighting, thermal comfort, CO_2 emissions, cost implications and optimize whole building designs. It uses EnergyPlus as a simulation engine for heating and cooling calculations by using hourly weather data. This thesis aims to find minimum annual energy consumption considering heating and cooling. Therefore, the case buildings were modelled in detail in DesignBuilder, then optimum solutions for energy efficiency were investigated.

Modelling involves a certain degree of abstraction. A simulation model is a simplified representation of all geometry and all processes in a building. Some simplifications and critical explanations for modelling regarding Muğla and Konya models are;

- Thermal zones

There is no ceiling of case building in Muğla. Therefore, the attic zone was merged with the spaces below. This is not the case in Konya because it has a flat roof.

- Twin House

The case building in Muğla has a unit of the twin house attached with adjacent bedrooms. In 3D model, therefore, the adjacent building to the case building was determined as an adiabatic and its material was selected as adobe, as well.

- Outside Components

Neighbouring buildings, trees, sunshades are modelled as component blocks. Their materials selected from DesignBuilder material library. Also, transmittance was added the material used for trees. Any decoration elements such as balustrades, reliefs, and door and window jambs on the façades are not modelled for the purpose of simplification.

- Climate

Climate data was gathered for the purpose of getting accurate data in simulation results. It is explained in Chapter 4.2.

- Indoor Components

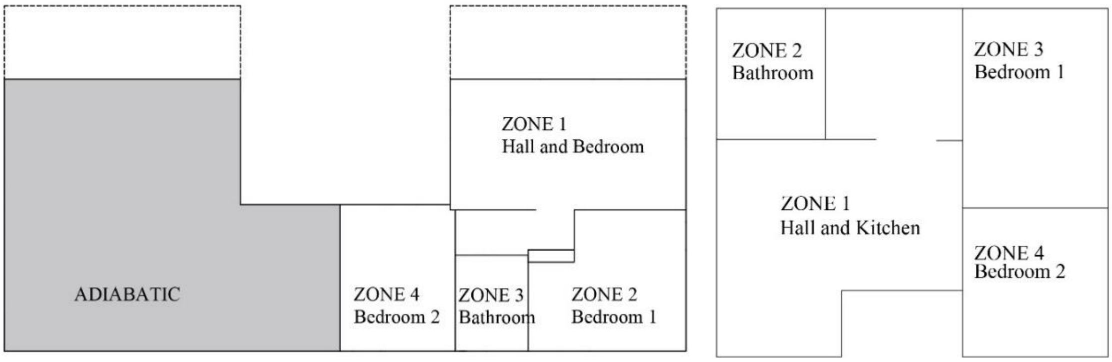
Doors in partitions separating interior spaces were specified to be open in summertime to evaluate the impact of night-time ventilation and closed in wintertime. It is explained in a detail in Chapter 4.8.1.

- Material and constructing technique

For hempcrete and straw bale, a wood framing system was assumed, with these two materials used as filling. In the model in DesignBuilder, the wood framing was not considered in calculation, its thermal behaviour on energy consumption was neglected. The wood framing system, therefore, was not modelled.

Geometry

Considering the geometry of buildings, architectural drawings were done based on on-site measurements. The as-built plans were drawn in AutoCAD 2018-Student Version (Autodesk, 2018). After the drawing of the plans, the outline of the exterior walls was drawn externally, and internal partitions were drawn medially.



(a) (b)

Figure 4.3. The outline plan of the case buildings in Muğla (a) and Konya (b)

For windows and doors, the pointer line was inserted in outline plan for ease of drawing later in DesignBuilder. This outline was exported as a .dxf (Drawing Exchange Format) file for importing dynamic simulation software DesignBuilder. After that the .dxf file is imported in DesignBuilder, the model was created in the dynamic simulation software. The simplified drawing is shown in Figure 4.3.

Modelling

First, ground is created then, the case buildings are modelled as three-dimensional objects. Afterwards, the adjacent (for Muğla) and surrounding neighbouring buildings and trees are modelled. Then windows and doors are imported.

Figure 4.4, Figure 4.5, Figure 4.6 and Figure 4.7 shows the case buildings and their surroundings in 3D user interface of DesignBuilder. After the model was generated, collected data was entered in DesignBuilder. This process is explained step by step below for each case building. Figure 4.8 shows the modelling flowchart.

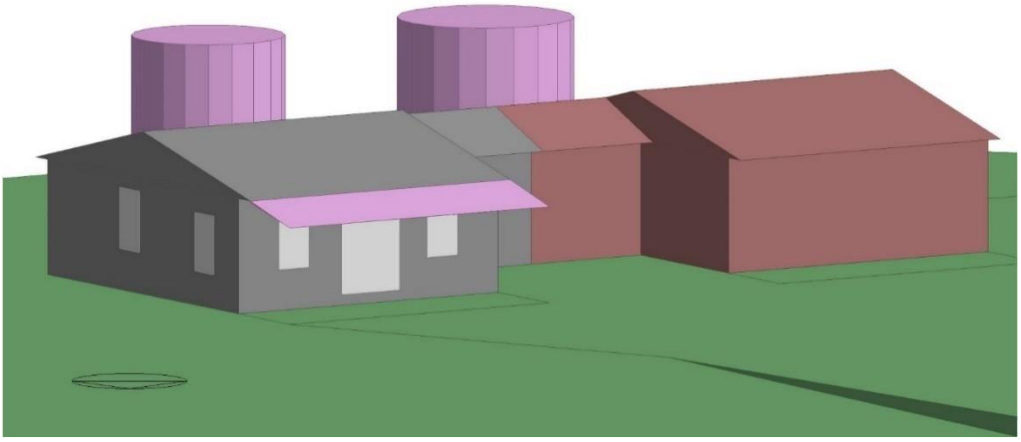


Figure 4.4. The model view of Muğla

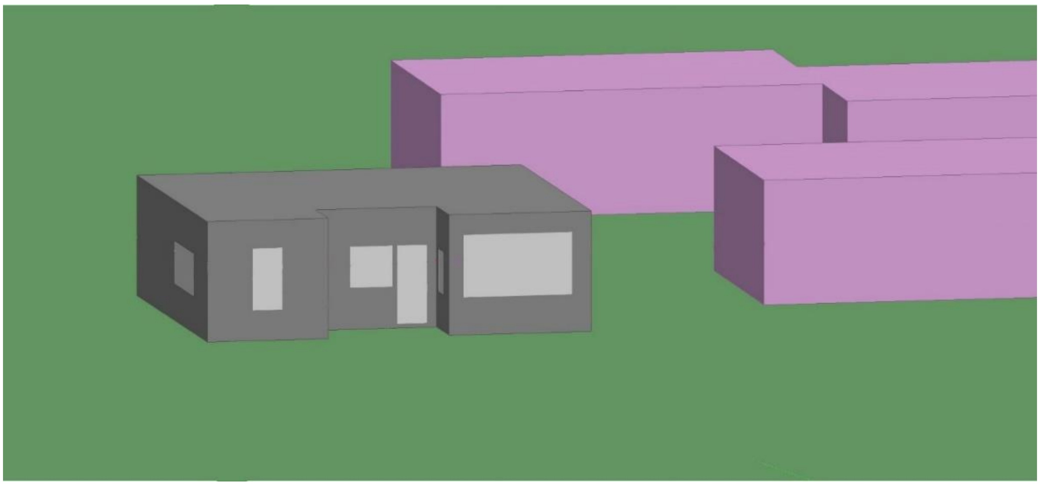


Figure 4.5. The model view of Konya

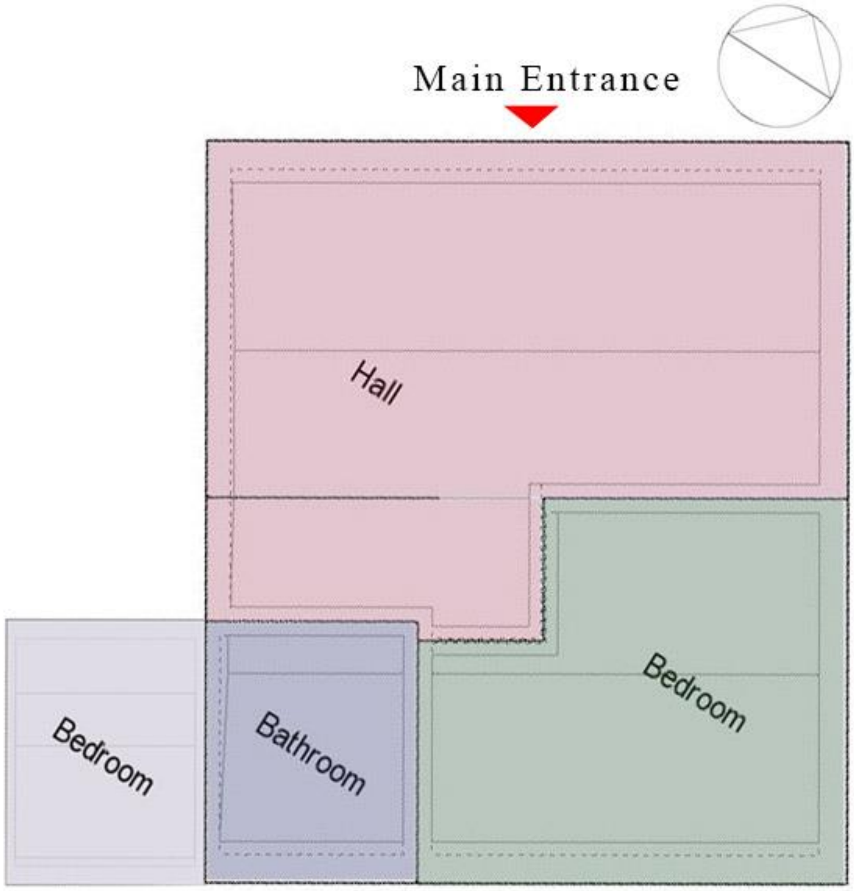


Figure 4.6: The plan from Muğla 3D model

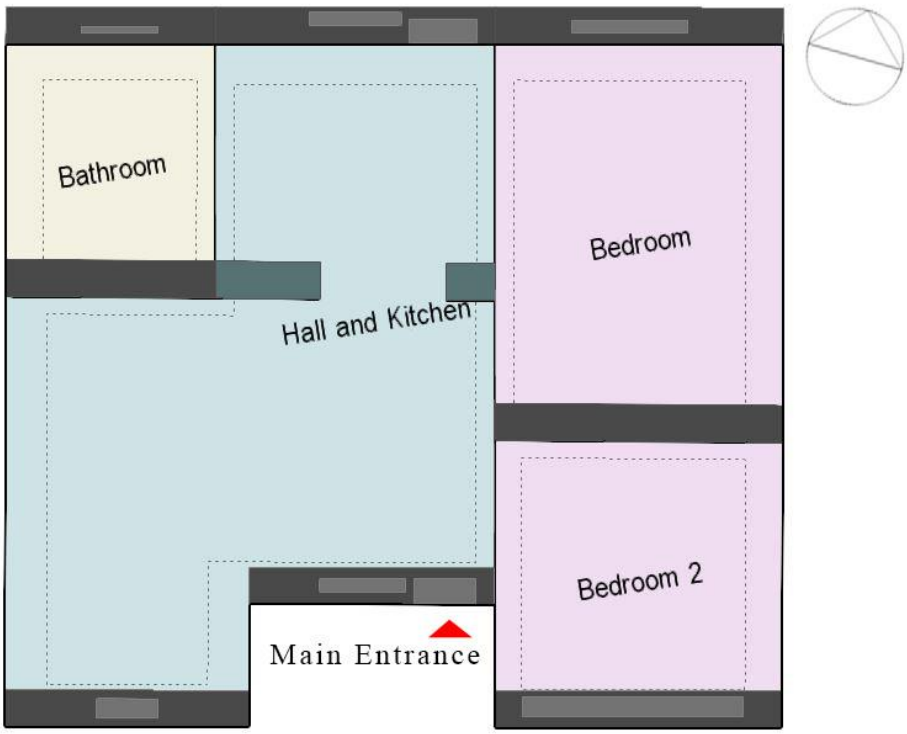


Figure 4.7: The plan from Konya 3D model

1. In DesignBuilder, in the first phase, site data should be entered. For two case buildings, the location template, site location and details, time and daylight saving, and simulation weather data was entered as mentioned in Chapter 3.

2. Environmental control settings were entered for two case buildings: Heating set point temperatures are 21°C and 19°C with the setback and cooling set point temperatures are 26°C and 28°C with the setback. No electrical equipment was considered - only cooling and heating.

3. The construction details were entered. The data mentioned in Chapter 3.1.2. and Chapter 3.2.2 and all values shown in Table 4.2 were entered. The models were specified to have an airtightness of 0.5 air changes per hour constant rate.

4. The external windows data were entered as mentioned in Chapter 3.1.2. and Chapter 3.2.2. All external windows % glazing area openings were entered as 0.5%. All internal doors are organized as closed all year long.

5. The lighting information was entered. The lights are considered to be off all year long because during the period data loggers were active all lights were off.

6. HVAC is the sixth phase. No mechanical ventilation is used in the case buildings while simulating or taking the data from data loggers. Natural ventilation is arranged as off because all doors and windows are kept closed while recording data.

After all data were entered, the two models were simulated from 28th of July 2017 till 10th of September 2017 for a total of 45 days and the simulation results were compared to results taken from data loggers to calibrate the models.

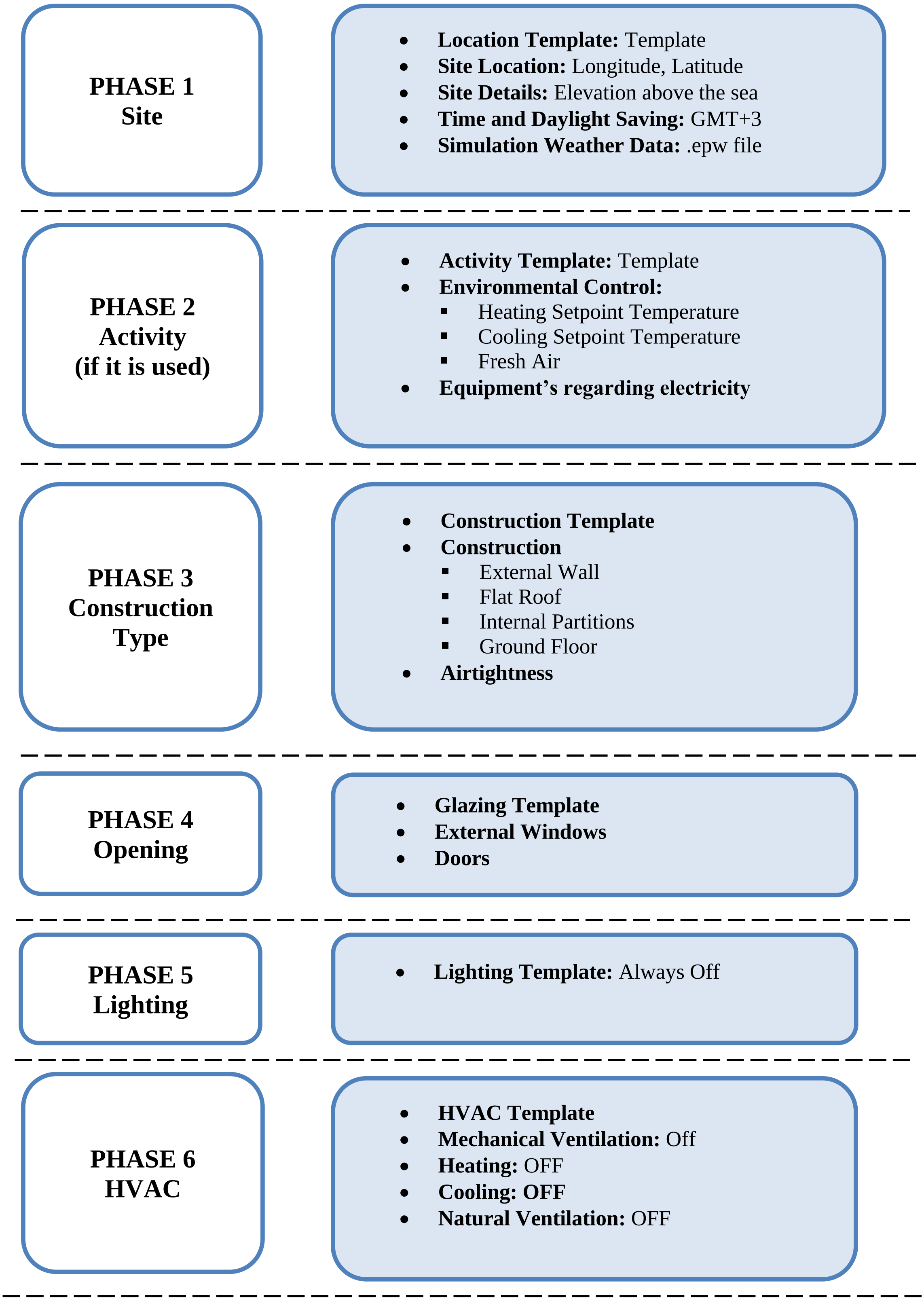


Figure 4.8. Modelling flowchart

Table 4.2. Component properties of material inserted in DB for Muğla and Konya model

Component	Position	MUĞLA CASE BUILDING						KONYA CASE BUILDIN					
		Layers	Thickness [m]	Specific Heat [J/kgK]	Density [Kg/m^3]	Thermal Conductivity [W/mK]	U-Value [W/m^{2}K]	Layers	Thickness [m]	Specific Heat [J/kgK]	Density [Kg/m^3]	Thermal Conductivity [W/mK]	U-Value [W/m^{2}K]
Wall	Internal External	Adobe Plaster	0.025	1250	1500	0.40	1.087	Adobe Plaster	0.025	1250	1500	0.40	0.704
		Adobe Brick	0.250	1250	1500	0.40		Adobe Brick	0.450	1250	1500	0.40	
		Adobe Plaster	0.025	1250	1500	0.40		Adobe Plaster	0.025	1250	1500	0.40	
Foundation	-	Stone	0.500	840	1300	0.350	0.610	Stone	0.500	840	1300	0.350	0.610
Ground Floor	-	Concrete	0.100	1000	1300	0.380	2.309	Concrete	0.100	1000	1300	0.380	2.309
Inner Floor	Up Down	Terracota Tile	0.010	850	1700	0.800	1.920	Hardwood	0.020	1200	650	0.140	2.422
		Mortar	0.010	840	1300	0.350							
Window	-	Single Glazing	0.003	-	-	3.835	3.835	Single Glazing	0.003	-	-	-	3.835
Door	-	Painted Oak	0.020	2390	700	0.190	2.823	Painted Oak	0.020	2390	700	0.190	2.823
Roof	Out In	Roof tile	0.025	800	2000	1.000	2.200	Earth	0.030	880	1460	1.280	0.387
		Roofing felt	0.005	837	960	0.190		Reed	0.100	1300	290	0.085	
								Membrane	0.005	1000	1700	0.500	
		Roof sheathing	0.050	840	30	0.040		Earth	0.030	880	1460	1.280	
								Reed	0.100	1300	290	0.085	

4.5. Calibration Process

The calibration process is based on three guidelines. These are, 1) ASHRAE Guideline 14-2002: Measurement of Energy and Demand Savings (ASHRAE14-2002, 2002), 2) IPMVP: International Performance Measurement and Verification Protocol (IPMVP, 2002), and 3) U.S. M & V guidelines (MVFEP): Measurement and Verification for Federal Energy Projects (M&VGuidelines, 2008)

These guidelines describe two statistical indices: Mean bias error (MBE) and root mean square error (CV-RMSE), both expressed as a percentage. Values close to zero in both indicate better prediction for the models. This study accepts the calibration with hourly data approach: MBE values should not be over ±10% according to ASHRAE 14-2002, ±20% according to IPMVP, and ±10% according to MVFEP. CV-RMSE values should not be exceeded 30% according to ASHRAE 14-2002, 20% according to IPMVP, and 30% according to MVFEP (ASHRAE14-2002, 2002; IPMVP, 2002; M&VGuidelines, 2008). The deviation of simulated data from monitored one is meant to be the error analysis. In this thesis, the zones where the dataloggers are located are evaluated for 45 days between 28th of July 2017 and 10th of September 2017 by investigating their hourly errors. CV-RMSE and MBE are used to analyse and determine the error between simulated and monitored hourly indoor temperatures. Equation 4.1 and 4.2 shows the formulas for CV-RMSE and MBE (ASHRAE14-2002, 2002).

$$CV\text{-}RMSE\ (\%) = (100/T_{ma})*[1/N*(S(T_s-T_m)^2)]^{1/20} \qquad (4.1)$$
$$MBE\ (\%) = (100/T_{ma})*[S(T_s-T_m)]\ /N \qquad (4.2)$$

where, T_{ma} is the mean measured temperatures, N is the number of observations, T_s is the simulated hourly temperatures and T_m is the measured hourly temperatures.

4.6. Thermal Capacity and Time Constant

Thermal capacity describes quantity of thermal energy that can be stored by the material. It is equivalent to thermal capacity (kJ/K). It is expressed as C, which describes the quantity of thermal energy that can be stored (Slee, Parkinson, and Hyde, 2014). It gives an information about heat that is needed to change the temperature of material by a unit temperature. For single type of materials, thermal capacitance is defined as (Jankovic, 2012);

$$C = m\ x\ c = (\rho\ x\ V)\ x\ c = \big(\rho\ x\ A\ x\ (wall\ thickness)\big) x\ c \tag{4.3}$$

where C(J/K) is the thermal capacity, m is the mass (kg) of the material that comes from density (kg/m^3), expressed as ρ, multiplying with its volume (m^3), expressed as V, and c is the specific heat (J/kgK), and volume can be stated as multiplying with the total area of the wall A (m^2) and wall thickness (m). If the material is layered, this equation is repeated, and they are aggregated for sum.

The parameter reflecting the time aspect to thermal mass is the time constant that indicates how much time material will take heat needed to change the temperature of material by a unit temperature (Jankovic, 2012). Time constant, expressed as t_c, is calculated by dividing the thermal capacitance by the overall transmittance-area product.

$$t_c = \frac{\sum_{i=l}^{i=n} \rho_i\ x\ V_i\ x\ c_i}{U\ x\ A} = \frac{\sum_{i=l}^{i=n} C}{U\ x\ A} \tag{4.4}$$

where t_c is time constant (hour), C (J/K) is the thermal capacity, U is the U-Value (W/m^{2}K) of the product and A is the area (m^2). If the material is layered, the density, volume and specific heat of the materials are multiplied and summed then divided into overall transmittance area.

4.7. Modified Decrement Factor and Time Lag

The time lag and decrement factor are dynamic heat transfer characteristics of the solar absorber. These parameters are identified based on differences of temperature fluctuations at the external and internal surface of the wall (Jankovic, 2012).

Firstly, outer surface of the building element (wall or roof) is exposed to a heat input, this input, however, will not be felt at the inner surface simultaneously. Only after a while, some considerable feeling occurs. The time it takes for heat to pass through a wall of a building is called 'time lag'. The hours between the peak temperature of the outer surface of the wall and the resulting peak temperature of the inner surface is addressed as delay.

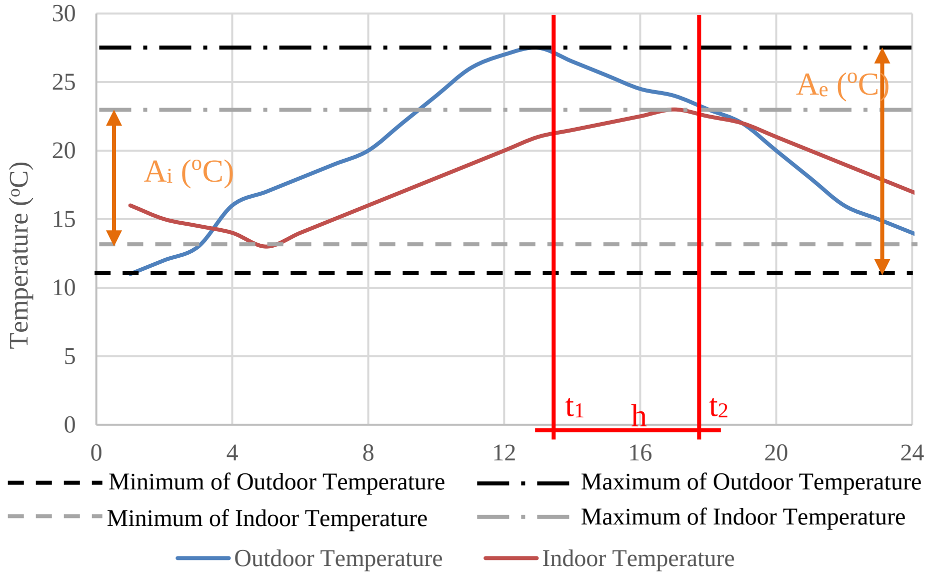


Figure 4.9: Modified Decrement Factor (MDF) and Time Lag

$$Modified\ Decrement\ Factor\ = \frac{A_i}{A_e} \tag{4.5}$$

$$Time\ lag\ (\varphi) = \ |t_1 - t_2| \tag{4.6}$$

Decrement factor is the ratio of the amplitude swings of outer and inner surface temperatures on an external wall (Duffin, 1984). It explains capacity heat wave during the propagation. These two factors are important in describing the heat storage ability of wall materials (Asan and Sancaktar, 1998).

In this research, decrement factor has been modified. Instead of wall surface temperature, decrement factor has been calculated using outside and inside temperatures and named modified decrement factor. Figure 4.9 shows how MDF and time lag calculate.

Thermal Diffusivity

If the temperature profile in the material changes with time, the thermal diffusivity is examined to explain this ability of the material. Thermal diffusivity is calculated by dividing thermal conductivity of the material by the density and the specific heat.

$$\alpha = \frac{k}{\rho x c} \tag{4.7}$$

where α (m^2/s) is thermal diffusivity, k (w/mK) is thermal conductivity, ρ (kg/m^3) is density and c (J/kgK) is specific heat.

4.8. Optimization Process

In this section, three optimization parameters have been put together in order to find the optimal designs with the scope of the study. These parameters are; firstly, to get together wall options considering material choice, thickness and availability of wall insulation material, secondly, investigate night-time ventilation effect on thermal mass and lastly, to determine building configuration of façades orientation according to wall option application.

4.8.1. Determination of Optimization Parameters

1- Determination of Wall options

Wall options have been determined within the context of research questions of thesis. These are s follow:

- What is the effect of thermal mass on energy consumption in natural building materials?
- What is the effect of thermal insulation on energy consumption?
- What is the effect of wall thickness on energy consumption?

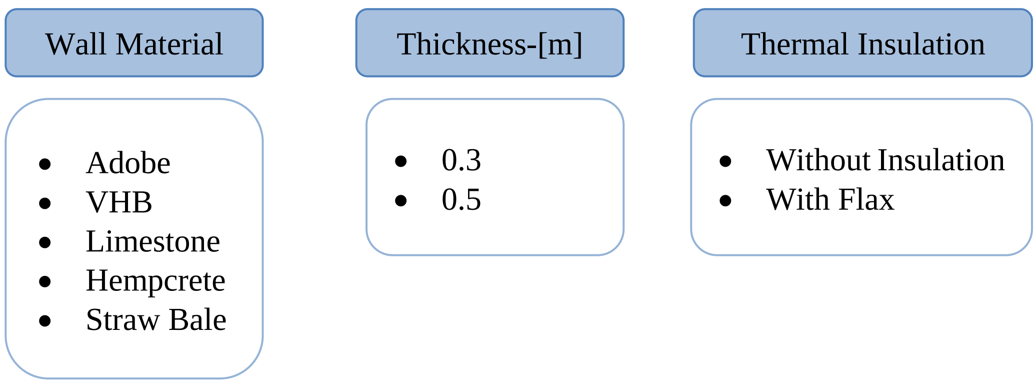


Figure 4.10. Wall option parameters

Within this framework, adobe, VHB, limestone, hempcrete and strawbale have been selected as building materials. These materials have been used in both 0.30 m and 0.50 m thicknesses. All combinations of materials and thicknesses, then, have further been combined with the presence or absence of flax as thermal insulation material. Figure 4.10 shows the classification the wall option parameters. All wall options are listed in Table 4.3 with their U-Value. Their sections are shown in Figure 4.11. The wall options 1 and 6 correspond to Muğla and Konya Case Buildings actual construction and named as 'case scenario's. For the rest of the wall options when all 4 walls are assigned the same wall option, they will be the 'base scenario's.

Table 4.3. Wall options and their U-Value

Wall option #	Thickness [meter]	Insulation Material	Material	U- Value [W/m^{2}K]
1 (Muğla Case Building)	0.3	Without Insulation	Adobe	1.087
2 (Base Scenario)			VHB	1.176
3 (Base Scenario)			Limestone	1.915
4 (Base Scenario)			Hempcrete	0.325
5 (Base Scenario)			Straw Bale	0.248
6 (Konya Case Building)	0.5		Adobe	0.704
7 (Base Scenario)			VHB	0.772
8 (Base Scenario)			Limestone	1.420
9 (Base Scenario)			Hempcrete	0.189
10 (Base Scenario)			Straw Bale	0.143
11 (Base Scenario)	0.3	Insulation Material as a Flax	Adobe	0.474
12 (Base Scenario)			VHB	0.487
13 (Base Scenario)			Limestone	0.558
14 (Base Scenario)			Hempcrete	0.261
15 (Base Scenario)			Straw Bale	0.218
16 (Base Scenario)	0.5		Adobe	0.383
17 (Base Scenario)			VHB	0.400
18 (Base Scenario)			Limestone	0.506
19 (Base Scenario)			Hempcrete	0.165
20 (Base Scenario)			Straw Bale	0.132

For optimization parameters, thermal properties of materials, especially their specific heat, was paid attention to and same values were avoided in order to compare the effects of thermal capacity on energy consumption. Thermal characteristics of materials that is generated in DesignBuilder as a building material is listed in Table 4.4.

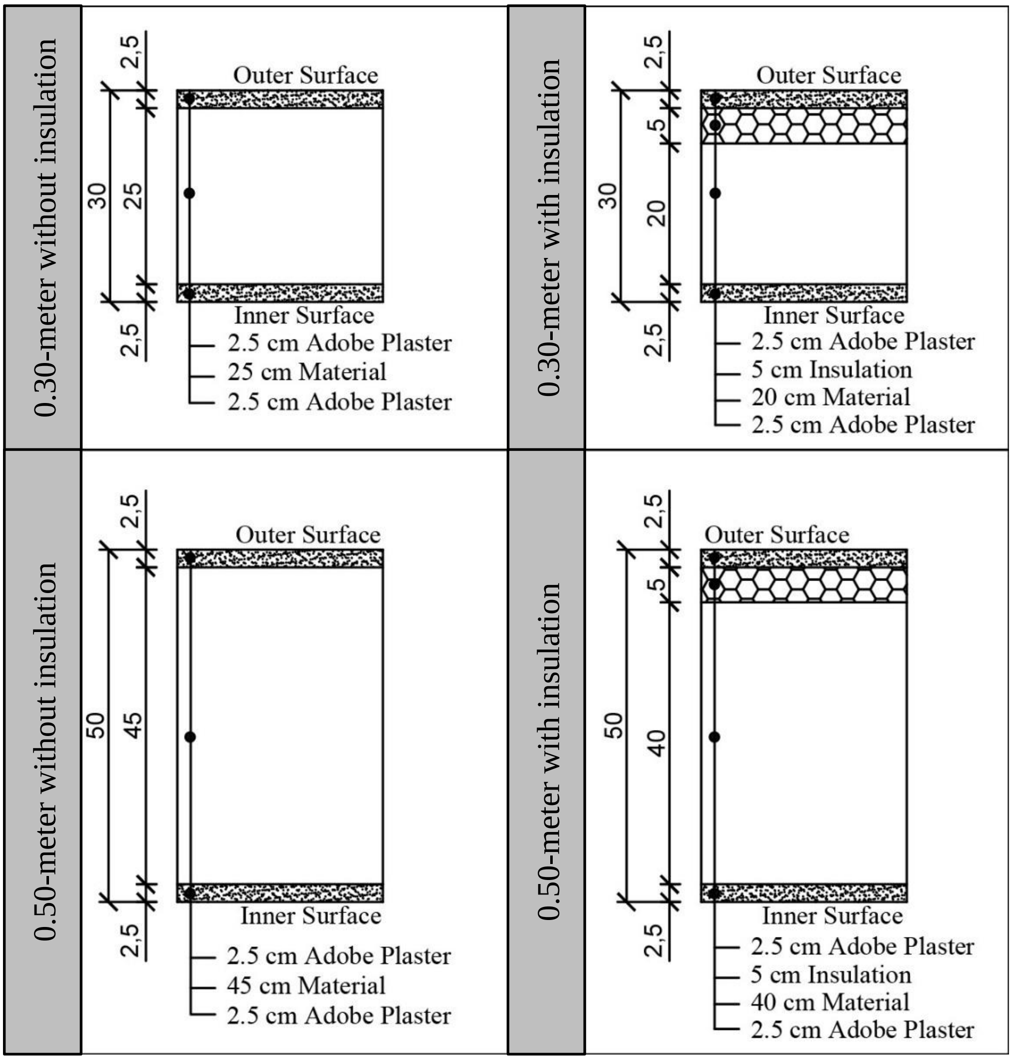


Figure 4.11. Layers of wall options in plan. Material is adobe, VHB, limestone, hempcrete, or strawbale

Table 4.4. Wall material properties

Material	**Conductivity [W/mK]**	**Specific Heat [J/kgK]**	**Density [kg/m^3]**	**Reference**
Adobe	0.400	1250	1500	(Acun and Gürdal, 2003)
VHB	0.450	850	1000	(Ulu, 2018)
Limestone	1.100	1000	1800	(DB, 2019)
Hempcrete	0.090	1600	330	(Goodhew and Griffiths, 2005)
Straw Bale	0.060	600	60	(Goodhew and Griffiths, 2005)
Flax	0.038	1600	76.5	(Eci, 2019)

The case buildings were constructed with loadbearing materials in real world. Both case buildings are made of adobe and they have no extra bearing system because adobe behaves as a loadbearing material. In this thesis's materials choices, vertical hollow brick is selected as a masonry, which is a loadbearing material as well. For hempcrete and straw bale, a wood framing bearing system was assumed, and these three materials were used as a filling. In the model in DesignBuilder, the wood framing was not considered in calculation, its thermal behaviour on energy consumption was neglected. The wood framing system, therefore, was not modelled.

2- Determination of Night-Time Ventilation and Heating-Cooling schedule

For both case buildings, night-time ventilation period and internal doors' opening schedules are the same as cooling time period and affect all building zones for the purpose of exploring the impact of night-time ventilation with thermal mass. Air changes per hour was set as 15 ac/h. The night-time ventilation was controlled in terms of shutting down when the inside temperature was either under 19°C or over 27°C.

The electricity from grid heating and cooling system has been installed with the coefficient of performance of 1.7 to evaluate the energy consumption for the whole year in both case buildings. For heating, set point temperatures have been determined as 21°C to 19°C with the set back and 26°C to 28°C with setback for cooling.

Table 4.5. Heating, cooling and night-time ventilation schedule for both case buildings

Schedules	**Case Building in Muğla and Konya**		
	Type of Fuel	**Unoccupied**	
		On	**Off**
Heating	Electricity from Grid	From 1 October to 31 May 7/24 Controlled by thermostat	From 1 June to 30 September
Cooling	Electricity from Grid	From 1 June to 30 September 7/24-Controlled by thermostat	From 1 October to 31 May 7/24
Night-time Ventilation	On	From 1 June to 30 September From 7 p.m. to 7 a.m.	From 1 October to 31 May 7/24

For each case building, according to weather data, the outside temperature is above 19°C after June 1st and drops below 19°C after September 30th in the evenings, temperature drops after 7 p.m. in the evening and increases after 7 a.m. in the morning between June 1st and September 30th on the average. For night-time ventilation, therefore, starting day has been determined as 1st of June, scheduled to be open from 7 p.m. to 7 a.m. and ends on September 30th. If outside temperature drops below 17°C, then night-time ventilation is off automatically because when outside temperature 17°C, inside temperature starts to drop below 19°C.

Cooling has been scheduled, like night-time ventilation, between June 1st and September 30th throughout four months. Heating has been scheduled through eight months between October 1st and May 31st. Table 4.5 shows the schedules regarding heating, cooling and night-time ventilation.

3- Determination of Optimization Options

The optimization options are designed to find the minimum energy consumption for which wall option is applied at which façade of the building. For this purpose, two different application methods have been determined according to type of application of wall options on façade(s):

- Constant, i.e. wall option kept same while other 19 wall options are tried on other façade(s).
- All options, i.e. there is not any constant wall option on the façade(s). All wall options are applied into façade(s) one by one.

For each case buildings, the optimization options are divided into two groups as single and double. In single group, all 20 wall options were tested on the single façade while the first material was applied on the other three façades and the minimum energy result was obtained from the first round. In the 2nd round, these three façades were re-tested with the 2nd wall material and 20 wall options of the selected façade and the minimum energy result of the second round was obtained. This continued for 20 rounds for each of the four façades.

In double group, all 20 wall options were tested on the double façade, while the first material was applied on the other double façades and the minimum energy result was obtained from the first round. In the 2nd round, these double façades were re-tested with the 2nd wall material and 20 wall options of the selected double façade and the minimum energy result of the second round was obtained. This continued for 20 rounds for each of the 6 pairings.

For example, on the North, West and South façades, 1st wall option is applied during all 20 wall options are applied on east façade for getting minimum energy results configuration, shown in . This round has 20 simulations. All 20 wall options are applied one by one on the North, West and South façades. Totally, 400 simulations were done for one façade. With four façades the single group required a total of 1600 simulations. For the double group, again 400 simulations were required for each pairing. With a total of six possible pairings, the required number of simulations was 2400. The complete optimization study required 4000 simulations. These simulations were repeated with night-time ventilation option so a total of 8000 simulations were done for just one case building. These simulations were complete in DesignBuilder with its 'Optimization and UA/SA Analysis' tool.

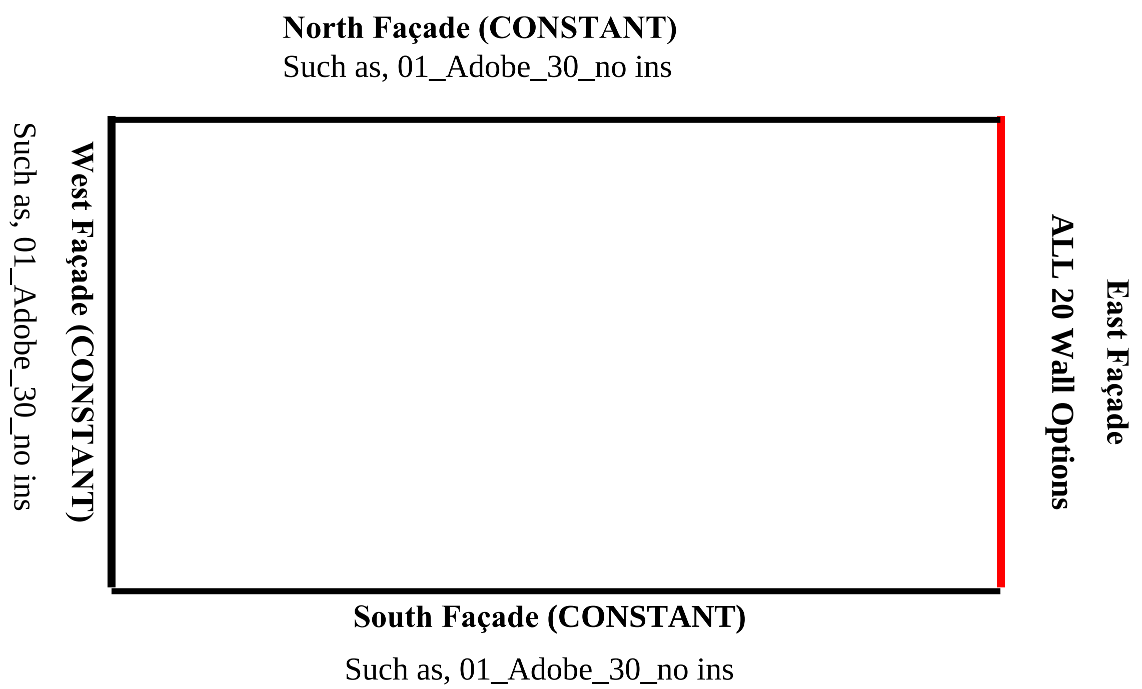
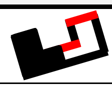
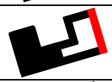
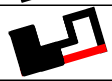
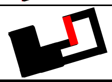
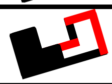
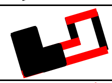
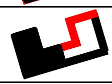
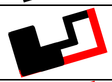
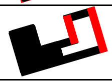
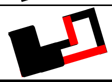


Figure 4.12: Example of 1st optimization option

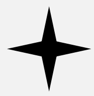
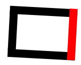
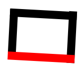
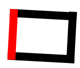
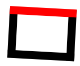
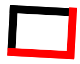
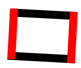
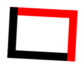
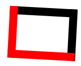
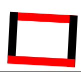
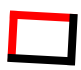
Table 4.6. Wall options applied configuration to be tried in each façade in the case buildings. The red lines indicate that in optimization option its façade applied all components, its façade keeps constant in black line in optimization option for Muğla

Optimization Option #	Quantity of Façade	Wall Options				Weather		Façade
		North East	South East	South West	North West	Night-Time Ventilation	Model Climate	N 
1	Single	All Opt.	Constant	Constant	Constant	+/-	Own Weather	
2		Constant	All Opt.	Constant	Constant	+/-	Own Weather	
3		Constant	Constant	All Opt.	Constant	+/-	Own Weather	
4		Constant	Constant	Constant	All Opt.	+/-	Own Weather	
5	Double	All Opt.	All Opt.	Constant	Constant	+/-	Own Weather	
6		All Opt.	Constant	All Opt.	Constant	+/-	Own Weather	
7		All Opt.	Constant	Constant	All Opt.	+/-	Own Weather	
8		Constant	All Opt.	All Opt.	Constant	+/-	Own Weather	
9		Constant	All Opt.	Constant	All Opt.	+/-	Own Weather	
10		Constant	Constant	All Opt.	All Opt.	+/-	Own Weather	

The 'Optimization and UA/SA Analysis' tool was used for each round. Therefore, optimization tool was run 400 times both with night-time ventilation on and off for each case building. Use of the optimization tool has the followings steps: First, minimum cooling (electricity) and minimum heating (electricity) were selected as objectives. Second, design variables were determined. Variable type, option list and target options are selected as external wall construction, 20 wall options and the walls which these options were to be applied. Screenshots of this process are respectively shown in Figure

4.13, Figure 4.14 and Figure 4.15. According to example shown in , walls orientated 9^o with North is selected which exist in Bathroom, Bedroom and Hall and Bedroom zones were selected while other walls were selected 1^{st} wall option as a default, shown in Figure 4.15. Thus, first round gives the optimal results.

Table 4.7. Wall options applied configuration to be tried in each façade in the case buildings. The red lines indicate that in optimization option its façade applied all components, its façade keeps constant in black line in optimization option for Konya

Optimization Option #	**Quantity of Façade**	**Wall Material**				**Weather**		**Façade**
		East	**South**	**West**	**North**	**Night-Time Ventilation**	**Model Climate**	**N** 
1	Single	All Opt.	Constant	Constant	Constant	+/-	Own Weather	
2	Single	Constant	All Opt.	Constant	Constant	+/-	Own Weather	
3	Single	Constant	Constant	All Opt.	Constant	+/-	Own Weather	
4	Single	Constant	Constant	Constant	All Opt.	+/-	Own Weather	
5	Double	All Opt.	All Opt.	Constant	Constant	+/-	Own Weather	
6	Double	All Opt.	Constant	All Opt..	Constant	+/-	Own Weather	
7	Double	All Opt.	Constant	Constant	All Opt.	+/-	Own Weather	
8	Double	Constant	All Opt.	All Opt.	Constant	+/-	Own Weather	
9	Double	Constant	All Opt.	Constant	All Opt.	+/-	Own Weather	
10	Double	Constant	Constant	All Opt.	All Opt.	+/-	Own Weather	

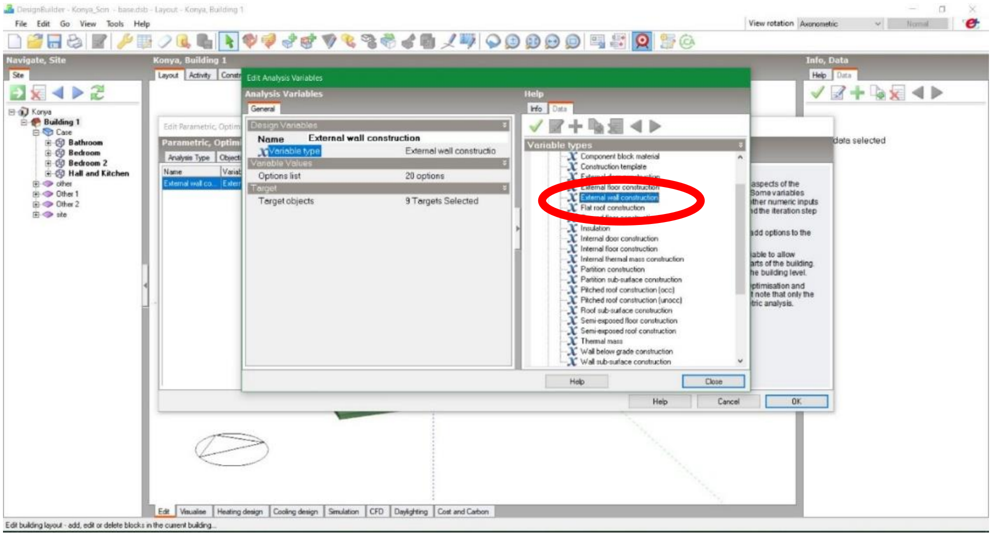


Figure 4.13. Optimization tool in DesignBuilder, example in Konya model for variation type

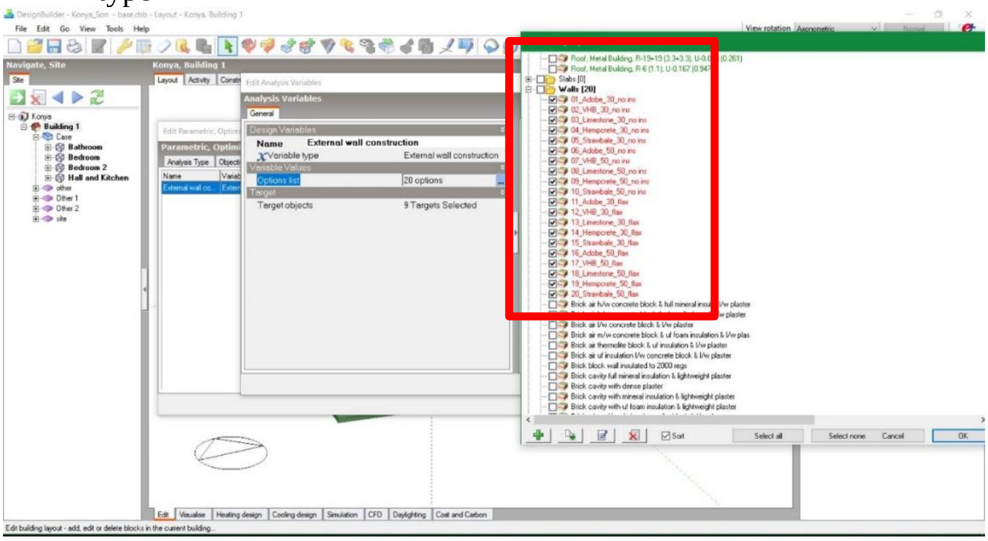


Figure 4.14. Optimization tool in DesignBuilder, example in Konya model for option list

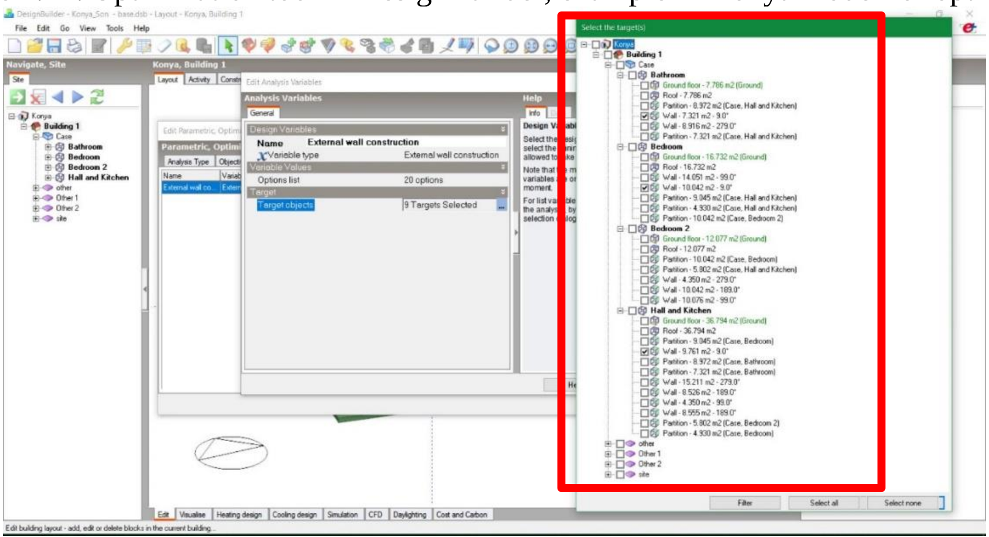


Figure 4.15. Optimization tool in DesignBuilder, example in Konya model for target objects

4.8.2. Classification of Simulation and Energy Consumption Results

Classification of results is divided into 4 groups considering for both Mugla and Konya case buildings. ‘Simulation and Energy Consumption Results’ is 4th part of the Results Chapter and it is divided into 3 subgroups in it. These are:

1. Modified Decrement Factor (MDF)

MDF of case building in Muğla and Konya is investigated over all 20 wall options and compared with each other.

2. and 3. Energy Consumption Results for Case Building in Muğla and Konya

- Energy Consumption of Case Buildings and Base Scenarios

These results consist of annual total energy consumption using each type of wall option on all building façades. Effect of individual material thickness and insulation on energy consumption are investigated in this section.

- Annual Energy Consumption Results of Optimization Options

Optimization options are considered in terms of annual energy consumption.

- Energy Consumption Results in Cooling Period for Optimization Options

Night-time ventilation was applied during summer. In this section, first, question of which materials should be applied to which building façades for the minimum energy solution is searched for and then comparison was made for the answers between each solution when night-time ventilation was on and off.

4. Climates and Buildings Switching

Climates switches for Muğla and Konya models and impact of climate on energy consumption is investigated.

The wall options of 1st and 6th are referred to as Muğla and Konya Case Building, while other wall options are referred to as base scenario. The case buildings investigated for direction were named as optimization option indicated in Table 4.6 and

CHAPTER 5

RESULTS AND DISCUSSION

In this chapter all results that were taken regarding thermal capacity and time constant, on site measurements, calibration, and simulation and energy consumption are explained and discussed.

5.1. Thermal Capacity and Time Constant Results

Thermal capacity (*C*) values of 20 wall options are calculated according to equation 4.3. The results are indicated in Figure 5.1 and Table 5.1. The total surface area of walls in Muğla and Konya case buildings is the same value of 100 m^2, shown in Table 3.1 and Table 3.3. For example, thermal capacity of the 1st wall option (adobe, 0.30-meter without insulation) is calculated for Muğla and Konya case buildings as follows:

C =	*1500 kg/m³ x 100 m² x 0.025 m (adobe plaster)*	*x 1250 J/kgK*	*= 4687500*
	1500 kg/m³ x 100 m² x 0.25 m (adobe)	*x 1250 J/kgK*	*=46875000*
+	*1500 kg/m³ x 100 m² x 0.025 m (adobe plaster)*	*x 1250 J/kgK*	*= 4687500*
			56250000 J/K = 56.2 MJ/K

Time constant (t_c) values of 20 wall options are calculated according to equation 4.4. The results are indicated in Figure 5.2 and Table 5.1. For example, time constant of the 1st wall option (adobe, 0.30-meter, without insulation) is calculated as follows:

$$t_c = \frac{56.2\,\frac{\mathrm{MJ}}{\mathrm{K}}}{1.087\,\frac{W}{m^2K}\ x\ 100\ m^2} = 15.63\ h$$

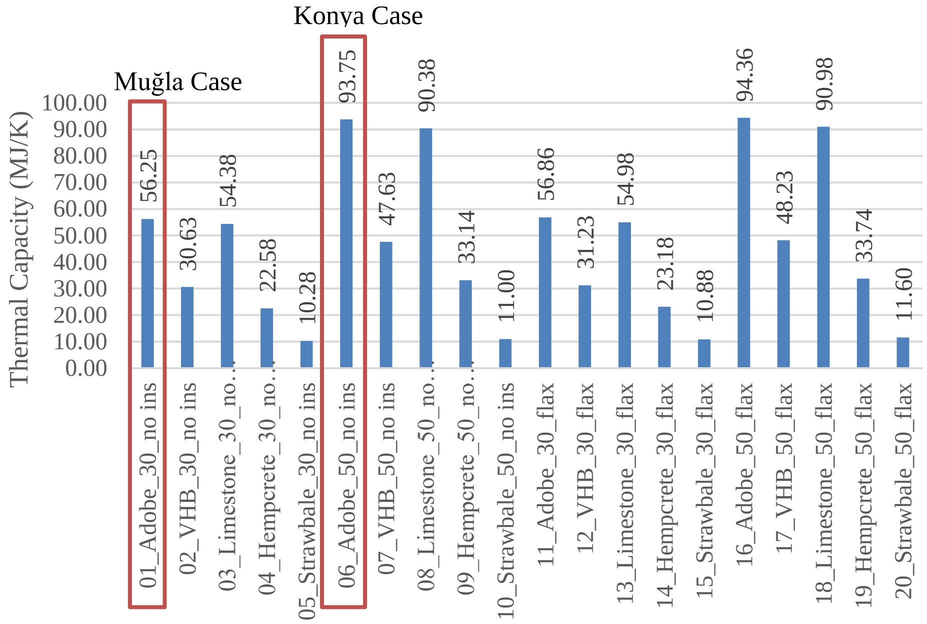


Figure 5.1. Thermal capacity results for each wall options

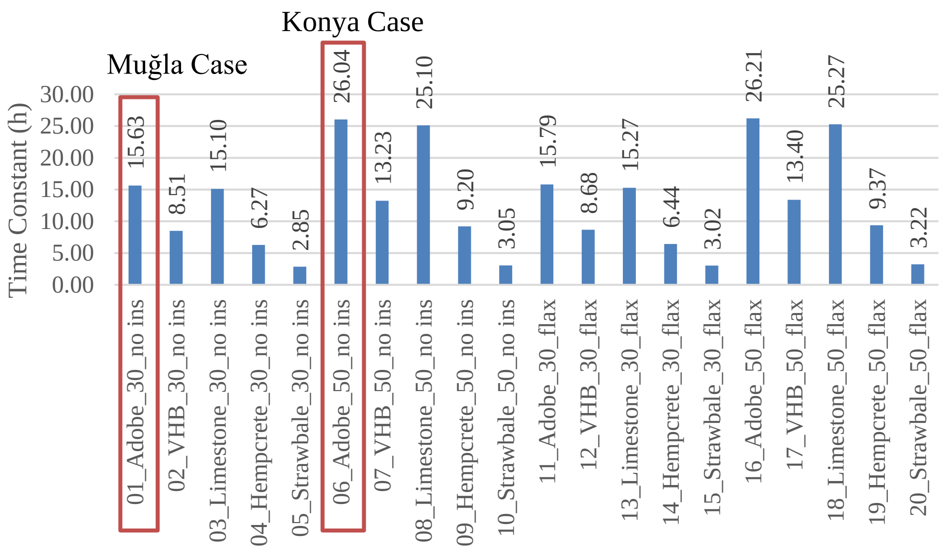


Figure 5.2. Time constant results for case scenario and base scenarios for Muğla and Konya

According to Figure 5.1, Figure 5.2 and Table 5.1, thermal capacity values for 1st wall option (current wall option of Muğla case building - adobe, 0.30-meter without insulation) is 56.25 MJ/K and 6th wall option (current wall option of Konya case building - adobe, 0.50-meter without insulation) is 93.75 MJ/K. Comparing to these wall options, 6th wall option store thermal energy 1.7 times more than 1st wall option. The material store minimum thermal capacity is 15th wall option (strawbale, 0.30-meter with flax) of 10.08 MJ/K whereas thermal capacity of 16th wall option (adobe, 0.50-meter with flax) is 94.36 MJ/K. Comparing to these wall options, 16th wall option store energy 9.4 times more than 15th wall option.

Time constant value for Muğla case building is 15.63 hours, while 26.04 hours for Konya. Time constant results of the current adobe buildings in Konya and Muğla gives information on how slowly responds to heat input Konya building and it minimizes inside temperature fluctuations. Comparing to case scenarios and base scenarios in terms of time constant, the 16th wall option (adobe, 0.50-meter with flax) has the maximum time constant value of 26.21 hours. The minimum time constant is with the 5th wall option (strawbale, 0.30-meter without insulation) of 2.85 hours. This conveys that the case buildings in Muğla and Konya with 16th wall option is cooled 9.19 times slowly than case buildings with 5th wall option.

Table 5.1: Thermal capacity and time constant results

Case Buildings and Base Scenarios	Thermal Capacity [MJ/K]	Time Constant [hours]
01_Adobe_30_no ins (Muğla Case Building)	56.25	15.63
02_VHB_30_no_ins	30.63	8.51
03_Limestone_30_no_ins	54.38	15.10
04_Hempcrete_30_no_ins	22.58	6.27
05_Strawbale_30_no_ins	10.28	2.85
06_Adobe_50_no_ins (Konya Case Building)	93.75	26.04
07_VHB_50_no_ins	47.63	13.23
08_Limestone_50_no_ins	90.38	25.10
09_Hempcrete_50_no_ins	33.14	9.20
10_Strawbale_50_no_ins	11.00	3.05
11_Adobe_30_flax	56.86	15.79
12_VHB_30_flax	31.23	8.68
13_Limestone_30 flax	54.98	15.27
14_Hempcrete_30_flax	23.18	6.44
15_Strawbale_30_flax	10.88	3.02
16_Adobe_50_flax	94.36	26.21
17_VHB_50_flax	48.23	13.40
18_Limestone_50 flax	90.98	25.27
19_Hempcrete_50 flax	33.74	9.37
20_Strawbale_50_ Flax	11.60	3.22

In Muğla case building, if the 5th wall option is applied, the building would have warmed up 5.48 times faster than the current case with 1st wall option (adobe, 0.30-meter without insulation). In Konya case building, if the 5th wall option is applied, the building would have warmed up 9.13 times faster than the current case with 6th wall option (adobe, 0.50-meter, without insulation).

The parameters of time constant and thermal capacity give an interpretation about how much time it will take in order to drop or increase unit temperature. The calculations of time constant put forward that adobe requires longer time to change the unit temperature, compared to VHB, limestone, hempcrete and strawbale, even if the increase in material thicknesses, or availability of insulation material.

5.2. Monitoring Results

The recorded outdoor and indoor air temperature and relative humidity data for a total of 45 days between 28th of July 2017 and 10th of September 2017 are indicated in Figure 5.3 and Figure 5.4. The maximum recorded outdoor temperature in Muğla (Mediterranean climate) is 38.3°C, while the maximum indoor one is 34.9°C. The minimum outdoor and indoor temperatures are 21.4°C and 23.6°C, respectively. The maximum recorded outdoor temperature in Konya (Continental climate) is 33.2°C, while the maximum indoor one is 25.7°C. The minimum recorded outdoor and indoor temperatures are 15.6°C and 21°C, respectively.

The comparison of internal daily temperature fluctuations indicates that the building with low thermal mass (Muğla) is affected with higher indoor temperature fluctuations (Figure 5.3). The high thermal mass in Konya case building guarantees lower temperature fluctuations, as parallel with adobe's time constant value (Figure 5.4).

The maximum recorded outdoor RH in Muğla is 74.2%, while the maximum indoor RH is 62.2% (Figure 5.5). The minimum outdoor and indoor RH is 31% and 5%, respectively. The inside RH at the same point is the maximum recorded outdoor RH of Konya is 63.3%, while the maximum internal one is 51.1%. The minimum recorded outdoor and indoor RH is 12.9% and 29.9%, respectively (Figure 5.6).

The outdoor RH values of Konya (Continental climate) in 2017 is generally lower than Muğla. The indoor RH values are within the 40-60% thermal comfort band, excepted 42nd and 43rd days when the outside RH value drops below 20% (Figure 5.6).

During the 45-day summer period of 2017 in Muğla, the outer RH shows a general trend over the 40-60% thermal comfort band (Figure 5.5). However, similar to Konya case, the indoor RH value are preserved within the thermal comfort band except the outer RH values drops into nearly 25% on the 42nd and 43rd days.

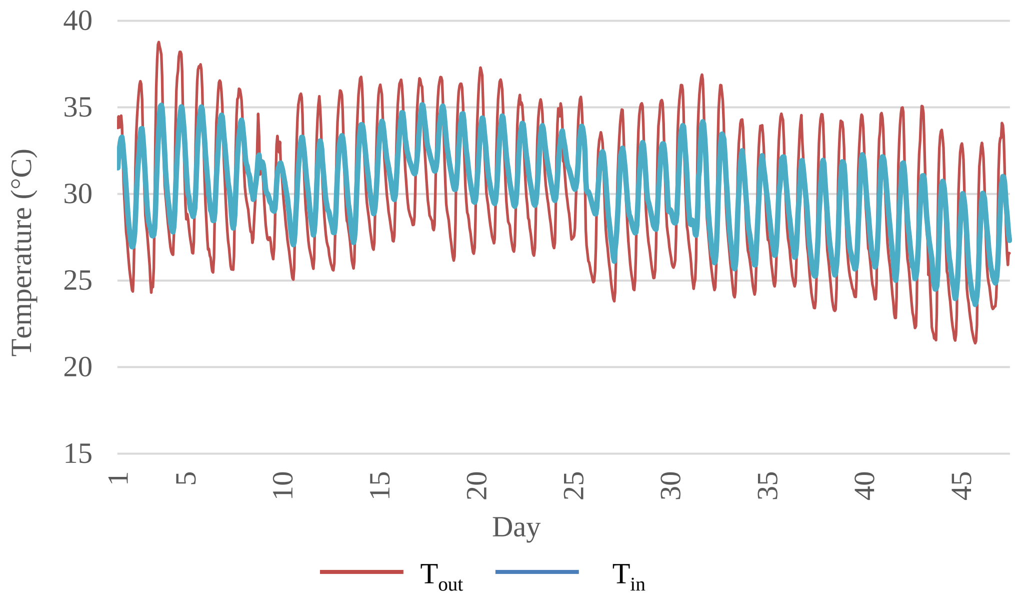


Figure 5.3. Temperature results of on-site measurements for case building in Muğla (28.07-10.09.2017)

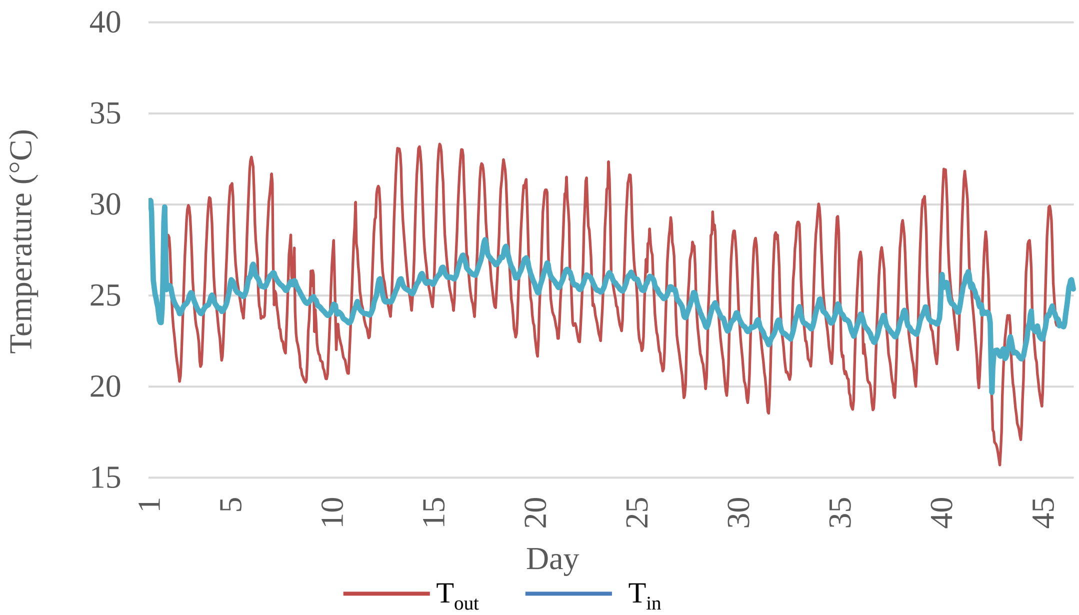


Figure 5.4. Temperature results of on-site measurements for case buildings in Konya (28.07-10.09.2017)

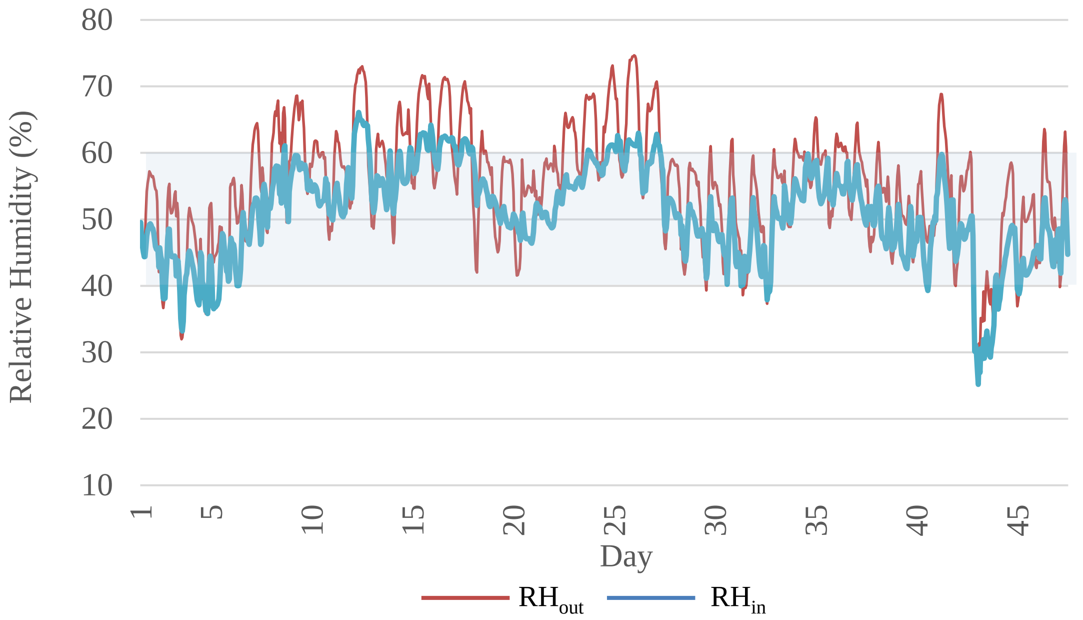


Figure 5.5. Relative humidity results of on-site measurements for case building in Muğla (28.07-10.09.2017)

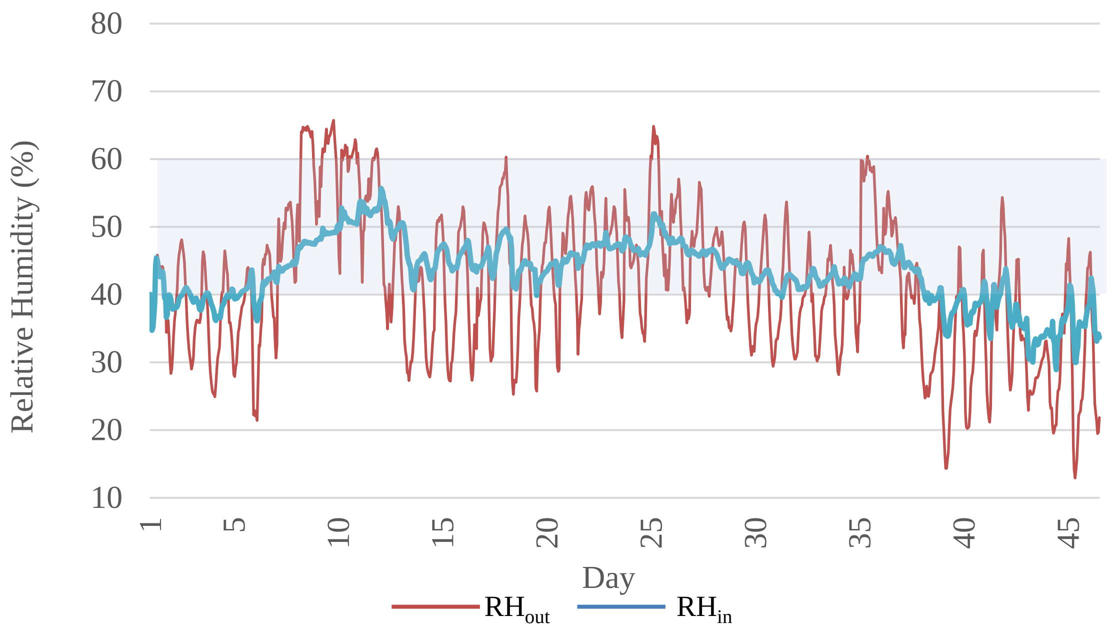


Figure 5.6. Relative humidity results of on-site measurements for case building in Konya (28.07-10.09.2017)

5.3. Calibration Results

MBE and CV-RMSE calibration results for case building in Muğla is 2.76% and 5.86% while Konya is 0.08 and 3.91, respectively (Table 5.2). Therefore, both models are accepted as calibrated within the acceptable range as indicated in three guidelines ASHRAE14-2002 (2002), IPMVP (2002) and M&VGuidelines (2008).

The calibration process for case building in Muğla was achieved with several changings. The calibration results of prior model were 9.40% of CV-RMSE and 7.78% of MBE. In order to minimize errors in both models, the ground material laid in the foundations and light transmittance value for surrounded trees and buildings were changed as the earth, and from 0.0 to 0.5, respectively.

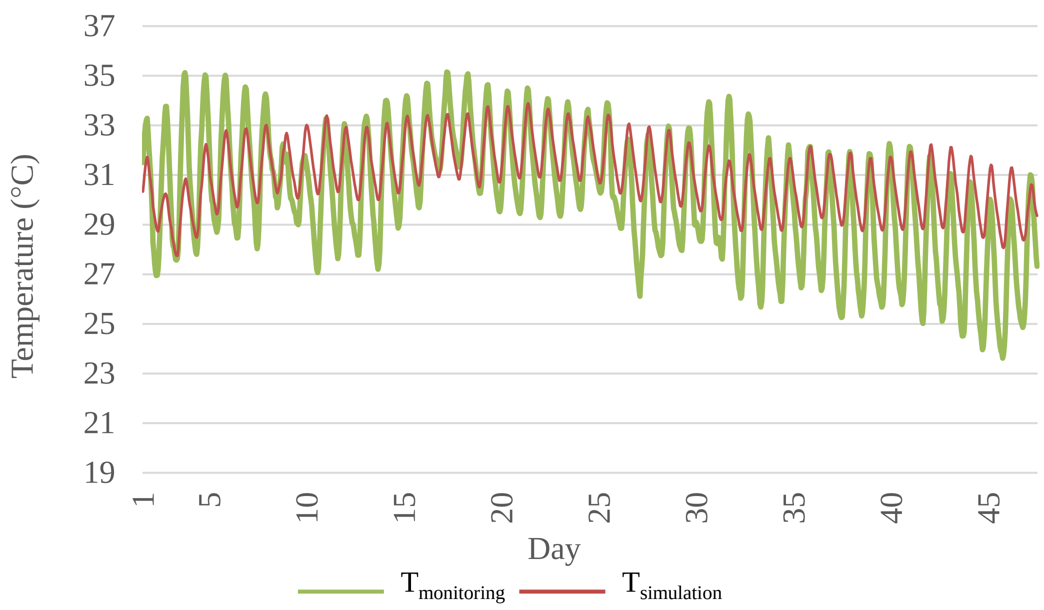


Figure 5.7. Monitored and simulated indoor temperatures for case building in Muğla

It is the fact that the adobe as a natural wall material is unavailable in the material library of DB. The thermal properties of adobe, specified in Table 4.2, are defined from the literature, given in Table 2.4. The simulation of base scenarios with 0.30-meter thicknesses for Muğla and 0.50-meter thicknesses for Konya were conducted by the same type of adobe properties, even if it may differ per each case. The monitored and simulated indoor temperatures in both locations express that, the temperature fluctuation in monitoring results of Muğla is more than calibrated one, while vice versa for Konya. It can be concluded that the thermal conductivity value of adobe in Muğla may be higher than that of the fictionalized computer. This explains that the thermal properties of adobe show difference in both regions (Figure 5.7 and Figure 5.8).

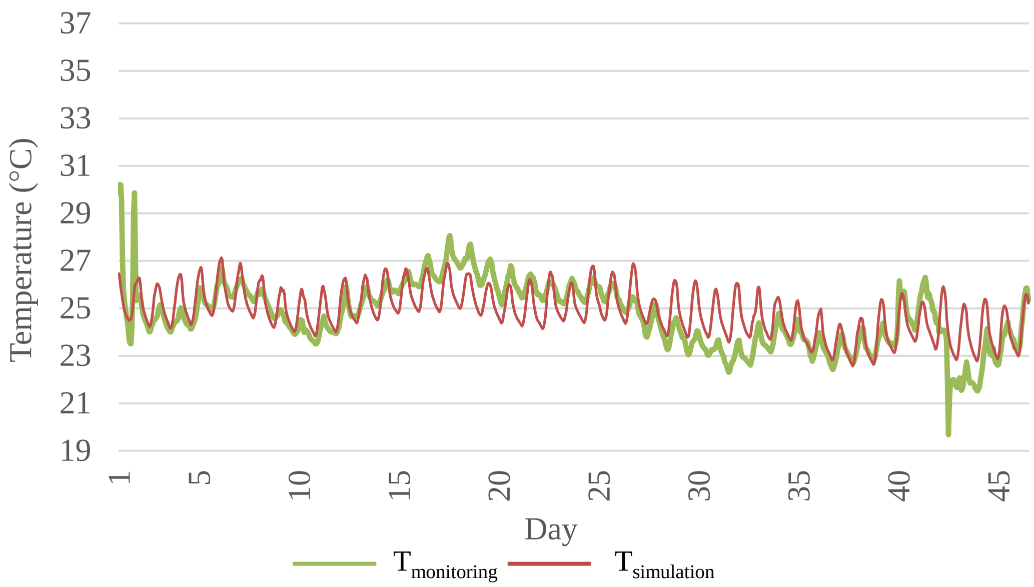


Figure 5.8. Monitored and simulated indoor temperatures for case building in Konya

Table 5.2. Calibration results for case building in Muğla and Konya

Statistical Indices		Ashare 14-2002 (%)	IPMVP (%)	MVFEP (%)	Calibrated Model-Muğla (%)	Calibrated Model-Konya (%)
hourly	MBE	±10	±20	±10	2.76	0.08
	RMSE	30	20	30	5.86	3.91

5.4. Simulation and Energy Consumption Results

In this chapter results gathered all simulations process were compared for both Mugla and Konya case buildings, respectively. The results are divided into four groups. These are firstly; modified decrement factor and time lag, secondly; energy consumption results for case building in Muğla, thirdly; energy consumption results for case building in Konya, and lastly; switch of climate per buildings. The two of these four groups were divided into three subgroups among themselves. These are firstly; energy consumption of case building and base scenarios, secondly; annual energy consumption results of optimization options and lastly; energy consumption results in cooling period for optimization option.

5.4.1. Modified Decrement Factor and Time Lag

Modified Decrement Factor and Time Lag results were tested on the building located in Muğla and Konya climate for 12th August. The reason for choosing the date of 12th August is because the temperature and humidity values between 10th, 11th, 12th and 13th August are more stable than the other days.

Thermal diffusivity is calculated for conducting the relationship with modified decrement factor of materials with equation 4.7. For example, for adobe, thermal diffusivity as follows:

$$\alpha = \frac{0.4\ \frac{W}{mK}}{1500\frac{kg}{m^3}\ x\ 1250\ \frac{J}{kgK}} = 2.1\ x\ 10^{-7}\ \frac{m^2}{s}$$

For VHB, limestone, hempcrete and strawbale, the calculation is made via equation 4.7, shown in Table 5.3. Considering the thermal diffusivity of the materials used in wall options, hempcrete has minimum thermal diffusivity with $1.7x10^{-7}$ and strawbale has maximum thermal diffusivity with $17x10^{-7}$. It is deduced from the calculation that the rate of heat transfer of strawbale from the hot end to the cold end is 10 times more than hempcrete.

Table 5.3. Thermal diffusivity of each wall material

Materials	Conductivity [W/mK]	Specific Heat [J/kgK]	Density [kg/m^3]	Thermal Diffusivity [m^2/s]
Adobe	0.400	1250	1500	2.1E-07
VHB	0.450	850	1000	5.3E-07
Limestone	1.100	1000	1800	6.1E-07
Hempcrete	0.090	1600	330	1.7E-07
Strawbale	0.060	600	60	17E-07

5.4.1.1. Modified Decrement Factor and Time Lag for Case Building in Muğla

In Muğla case building, the monitored indoor and outdoor temperatures of 10th, 11th, 12th and 13th August are observed, shown in

Figure 5.9, and 12th August is selected for investigating. According to the monitoring results during 12th August, shown in

Figure 5.10, the maximum recorded outdoor and indoor temperatures are 36.6°C at 14.00 and 35.15°C at 17.00, respectively whereas the minimum recorded outdoor and indoor temperatures are 28.2°C at 06.00 and 31.1°C at 08.00 in the morning respectively.

When the maximum recorded indoor and outdoor temperatures are investigated, it is seen that there is a delay of 3 hours to increase indoor temperature, and the MDF is calculated as 0.817.

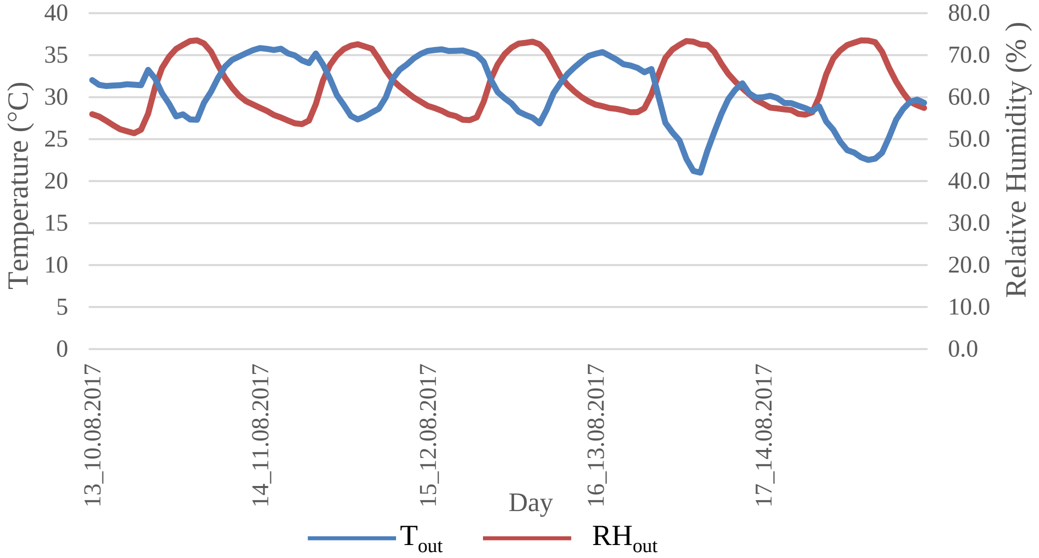


Figure 5.9. Monitoring temperature and relative humidity results for case building in Muğla for 10th, 11th, 12th and 13th August 2017

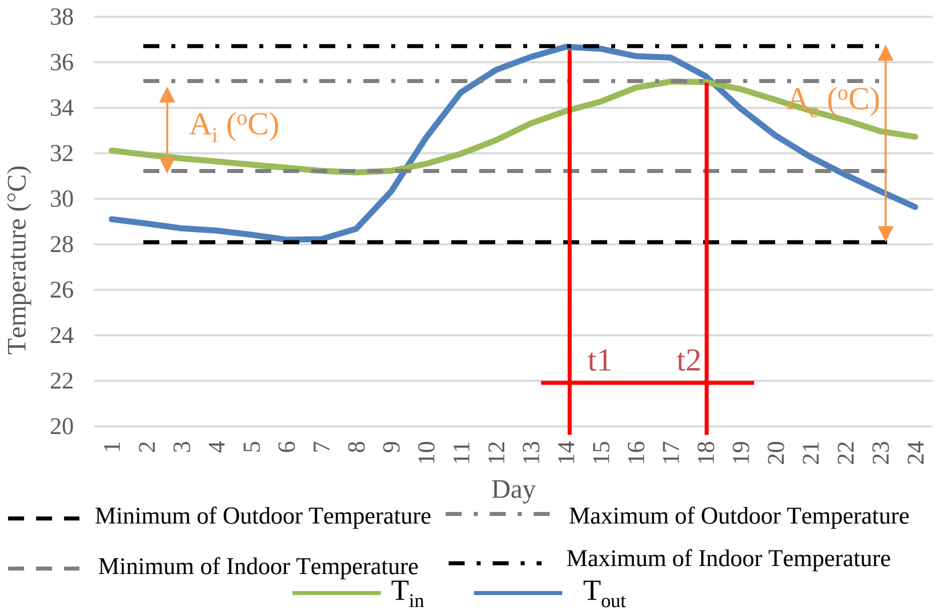


Figure 5.10. 12th August monitoring results for case building in Muğla

When Muğla model is simulated with 1st wall option with its own wall material (adobe, 0.30-meter without insulation) in 12th August, the maximum and minimum simulated indoor temperatures are 28.1°C at 18.00 and 25.2°C whereas the maximum and minimum outdoor temperatures are 36.6°C at 14.00 and 28.2°C at 06.00 in the morning, respectively. MDF is calculated as 0.3341, shown in Table 5.4.

Table 5.4. MDF and time lag simulation results for case building in Muğla

Base Scenarios of all Wall options	**T_{inside} max [°C]**	**T_{inside} min [°C]**	**T_{inside} max Hour**	**T_{inside} (max-min) [°C]**	**$T_{outside}$ (max-min) [°C]**	**Time Lag [hours]**	**Modified Decrement Factor**
01_Adobe_30_no ins (Muğla Case Building)	28.07	25.25	17:00	2.82	8.44	3	0.3342
02_VHB_30_no_ins	28.15	25.24	18:00	2.90	8.44	4	0.3440
03_Limestone_30_no_ins	28.61	25.84	19:00	2.76	8.44	5	0.3273
04_Hempcrete_30_no_ins	27.59	24.51	18:00	3.09	8.44	4	0.3656
05_Strawbale_30_no_ins	27.64	24.31	18:00	3.33	8.44	4	0.3948
06_Adobe_50_no_ins	27.80	24.80	18:00	3.00	8.44	4	0.3558
07_VHB_50_no_ins	27.88	24.95	18:00	2.93	8.44	4	0.3474
08_Limestone_50_no_ins	28.28	25.50	18:00	2.78	8.44	4	0.3292
09_Hempcrete_50_no_ins	27.49	24.35	18:00	3.14	8.44	4	0.3720
10_Strawbale_50_no_ins	27.49	24.28	18:00	3.22	8.44	4	0.3810
11_Adobe_30_flax	27.54	24.78	18:00	2.77	8.44	4	0.3278
12_VHB_30_flax	27.68	24.68	17:00	3.01	8.44	3	0.3561
13_Limestone_30 flax	27.70	24.74	18:00	2.96	8.44	4	0.3505
14_Hempcrete_30_flax	27.55	24.44	18:00	3.11	8.44	4	0.3680
15_Strawbale_30_flax	27.59	24.31	18:00	3.29	8.44	4	0.3895
16_Adobe_50_flax	27.49	24.44	18:00	3.05	8.44	4	0.3615
17_VHB_50_flax	27.61	24.57	18:00	3.04	8.44	4	0.3603
18_Limestone_50 flax	27.59	24.58	18:00	3.00	8.44	4	0.3555
19_Hempcrete_50 flax	27.46	24.32	18:00	3.14	8.44	4	0.3722
20_Strawbale_50_ Flax	27.48	24.28	18:00	3.20	8.44	4	0.3788

When the other 19 scenarios are assessed, the maximum and minimum MDF results are 0.3948 and 0.3273 with 5th wall option (strawbale, 0.30-meter without insulation) and 3rd wall option (limestone, 0.30-meter without insulation), respectively. When the results of time lag were examined, maximum 5 hours with 3rd wall option (limestone, 0.30-meter without insulation) and minimum 3 hours with 1st wall option (adobe, 0.30-meter without insulation) were obtained. It was assumed that the time lag result was not significant due to the modification of decrement factor calculation. In the actual calculation, the maximum and minimum temperatures of the wall surface and the time at those points were taken. However, the ambient temperatures in the modified equation were taken in this research study.

Table 5.5: Comparison monitoring and simulation MDF and time lag results for case building in Muğla with its own wall material

Muğla Case Building	MDF	Time Lag (hours)
Monitoring MDF	0.3342	3
Simulation MDF	0.817	3

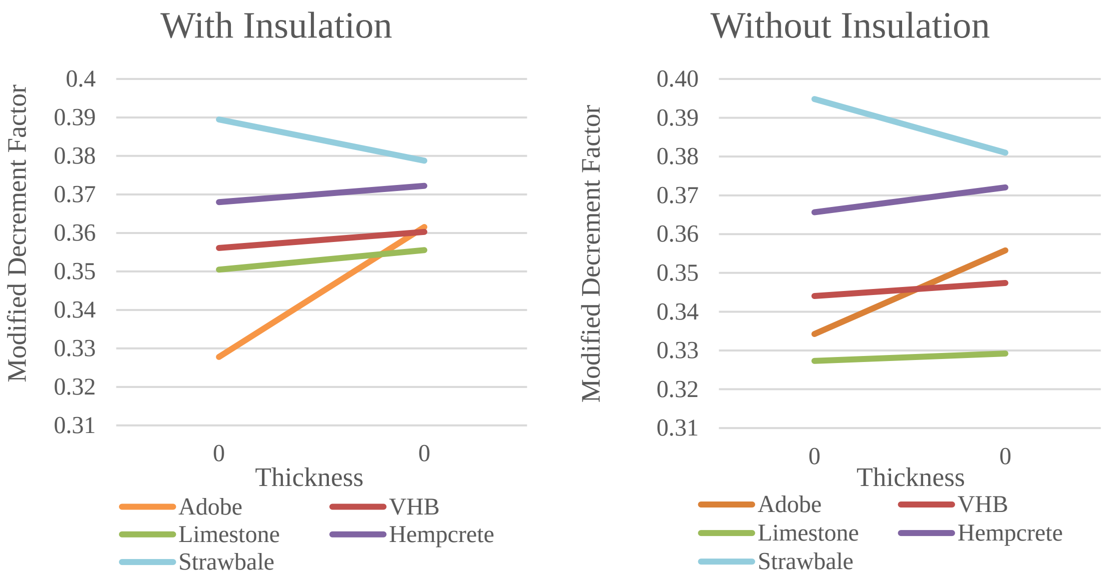


Figure 5.11. Materials with and without insulation of MDF results for case building in Muğla

Decrement factor gives us information regarding how the inside temperature affected outside temperature. Decrement factor is never 1 because if the decrement factor is 1 then the outside air temperature would eventually be achieved internally. This circumstance is not wanted. Therefore, minimum decrement factor means that the difference between maximum and minimum temperatures means less. In this study, decrement factor is modified, and it is uses ambient temperature, not surface temperature. Therefore, materials, thickness and insulation cannot be associated with modified decrement factor in a meaningful way, shown in Figure 5.11. Figure 5.12 shows the simulation results in 12th August for case scenario and base scenarios for Muğla.

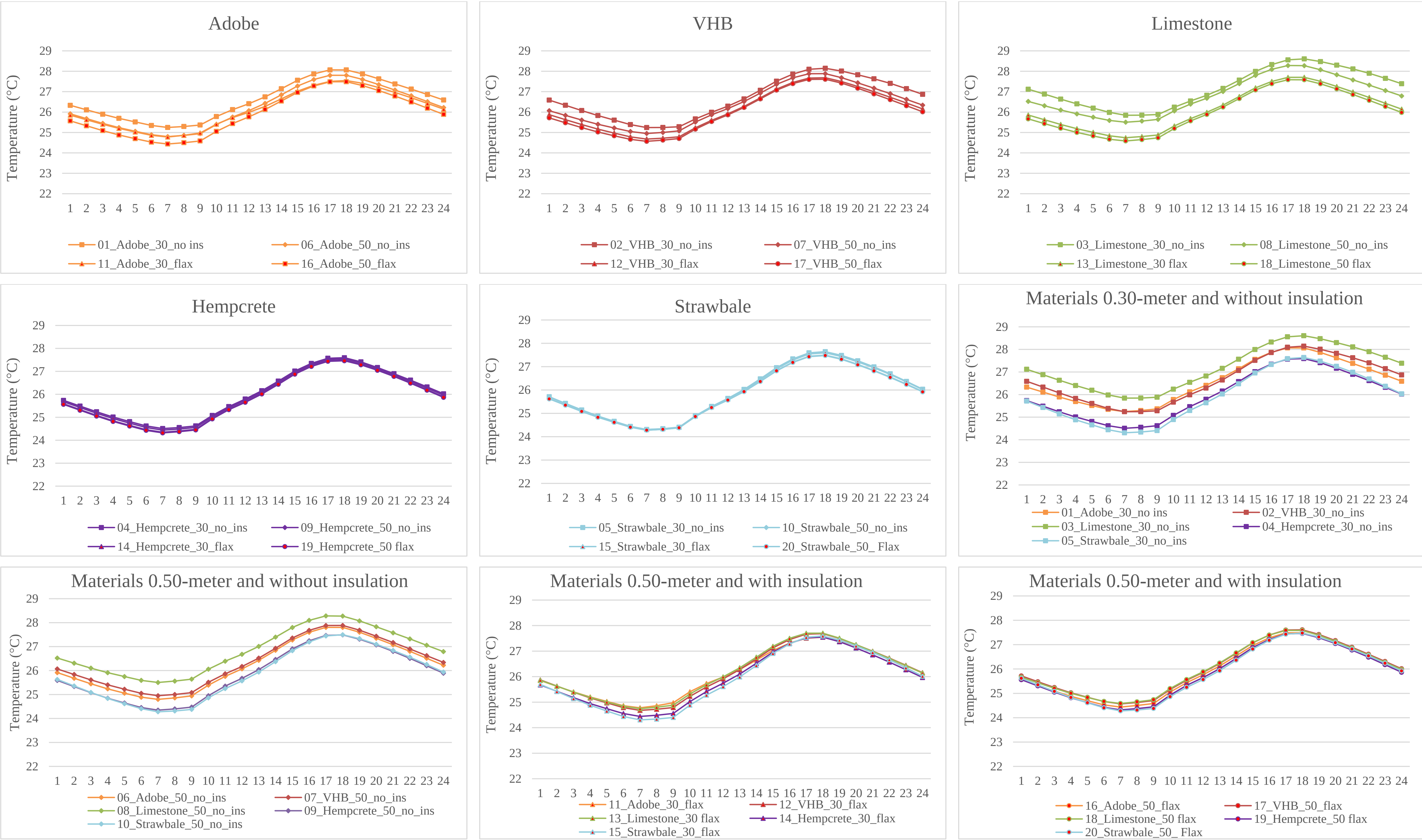


Figure 5.12. Temperature results for 12th August for case scenario and base scenarios for Muğla

5.4.1.2. Modified Decrement Factor and Time Lag for Case Building in Konya

In Muğla case building, the monitored indoor and outdoor temperatures of 10th, 11th, 12th and 13th August are observed, shown in

Figure 5.13, and 12th August is selected for investigating. According to the monitoring results during 12th August, shown in Figure 5.14, the maximum recorded outdoor and indoor temperatures are 33.2°C at 15.00 and 27.2°C at 17.0, respectively whereas the minimum recorded outdoor and indoor temperatures are 24.2°C at 06.00 and 25.9°C at 06.00 in the morning, respectively.

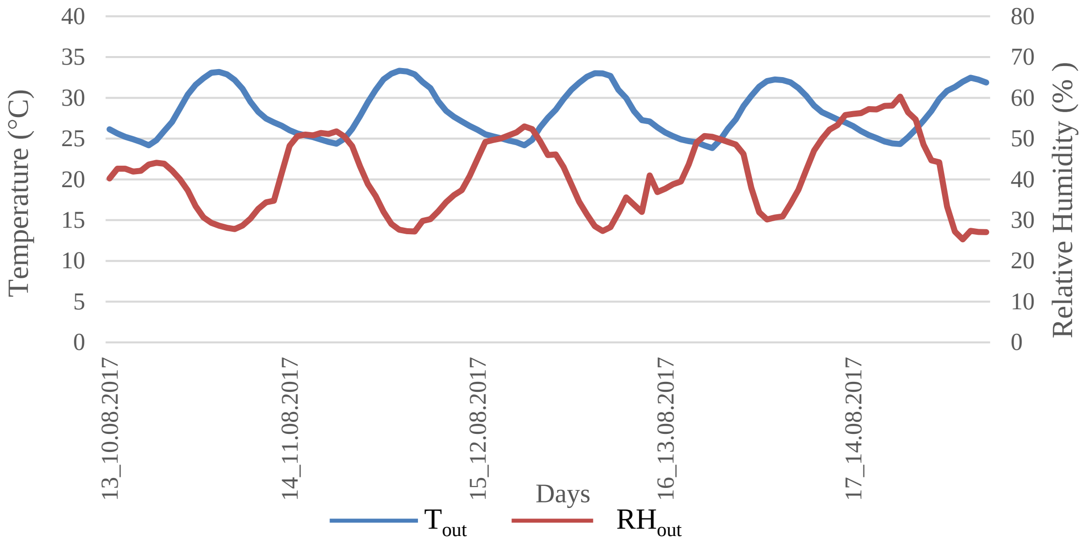


Figure 5.13. Monitoring temperature and relative humidity results for case building in Muğla for 10th, 11th, 12th and 13th August 2017

When the maximum recorded indoor and outdoor temperatures are assessed, it is seen that there is a delay of 2 hours to increase indoor temperature. MDF is calculated as 0.1473 when monitoring results calculated.

When Konya model is simulated with 6th wall option with its own material (adobe, 0.50-meter thickness without insulation), the maximum and minimum indoor temperatures are 24.1°C at 14.00 and 22.1°C whereas the maximum and minimum outdoor temperatures are 33.0°C at 15.00 and 24.2°C at 06.00 in the morning. MDF is calculated as 0.2294, shown in Table 5.6.

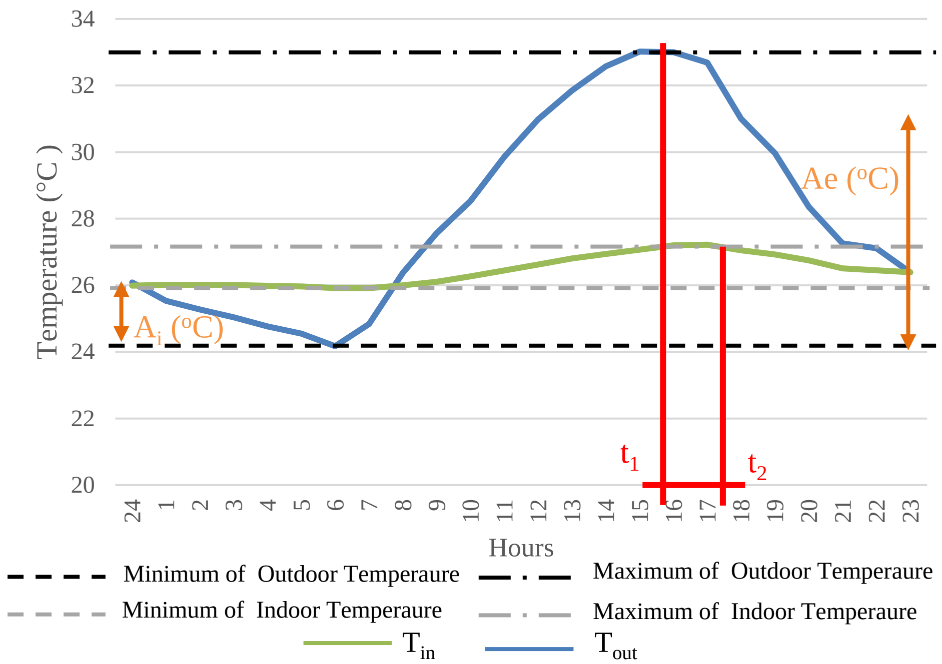


Figure 5.14. 12th August monitoring results for case building in Konya

Table 5.6. MDF and time lag simulation results for case building in Konya

Base Scenarios of all Wall options	**T_{inside} max [°C]**	**T_{inside} min [°C]**	**T_{inside} max Hour**	**T_{inside} (max-min) [°C]**	**$T_{outside}$ (max-min) [°C]**	**Time Lag [hours]**	**Modified Decrement Factor**
01_Adobe_30_no ins	24.55	22.63	14:00	1.91	8.69	1	0.2160
02_VHB_30_no_ins	24.60	22.67	15:00	1.93	8.69	0	0.2180
03_Limestone_30_no_ins	25.07	23.37	15:00	1.71	8.69	0	0.1927
04_Hempcrete_30_no_ins	23.93	21.69	16:00	2.24	8.69	1	0.2533
05_Strawbale_30_no_ins	23.96	21.45	15:00	2.50	8.69	0	0.2830
06_Adobe_50_no_ins (Konya Case Building)	24.13	22.10	14:00	2.03	8.69	1	0.2294
07_VHB_50_no_ins	24.25	22.24	14:00	2.00	8.69	1	0.2265
08_Limestone_50_no_ins	24.72	22.93	14:00	1.79	8.69	1	0.2021
09_Hempcrete_50_no_ins	23.70	21.47	16:00	2.23	8.69	1	0.2519
10_Strawbale_50_no_ins	23.70	21.36	15:00	2.33	8.69	0	0.2638
11_Adobe_30_flax	23.99	21.94	14:00	2.05	8.69	1	0.2319
12_VHB_30_flax	24.02	21.95	15:00	2.07	8.69	0	0.2336
13_Limestone_30 flax	24.04	22.08	15:00	1.96	8.69	0	0.2218
14_Hempcrete_30_flax	23.86	21.60	16:00	2.25	8.69	1	0.2548
15_Strawbale_30_flax	23.90	21.44	15:00	2.45	8.69	0	0.2772
16_Adobe_50_flax	23.79	21.74	14:00	2.05	8.69	1	0.2313
17_VHB_50_flax	23.87	21.79	14:00	2.08	8.69	1	0.2347
18_Limestone_50 flax	23.91	21.94	14:00	1.96	8.69	1	0.2218
19_Hempcrete_50 flax	23.66	21.44	16:00	2.23	8.69	1	0.2516
20_Strawbale_50_ Flax	23.68	21.36	15:00	2.32	8.69	0	0.2620

When the base scenarios are examined, the maximum and minimum MDF results are 0.2830 and 0.1927 for 5th wall option (strawbale, 0.30-meter without insulation) and 3rd wall option (limestone, 0.30-meter without insulation), respectively. When the results of time lag were examined, maximum 1 hours and minimum 0 hours were obtained. It was assumed that the time lag results were not significant due to the modification of decrement factor calculation. In the actual calculation, the maximum and minimum temperatures of the wall surface and the time at those points were taken, while the ambient temperatures in the modified equation were taken.

Table 5.7: Comparison monitoring and simulation MDF and time lag results for case building in Konya with its own wall material

Konya Case Building	MDF	Time Lag [hours]
Monitoring MDF	0.1473	2
Simulation MDF	0.2294	1

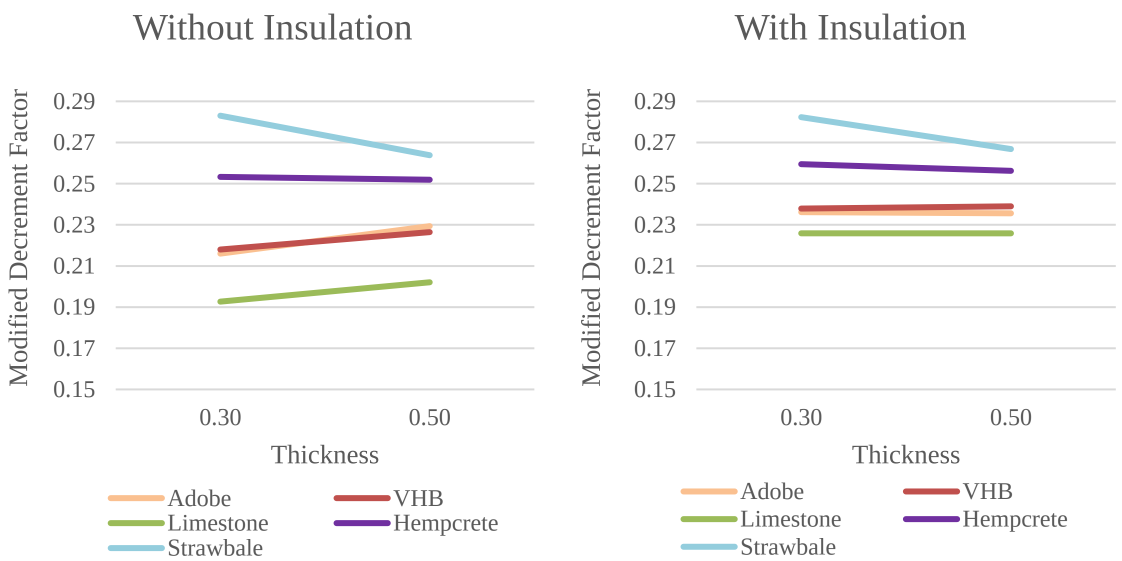


Figure 5.15. Materials with and without insulation of MDF results for case building in Konya

In this study, decrement factor is modified, and it is uses ambient temperature, not surface temperature. Therefore, materials, thickness and insulation cannot be associated with modified decrement factor in a meaningful way, shown in Figure 5.15. Figure 5.16 shows the simulation results in 12th August for case scenario and base scenarios for Muğla.

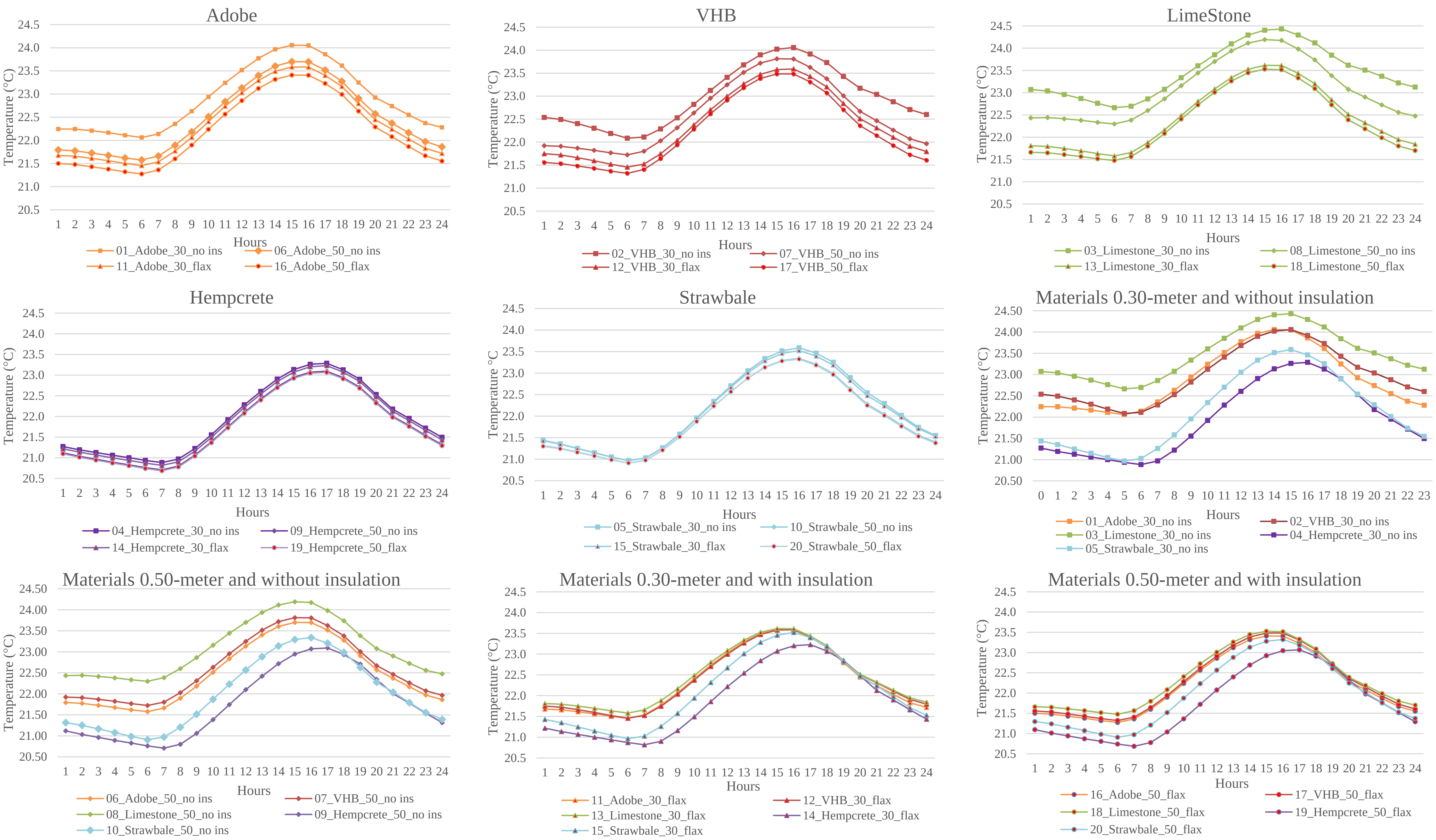


Figure 5.16. Temperature results for 12th August for all 20th wall option scenario for Konya model.

5.4.2. Energy Consumption Results for Case Building in Muğla

5.4.2.1. Energy Consumption of Case Building and Base Scenarios

The annual energy consumption results for 19 base scenarios and the case scenario (1st wall option) are presented in Table 5.8 and Figure 5.17 for Muğla model. The base scenarios represent the wall options with same wall material for four façades. Scenarios in this section has no natural ventilation, because they are the base case scenarios in which all openings are kept closed as applied in on-site measurements.

Table 5.8. Comparison of energy consumption values for 19 base scenarios and the case scenario of Muğla model ('-': decrease in energy consumption)

Base Scenarios of all Wall Options	**Cooling (kWh)**	**Heating (kWh)**	**Total (kWh)**	**Ratio (Cooling)**	**Ratio (Heating)**	**Ratio (Total)**
01_Adobe_30_no ins (Muğla Case Building)	1795	3789	5584	-	-	-
02_VHB_30_no ins	1837	3890	5727	2.3%	2.7%	2.6%
03_Limestone_30_no ins	2203	4449	6652	22.7%	17.4%	19.1%
04_Hempcrete_30_no ins	1361	3146	4507	-24.2%	-17.0%	-19.3%
05_Strawbale_30_no ins	1327	3094	4421	-26.1%	-18.3%	-20.8%
06_Adobe_50_no ins	1584	3451	5035	-11.8%	-8.9%	-9.8%
07_VHB_50_no_ins	1620	3529	5149	-9.7%	-6.9%	-7.8%
08_Limestone_50_no ins	1971	4038	6009	9.8%	6.6%	7.6%
09_Hempcrete_50_no ins	1282	3013	4295	-28.6%	-20.5%	-23.1%
10_Strawbale_50_no ins	1258	2983	4241	-29.9%	-21.3%	-24.1%
11_Adobe_30_flax	1435	3271	4706	-20.1%	-13.7%	-15.7%
12_VHB_30_flax	1447	3295	4742	-19.4%	-13.0%	-15.1%
13_Limestone_30 flax	1483	3349	4832	-17.4%	-11.6%	-13.5%
14_Hempcrete_30_flax	1321	3087	4408	-26.4%	-18.5%	-21.1%
15_Strawbale_30_flax	1307	3061	4368	-27.2%	-19.2%	-21.8%
16_Adobe_50_flax	1376	3176	4552	-23.3%	-16.2%	-18.5%
17_VHB_50_flax	1397	3205	4602	-22.2%	-15.4%	-17.6%
18_Limestone_50 flax	1449	3287	4736	-19.3%	-13.2%	-15.2%
19_Hempcrete_50 flax	1266	2991	4257	-29.5%	-21.1%	-23.8%
20_Strawbale_50_ Flax (Minimum Energy Result)	1250	2971	4221	-30.4%	-21.6%	-24.4%

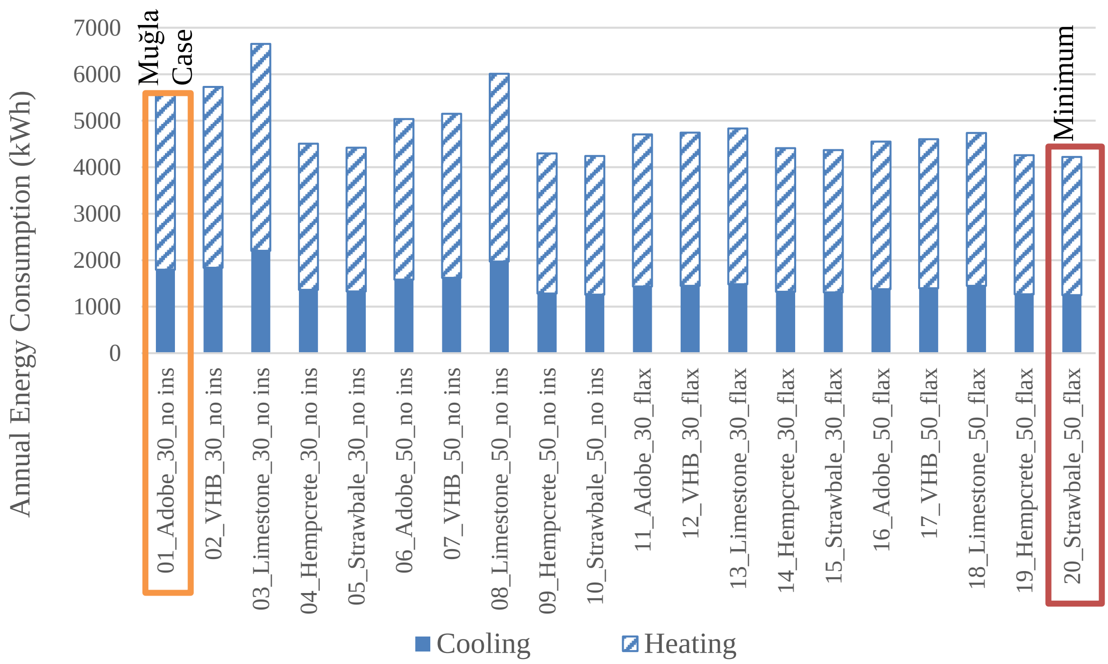


Figure 5.17. Annual energy consumption for 19 base scenarios and the case scenarios in Muğla model

According to Table 5.8, the building with 20th wall option (strawbale, 0.50- meter with flax insulation) consumes minimum energy for whole year of 4221 kWh, while the consumption of existing building, i.e. case scenario with the 1st wall option (adobe, 0.30-meter without insulation), is 5584 kWh. In other words, the annual energy decreases with the ratio of 24.4%, when 0.50-meter strawbale with flax insulation is used.

Besides, the minimum heating and cooling energy consumptions are with the same wall option i.e. 20th, values of 2971 kWh and 1250 kWh, respectively. Compared to the case scenario, their heating and cooling energy consumption drop into the ratio of 30.4% and 21.6%, respectively. All wall options about adobe, hempcrete and strawbale provide less energy consumption.

2nd (VHB, 0.30-meter with flax insulation) and 3rd (limestone, 0.30-meter with flax insulation) wall options provide more energy consumption. According to Figure 5.17, the maximum energy consumption is with 3rd wall option of 6652 kWh, annually. Compared to the case scenario, this wall option causes to increase in consumption with the ratio of 19.1%.

5.4.2.2. Annual Energy Consumption Results of Optimization Options

Various combinations of wall options and façade orientations are investigated in Muğla model to find which material and façade combination will provide the minimum energy consumption. Here, single or double façades of building are kept constant with just one wall option while all 20 wall options are applied simultaneously to other façade(s). For 10 optimisation options, totally, 8000 combinations are analysed in DB optimization tool.

For annual energy consumption, the 7th optimization option gives minimum results while nigh- time ventilation is on. 20 wall options were applied one by one into the wall on the southeast and southwest side (Figure 5.19). During each application to these façades, 20 wall options were examined on the other façades, simultaneously. Afterwards, energy consumption results were obtained from each combination. Table 5.9 shows the minimum energy consumption results.

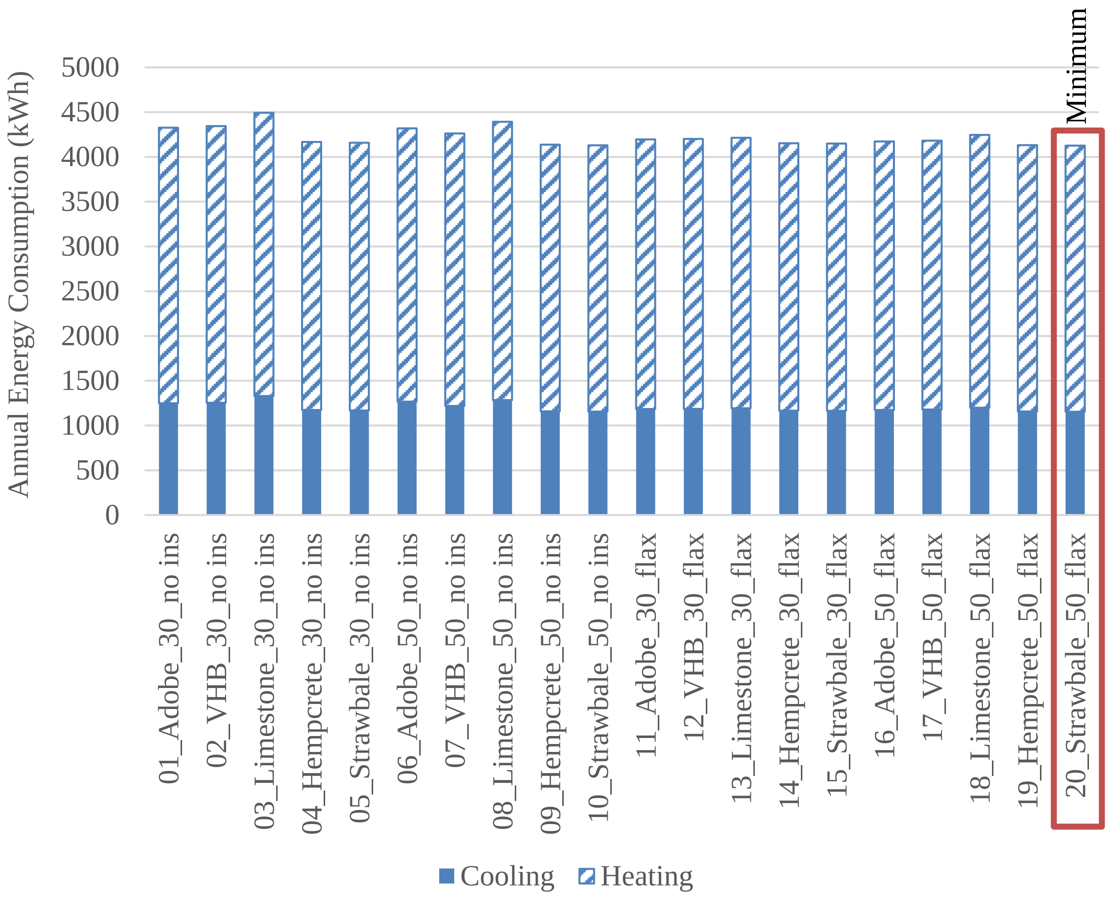


Figure 5.18. Annual energy consumption for 7th optimisation option while night-time ventilation is on, in Muğla model

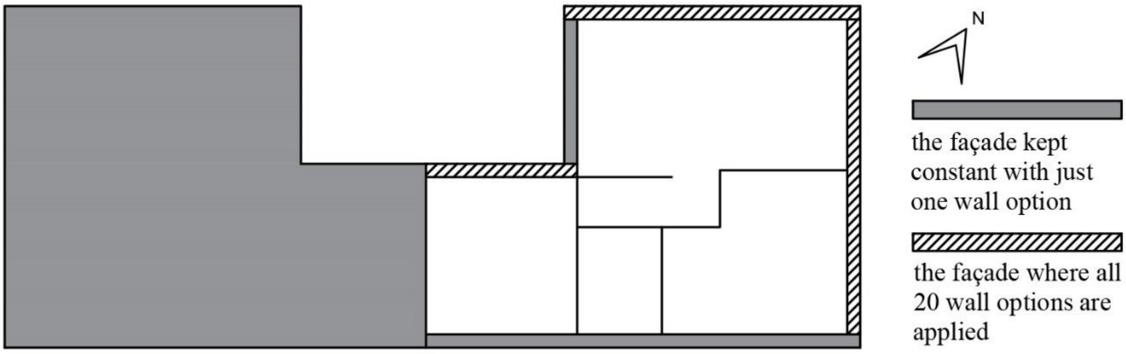


Figure 5.19. Schematic plan for 7th optimization option which southeast and southwest façades are kept constant, and other two façades are examined with 20-wall options in Muğla model

Table 5.9. Comparison of energy consumption results for 7th optimization option while night-time ventilation is on, in Muğla model ('-' decrease in energy consumption)

Wall option kept constant (on southeast and southwest façades)	**20 wall options (on northeast and northwest façades)**	**Cooling (kWh)**	**Heating (kWh)**	**Total (kWh)**	**Ratio (Cooling)**	**Ratio (Heating)**	**Ratio (Total)**
01_Adobe_30_no ins (Muğla Case Scenario)		1795	3784	5584	-	-	-
01_Adobe_30_no ins	20_Strawbale_50_ Flax	1436	3223	4659	-20.0%	-14.9%	-16.6%
02_VHB_30_no ins	20_Strawbale_50_ Flax	1456	3263	4719	-18.9%	-13.9%	-15.5%
03_Limestone_30_no ins	20_Strawbale_50_ Flax	1669	3440	5109	-7.0%	-9.2%	-8.5%
04_Hempcrete_30_no ins	20_Strawbale_50_ Flax	1210	3026	4236	-32.6%	-20.1%	-24.1%
05_Strawbale_30_no ins	20_Strawbale_50_ Flax	1194	3015	4209	-33.5%	-20.4%	-24.6%
06_Adobe_50_no ins	20_Strawbale_50_ Flax	1325	3112	4437	-26.2%	-17.9%	-20.5%
07_VHB_50_no ins	20_Strawbale_50_ Flax	1344	3142	4486	-25.1%	-17.1%	-19.7%
08_Limestone_50_no ins	20_Strawbale_50_ Flax	1535	3297	4833	-14.5%	-13.0%	-13.5%
09_Hempcrete_50 no ins	20_Strawbale_50_ Flax	1170	2982	4153	-34.8%	-21.3%	-25.6%
10_Strawbale_50_no ins	20_Strawbale_50_ Flax	1158	2977	4134	-35.5%	-21.4%	-26.0%
11_Adobe_30_flax	20_Strawbale_50_ Flax	1248	3064	4312	-30.5%	-19.1%	-22.8%
12_VHB_30_flax	20_Strawbale_50_ Flax	1253	3075	4328	-30.2%	-18.9%	-22.5%
13_Limestone_30 flax	20_Strawbale_50_ Flax	1272	3091	4363	-29.1%	-18.4%	-21.9%
14_Hempcrete_30_flax	20_Strawbale_50_ Flax	1190	3008	4198	-33.7%	-20.6%	-24.8%
15_Strawbale_30_flax	20_Strawbale_50_ Flax	1183	3003	4186	-34.1%	-20.7%	-25.0%
16_Adobe_50_flax	20_Strawbale_50_ Flax	1218	3031	4249	-32.1%	-20.0%	-23.9%
17_VHB_50_flax	20_Strawbale_50_ Flax	1228	3044	4272	-31.6%	-19.7%	-23.5%
18_Limestone_50 flax	20_Strawbale_50_ Flax	1255	3067	4322	-30.1%	-19.1%	-22.6%
19_Hempcrete_50 flax	20_Strawbale_50_ Flax	1162	2976	4138	-35.3%	-21.5%	-25.9%
20_Strawbale_50_ Flax (Minimum Energy Result)	20_Strawbale_50_ Flax	1154	2973	4126	-35.7%	-21.5%	-26.1%

The best result for annual energy consumption was when all wall façades were applied with the 20th wall option (strawbale, 0.50-meter thickness, with flax) of 4126 kWh, while night-time ventilation was on. Thus the annual energy consumption of case building decreases with the ratio of 26.1%.

According to Figure 5.18 and Table 5.9, the lowest energy consumption for heating and cooling is seen when 20th (strawbale, 0.50- meter with flax insulation) wall option applied for four façades with the values of 2973 kWh and 1154 kWh, respectively. In other words, the best optimisation option enables the decrease in consumption with the ratio of 21.5% and 35.7% for heating and cooling, respectively.

5.4.2.3. Energy Consumption Results in Cooling Period for Optimization Options

Various combinations of wall options and façade orientations are investigated in Konya model to find which material and façade combination will provide the minimum energy consumption for cooling. Here, single or double façades of building are kept constant with just one wall option, while all 20 wall options are applied simultaneously to other façade(s). Totally, 8000 combinations are analysed.

For energy consumption in summer, the 5th optimization option provides the minimum results while night-time ventilation is on. 20 wall options were applied one by one to the wall on the southwest and northwest sides (Figure 5.20). During each application to these façades, 20 wall options were examined on the other façades, simultaneously. Afterwards, energy consumption results were obtained from each combination.

According to Table 5.10 and Figure 5.21, the best result for minimum energy consumption in cooling season was when all wall façades were applied the 20th (strawbale, 0.50- meter with flax insulation) of 1154 kWh, while night-time ventilation was on. Thus the energy for cooling in case building decreases with the ratio of 35.7%.

The effect of night-time ventilation for cooling consumption is indicated in Figure 5.21. The opening of all outer windows enables approximately 100 kWh less consumption while night-time ventilation on.

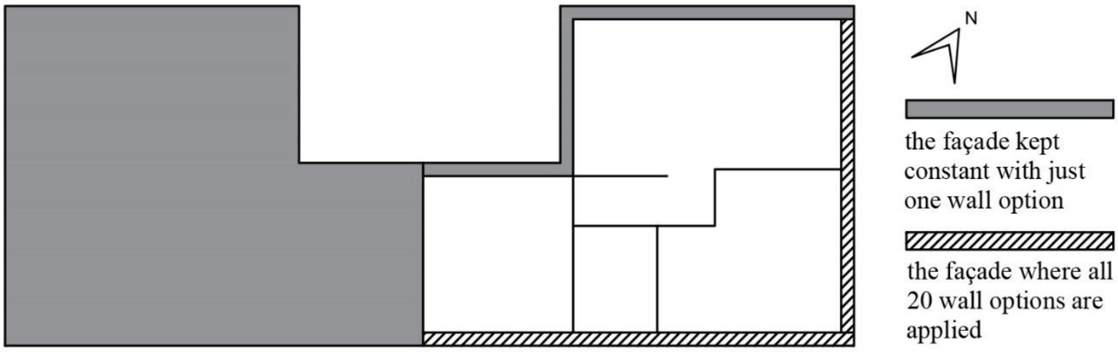


Figure 5.20. Schematic plan for the 5th optimization option which southwest and northwest façades are kept constant, and other façades are examined with 20-wall options in Muğla model

Table 5.10. Comparison of energy consumption results for 5th optimization option while night-time ventilation is on, in Konya model ('-' decrease in energy consumption)

Wall option kept constant (northwest and southwest)	20 wall options (on northeast and southeast)	Cooling (kWh) (NTV on)	Heating (kWh)	Total (kWh)	Ratio (Cooling)	Ratio (Heating)	Ratio (Total)
01_Adobe_30_no ins (Muğla Case Scenario)		1795	3784	5584	-	-	-
01_Adobe_30_no ins	20_Strawbale_50_ Flax	1326	3333	4659	-26.2%	-12.0%	-16.6%
02_VHB_30_no ins	20_Strawbale_50_ Flax	1334	3374	4708	-25.7%	-11.0%	-15.7%
03_Limestone_30_no ins	20_Strawbale_50_ Flax	1467	3625	5093	-18.3%	-4.3%	-8.8%
04_Hempcrete_30_no ins	20_Strawbale_50_ Flax	1189	3049	4238	-33.8%	-19.5%	-24.1%
05_Strawbale_30_no ins	20_Strawbale_50_ Flax	1180	3025	4205	-34.2%	-20.2%	-24.7%
06_Adobe_50_no ins	20_Strawbale_50_ Flax	1258	3186	4445	-29.9%	-15.9%	-20.4%
07_VHB_50_no ins	20_Strawbale_50_ Flax	1270	3218	4488	-29.2%	-15.1%	-19.6%
08_Limestone_50_no ins	20_Strawbale_50_ Flax	1387	3446	4833	-22.7%	-9.1%	-13.5%
09_Hempcrete_50 no ins	20_Strawbale_50_ Flax	1164	2993	4157	-35.1%	-21.0%	-25.6%
10_Strawbale_50_no ins	20_Strawbale_50_ Flax	1156	2978	4134	-35.6%	-21.4%	-26.0%
11_Adobe_30_flax	20_Strawbale_50_ Flax	1211	3105	4315	-32.6%	-18.1%	-22.7%
12_VHB_30_flax	20_Strawbale_50_ Flax	1213	3114	4326	-32.4%	-17.8%	-22.5%
13_Limestone_30 flax	20_Strawbale_50_ Flax	1224	3139	4363	-31.8%	-17.2%	-21.9%
14_Hempcrete_30_flax	20_Strawbale_50_ Flax	1176	3024	4200	-34.5%	-20.2%	-24.8%
15_Strawbale_30_flax	20_Strawbale_50_ Flax	1172	3011	4183	-34.7%	-20.5%	-25.1%
16_Adobe_50_flax	20_Strawbale_50_ Flax	1192	3065	4257	-33.6%	-19.1%	-23.8%
17_VHB_50_flax	20_Strawbale_50_ Flax	1199	3076	4275	-33.2%	-18.8%	-23.4%
18_Limestone_50 flax	20_Strawbale_50_ Flax	1215	3113	4328	-32.3%	-17.8%	-22.5%
19_Hempcrete_50 flax	20_Strawbale_50_ Flax	1159	2983	4142	-35.4%	-21.3%	-25.8%
20_Strawbale_50_ Flax (Minimum Energy Result)	20_Strawbale_50_ Flax	1154	2973	4126	-35.7%	-21.5%	-26.1%

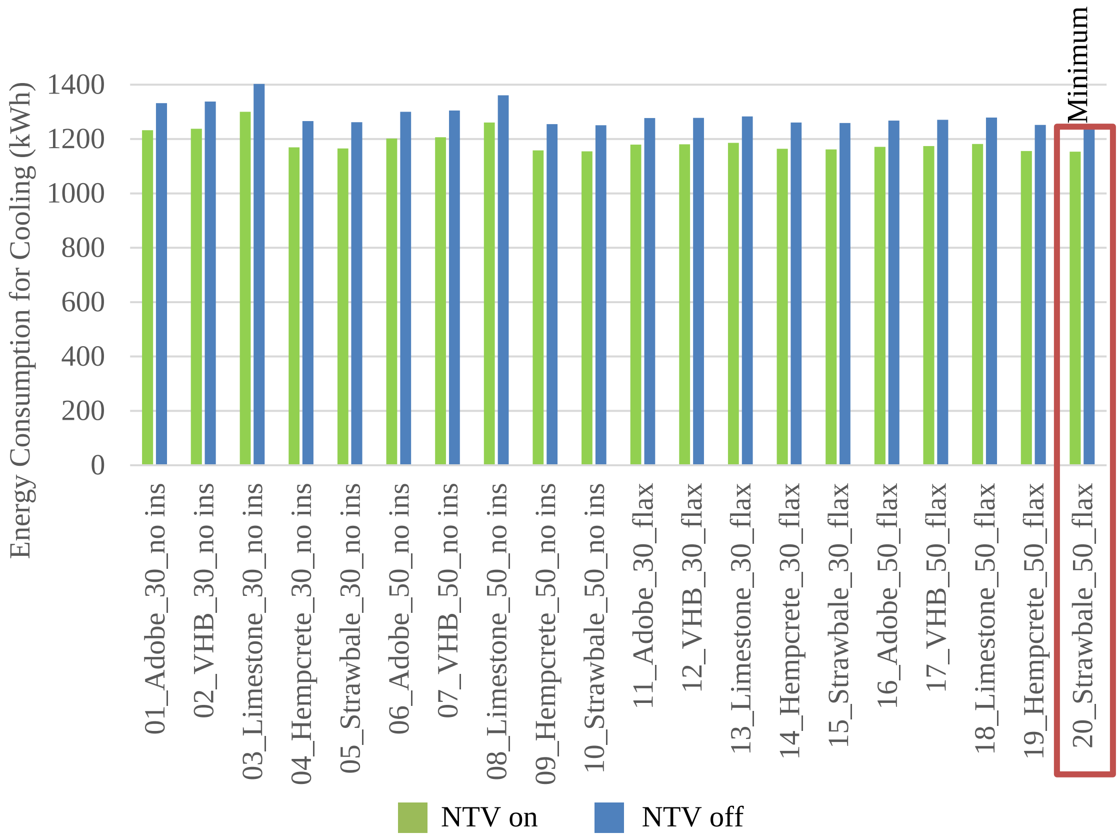


Figure 5.21. Effect of night-time ventilation on energy consumptions for cooling in 5th optimisation option in Muğla model

5.4.3. Energy Consumption Results for Case Building in Konya

5.4.3.1. Energy Consumption of Case Scenario and Base Scenarios

The annual energy consumption results for 19 base scenarios and the case scenario (6th wall option) are presented in Figure 5.22 for Konya model. The base scenarios represent the wall options with the same wall material for four façades. Scenarios in this section has no ventilation because they are base case scenarios in which all openings are kept closed as seen in on-site measurements.

According to Figure 5.22, the building with 20th wall option (strawbale, 0.50-meter with flax insulation) consumes minimum energy for whole year of 3197 kWh, when night-time ventilation is off. The existing building, i.e. case scenario with the 6th wall option (adobe, 0.50-meter without insulation) consumes 5945 kWh. In other words, the annual energy consumption decreases with the ratio of 33.6%, compared to the 20th wall option (strawbale, 0.50- meter with flax insulation).

Table 5.11. Comparison of energy consumption values for 19 base scenarios and the case scenario of Konya model ('-' decrease in energy consumption)

Wall option Base Scenarios	Cooling (kWh)	Heating (kWh)	Total (kWh)	Ratio (Cooling)	Ratio (Heating)	Ratio (Total)
01_Adobe_30_no ins	209	5736	5945	22.1%	23.6%	23.5%
02_VHB_30_no ins	218	5982	6199	27.1%	28.8%	28.8%
03_Limestone_30_no ins	262	7825	8087	52.9%	68.6%	68.0%
04_Hempcrete_30_no ins	175	3638	3812	2.0%	-21.6%	-20.8%
05_Strawbale_30_no ins	187	3435	3622	9.2%	-26.0%	-24.8%
06_Adobe_50_no ins (Konya Case Building)	171	4643	4814	-	-	-
07_VHB_50_no ins	186	4856	5042	8.6%	4.6%	4.7%
08_Limestone_50_no ins	217	6555	6772	26.6%	41.2%	40.7%
09_Hempcrete_50 no ins	157	3191	3348	-8.1%	-31.3%	-30.4%
10_Strawbale_50_no ins	163	3068	3232	-4.6%	-33.9%	-32.9%
11_Adobe_30_flax	166	4049	4215	-3.0%	-12.8%	-12.4%
12_VHB_30_flax	172	4095	4267	0.2%	-11.8%	-11.4%
13_Limestone_30 flax	166	4287	4453	-2.7%	-7.7%	-7.5%
14_Hempcrete_30_flax	170	3449	3619	-0.5%	-25.7%	-24.8%
15_Strawbale_30_flax	180	3338	3518	5.4%	-28.1%	-26.9%
16_Adobe_50_flax	148	3728	3875	-13.7%	-19.7%	-19.5%
17_VHB_50_flax	159	3803	3961	-7.3%	-18.1%	-17.7%
18_Limestone_50 flax	152	4088	4240	-11.1%	-12.0%	-11.9%
19_Hempcrete_50 flax	155	3120	3276	-9.2%	-32.8%	-32.0%
20_Strawbale_50_ Flax (Minimum Energy Result)	162	3035	3197	-5.5%	-34.6%	-33.6%

According to Table 5.11, the maximum energy consumption is 3rd wall option (limestone, 0.30-meter with flax insulation) which consumes 8087 kWh annually. Compared to the case scenario, its consumption increases with the ratio of 68.0%. The minimum heating and cooling energy consumptions are 20th (strawbale, 0.50- meter with flax insulation) wall option and 16th wall option (adobe, 0.50-meter with flax insulation) which consume 3035 kWh and 148 kWh, respectively. Compared to the case scenario, their minimum heating and cooling energy consumption decrease with the ratio of 34.6% and -13.7%, respectively.

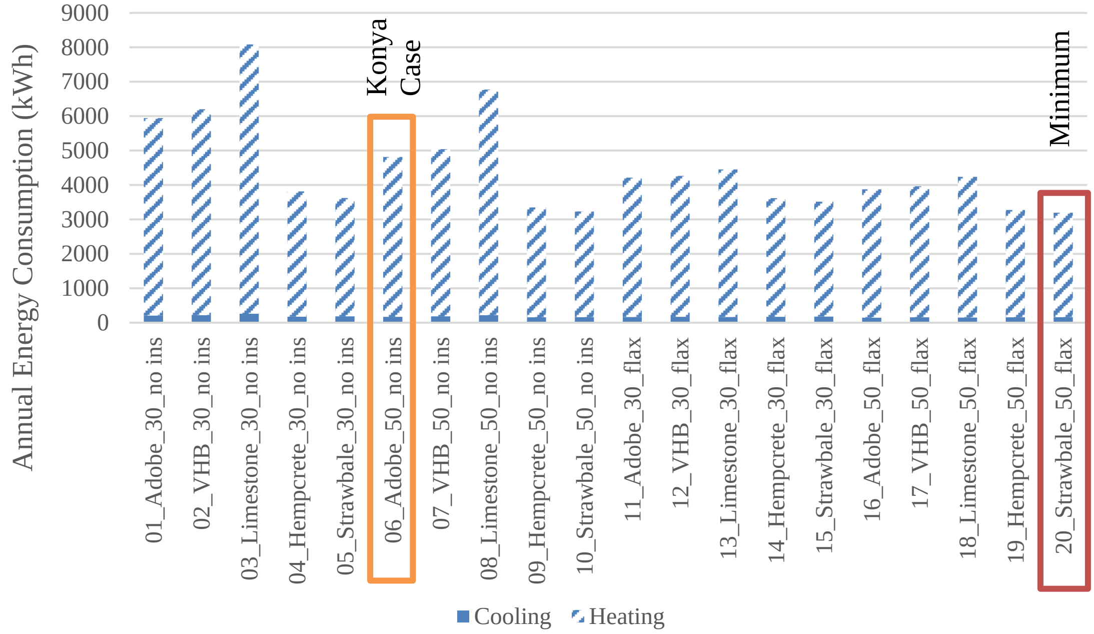


Figure 5.22. Annual energy consumption for 19 base scenarios and the case scenarios in Konya model

5.4.3.2. Annual Energy Consumption Results of Optimization Options

Various combinations of wall options and façade orientations are investigated in Konya model to find which material and façade combination will provide the minimum energy consumption. Here single or double façades of building are kept constant with just one wall option while all 20 wall options are applied simultaneously to other façade(s). Totally 8000 combinations are analysed. For annual energy consumption, the 7th optimization option gives minimum results while nigh- time ventilation is on.

20 wall options were applied individually to the wall on the south and west side. During each application to this southern and western façades, 20 wall options were applied to the walls of the other façades, simultaneously. Afterwards, energy consumption results were obtained from each combination. Table 5.12 shows the minimum energy consumption results. The best result for annual energy consumption was when all wall façades were applied the 20th wall option (strawbale, 0.50-meter thickness, with flax) 3145 kWh while night-time ventilation was on. The annual energy consumption in case building decreases with the ratio of 34.7% when 20th wall option (strawbale, 0.50-meter with flax insulation) is applied.

According to Table 5.12 the minimum heating and cooling energy consumptions are 20th (strawbale, 0.50- meter with flax insulation) wall option and 16th wall option (adobe, 0.50-meter with flax insulation) which consumes 3038 kWh and 99 kWh, respectively. Compared to the case scenario, their minimum heating and cooling energy consumption decrease with the ratio of 34.6% and 42.3%, respectively.

Table 5.12. Comparison of energy consumption results for 7th optimization option while night-time ventilation is on, in Konya model ('-' decrease in energy consumption)

Wall option kept constant (on south and west façade)	**20 wall options (on north and east)**	**Cooling (kWh)**	**Heating (kWh)**	**Total (kWh)**	**Ratio (Cooling)**	**Ratio (Heating)**	**Ratio (Total)**
06_Adobe_50_no ins (Konya Case Scenario)		171	4643	4814	-	-	-
01_Adobe_30_no ins	20_Strawbale_50_ Flax	134	4255	4389	-21.5%	-8.3%	-8.8%
02_VHB_30_no ins	20_Strawbale_50_ Flax	142	4371	4512	-17.3%	-5.9%	-6.3%
03_Limestone_30_no ins	20_Strawbale_50_ Flax	167	5230	5397	-2.2%	12.7%	12.1%
04_Hempcrete_30_no_ins	20_Strawbale_50_ Flax	114	3307	3421	-33.6%	-28.8%	-28.9%
05_Strawbale_30_no ins	20_Strawbale_50_ Flax	123	3222	3345	-28.2%	-30.6%	-30.5%
06_Adobe_50_no ins	20_Strawbale_50_ Flax	113	3753	3866	-34.0%	-19.2%	-19.7%
07_VHB_50_no ins	20_Strawbale_50_ Flax	121	3853	3974	-29.2%	-17.0%	-17.4%
08_Limestone_50_no ins	20_Strawbale_50_ Flax	140	4631	4771	-18.4%	-0.2%	-0.9%
09_Hempcrete_50 no ins	20_Strawbale_50_ Flax	104	3105	3209	-39.4%	-33.1%	-33.3%
10_Strawbale_50_no ins	20_Strawbale_50_ Flax	108	3056	3164	-36.8%	-34.2%	-34.3%
11_Adobe_30_flax	20_Strawbale_50_ Flax	105	3584	3689	-38.7%	-22.8%	-23.4%
12_VHB_30_flax	20_Strawbale_50_ Flax	113	3510	3623	-33.9%	-24.4%	-24.7%
13_Limestone_30 flax	20_Strawbale_50_ Flax	110	3594	3704	-35.8%	-22.6%	-23.1%
14_Hempcrete_30_flax	20_Strawbale_50_ Flax	111	3223	3334	-35.1%	-30.6%	-30.7%
15_Strawbale_30_flax	20_Strawbale_50_ Flax	119	3177	3296	-30.6%	-31.6%	-31.5%
16_Adobe_50_flax	20_Strawbale_50_ Flax	99	3341	3439	-42.3%	-28.0%	-28.5%
17_VHB_50_flax	20_Strawbale_50_ Flax	105	3377	3482	-38.6%	-27.3%	-27.7%
18_Limestone_50 flax	20_Strawbale_50_ Flax	101	3501	3603	-40.9%	-24.6%	-25.2%
19_Hempcrete_50 flax	20_Strawbale_50_ Flax	103	3073	3176	-40.1%	-33.8%	-34.0%
20_Strawbale_50_ Flax (Minimum Energy Result)	20_Strawbale_50_ Flax	107	3038	3145	-37.3%	-34.6%	-34.7%

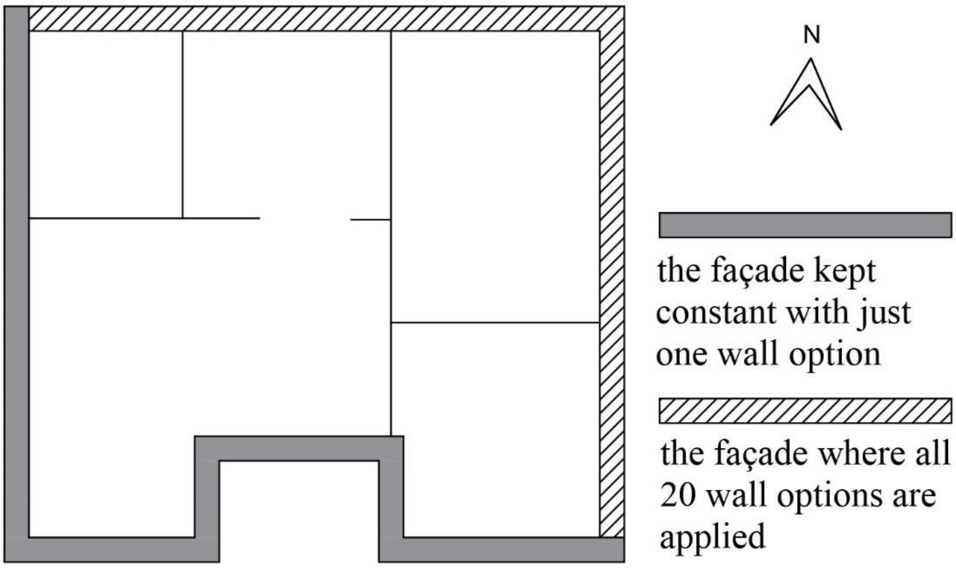


Figure 5.23. The schematic plan for 7th optimization option which south and west façades are kept constant, and other two façades are examined with 20-wall options in Konya model

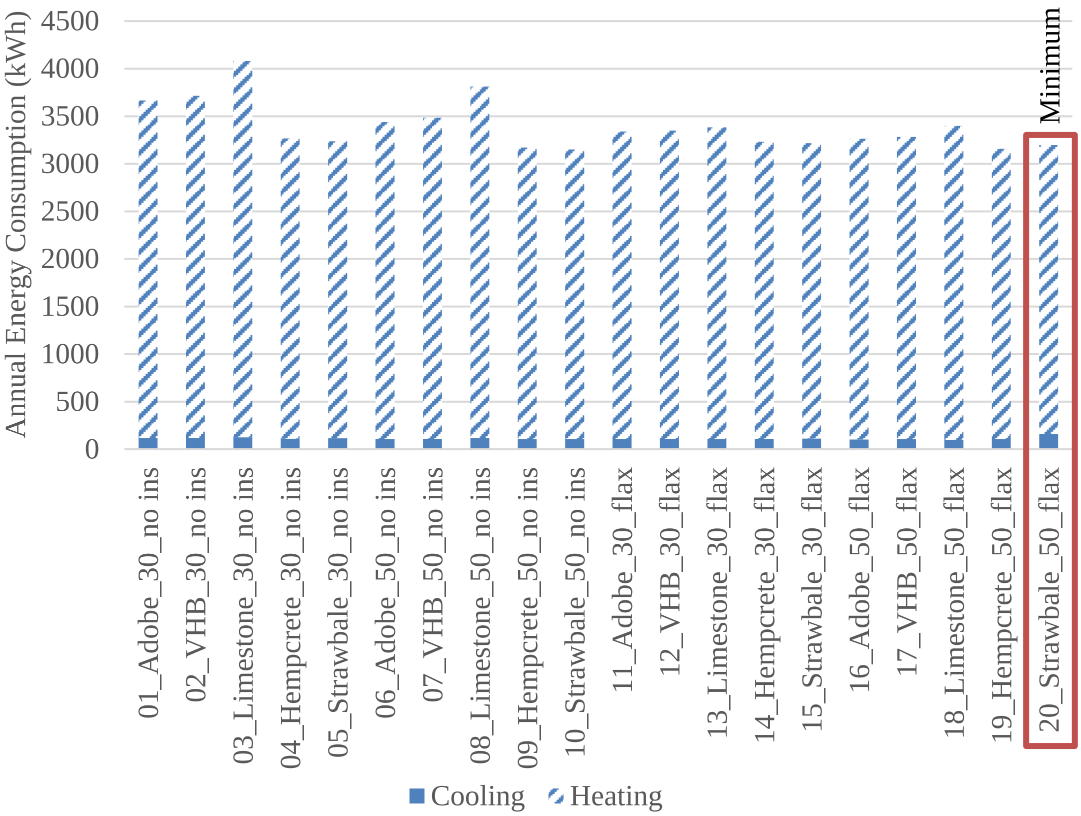


Figure 5.24. Annual energy consumptions for 7th optimisation option while night-time ventilation is on, in Konya model

5.4.3.3. Energy Consumption Results in Cooling Period for Optimization Options

Various combinations of wall options and façade orientations are investigated in Konya model to find which material and façade combination will provide the minimum energy consumption for cooling. Here, single or double façades of building are kept constant with just one wall option while all 20 wall options are applied simultaneously to other façade(s). Totally 8000 combinations are analysed.

For energy consumption for summer, the 9th optimization option provides minimum results while night-time ventilation is on. 20 wall options were applied one by one to the wall on the east and west side (Figure 5.25). During each application to this southern and western façades, 20 wall options were applied to the walls of the other façades, simultaneously. Afterwards, energy consumption results were obtained from each combination.

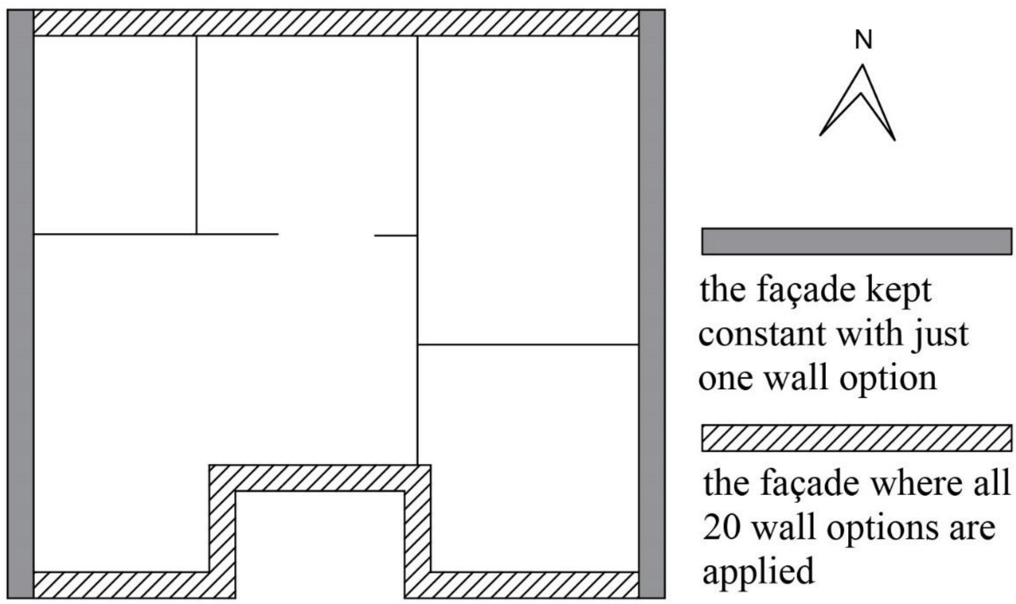


Figure 5.25. Schematic plan for the 9th optimization option which east and west façade are kept constant, and other façades are examined with 20-wall options in Konya model

According to Table 5.13 and Figure 5.26, the best result for minimum energy consumption in cooling season was when all wall façades were applied the 16th wall option (adobe, 0.50-meter thickness, with flax) of 99 kWh while night-time ventilation was on. Thus the energy for cooling in case building decreases with the ratio of 42.2%.

The effect of night-time ventilation for cooling consumption is indicated in Figure 5.26. The opening of all outer windows enables approximately 50kWh less consumption while night-time ventilation on.

Table 5.13. Comparison of energy consumption results for 9th optimization option while night-time ventilation is on in Konya ('-' decrease in energy consumption)

Wall option kept constant (on east and west façade)	**20 wall options (on north and south)**	**Cooling (kWh) (NTV on)**	**Heating (kWh)**	**Total (kWh)**	**Ratio (Cooling)**	**Ratio (Heating)**	**Ratio (Total)**
06_Adobe_50_no ins (Konya Case Scenario)		171	4643	4814	-	-	-
01_Adobe_30_no ins	16_Adobe_50_flax	113	4681	4795	-33.8%	0.8%	-0.4%
02_VHB_30_no ins	16_Adobe_50_flax	114	4799	4913	-33.4%	3.4%	2.1%
03_Limestone_30_no ins	16_Adobe_50_flax	125	5700	5825	-27.0%	22.8%	21.0%
04_Hempcrete_30_no ins	16_Adobe_50_flax	106	3692	3798	-38.3%	-20.5%	-21.1%
05_Strawbale_30_no ins	16_Adobe_50_flax	110	3596	3706	-35.7%	-22.5%	-23.0%
06_Adobe_50_no ins	16_Adobe_50_flax	102	4160	4262	-40.5%	-10.4%	-11.5%
07_VHB_50_no ins	16_Adobe_50_flax	132	4859	4991	-23.0%	4.7%	3.7%
08_Limestone_50_no ins	16_Adobe_50_flax	160	6557	6717	-6.5%	41.2%	39.6%
09_Hempcrete_50 no ins	16_Adobe_50_flax	99	3483	3582	-42.0%	-25.0%	-25.6%
10_Strawbale_50_no ins	16_Adobe_50_flax	99	3483	3988	-42.0%	-25.0%	-17.2%
11_Adobe_30_flax	16_Adobe_50_flax	102	3886	3582	-40.4%	-16.3%	-25.6%
12_VHB_30_flax	16_Adobe_50_flax	104	3906	4010	-39.4%	-15.9%	-16.7%
13_Limestone_30 flax	16_Adobe_50_flax	102	3888	3989	-40.6%	-16.3%	-17.1%
14_Hempcrete_30_flax	16_Adobe_50_flax	104	3605	3709	-39.0%	-22.4%	-22.9%
15_Strawbale_30_flax	16_Adobe_50_flax	108	3551	3659	-37.0%	-23.5%	-24.0%
16_Adobe_50_flax (Minimum Energy Result)	16_Adobe_50_flax	$\boxed{99}$	3767	3866	$\boxed{-42.2\%}$	-18.9%	-19.7%
17_VHB_50_flax	16_Adobe_50_flax	96	3902	3998	-43.9%	-16.0%	-16.9%
18_Limestone_50 flax	16_Adobe_50_flax	99	3450	3549	-42.3%	-25.7%	-26.3%
19_Hempcrete_50 flax	16_Adobe_50_flax	99	3450	3549	-42.3%	-25.7%	-26.3%
20_Strawbale_50_ Flax	16_Adobe_50_flax	101	3410	3511	-40.8%	-26.6%	-27.1%

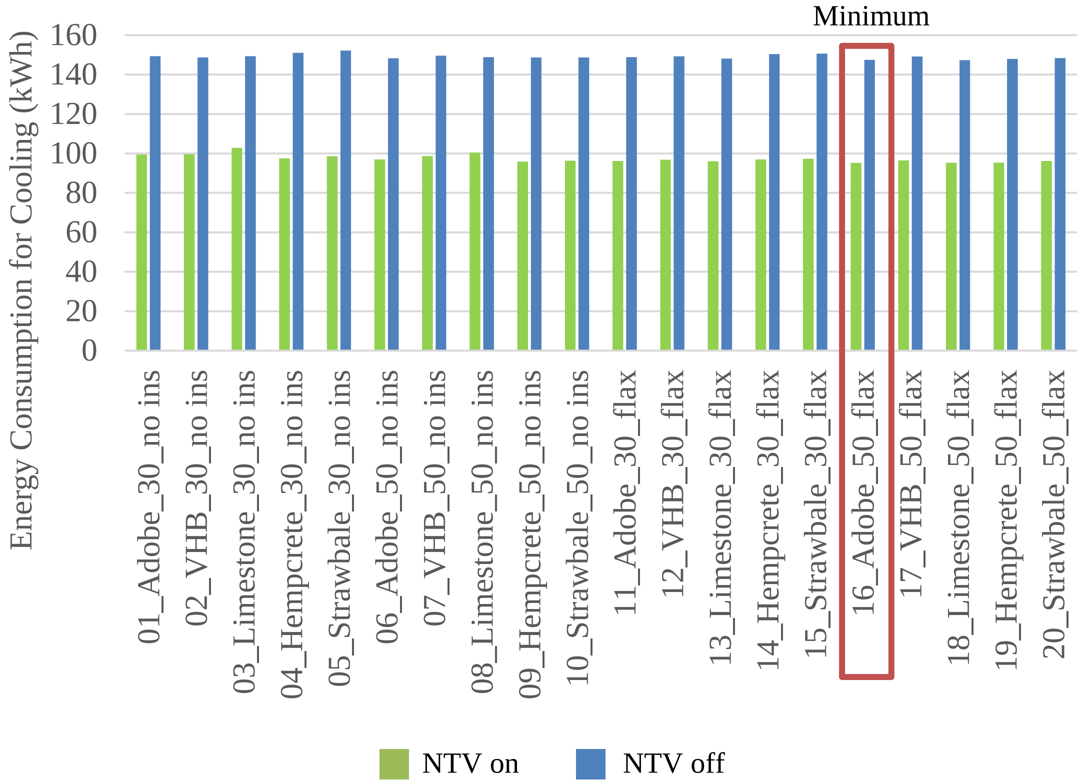


Figure 5.26. Effect of night-time ventilation on energy consumptions for cooling in 9th optimisation option in Konya model

5.4.4. Switch of Climate per Buildings

In this study, the exterior walls are investigated via different wall options in Mediterranean and Continental climates. It is initiated in this research that the only common parameter between case buildings are their adobe walls. However, two case building's climate, shape, glazing ratio, floor area and roof layers are different, as shown in Table 3.1 and Table 3.3.

The roofs of case buildings in Muğla and Konya are the most different building component among six surfaces (including walls, roof and ground floor) in terms of thickness, layers, shape and area. The roof can be influential on energy consumption to the larger extent comparing to the other components of buildings. The case building in Muğla differentiates with its gabled roof detail as timber plank ceiling, water insulation and roof tile with the U-Value of 2.200 W/m^{2}K, whereas the roof of case building in Konya has 0.50-meter flat earth roof stabilized with reed and U-Value of 0.387 W/m^{2}K.

Understanding the effect of roof and climate are of the questions of this research. Thus the switch of climates per case buildings is tested. It is thought that Muğla model would be assumed to build in Sonsuz Şükran Village, Hüyük, Konya ,and Konya model would be assumed to build in Pastoral Valley Eco Farm, Fethiye, Muğla. Therefore, Muğla model is simulated with Konya climate and location data, while Konya model is simulated with Muğla climate and location data. All simulations are conducted when the same wall option are applied for all façades (base scenarios).

5.4.4.1. Muğla model with Continental Climate and location data

The annual energy consumption results for 19 base scenarios and the case scenario (1st wall option-adobe, 0.30-meter without insulation) are presented in Table 5.14 for Muğla model with its own climate (Mediterranean) and test climate (Continental). The base scenarios represent the wall options with the same wall material for four façades. Scenarios in this section has no ventilation because they are base case scenarios in which all openings are kept closed as seen in on-site measurements.

According to Table 5.14, the existing building, i.e. case scenario with the 1st wall option (adobe, 0.30- meter without insulation), consumes energy for whole year of 5584 kWh with its own climate (Mediterranean). Annual energy consumption of the same case scenario consumes 7488 kWh with test climate (Continental). The annual energy consumption increases with the ratio of 34.1%, when Muğla model is transferred into Konya.

The maximum increase regarding annual energy consumption is experienced for the 3rd wall option (limestone, 0.30-meter without insulation) with the ratio of 36%. The annual energy consumption rises up from 6652 kWh to 9044 kWh.

The minimum changes in annual energy consumption are with the 5th and 15th wall options (strawbale, 0.30-meter with and without flax insulation), from 4421 kWh and 4368 kWh to 5821 kWh and 5753 kWh, respectively. Compared to changes with their own climate, their consumptions increase with the ratio of 31.7%. The energy consumption for cooling decreases, whereas consumption for heating increases for all scenarios.

Table 5.14. Muğla model with its own climate (Mediterranean) and test climate (Continental) ('-': decrease in energy consumption)

Base Scenarios of all Wall Options	Mediterranean (Climate of Muğla)			Continental (Test Climate)			RATIO
	Cooling (kWh)	Heating (kWh)	Total (kWh)	Cooling (kWh)	Heating (kWh)	Total (kWh)	
01_Adobe_30_no ins (Muğla Case Building)	1795	3789	5584	35	7453	7488	34.1%
02_VHB_30_no_ins	1837	3890	5727	47	7630	7677	34.0%
03_Limestone_30_no_ins	2203	4449	6652	82	8962	9044	36.0%
04_Hempcrete_30_no_ins	1361	3146	4507	12	5958	5971	32.5%
05_Strawbale_30_no_ins	1327	3094	4421	14	5806	5821	31.7%
06_Adobe_50_no_ins	1584	3451	5035	18	6705	6723	33.5%
07_VHB_50_no_ins	1620	3529	5149	24	6850	6874	33.5%
08_Limestone_50_no_ins	1971	4038	6009	45	8064	8110	35.0%
09_Hempcrete_50_no_ins	1282	3013	4295	9	5672	5680	32.2%
10_Strawbale_50_no_ins	1258	2983	4241	10	5580	5589	31.8%
11_Adobe_30_flax	1435	3271	4706	13	6262	6275	33.3%
12_VHB_30_flax	1447	3295	4742	16	6290	6306	33.0%
13_Limestone_30 flax	1483	3349	4832	15	6434	6449	33.5%
14_Hempcrete_30_flax	1321	3087	4408	11	5826	5836	32.4%
15_Strawbale_30_flax	1307	3061	4368	13	5740	5753	31.7%
16_Adobe_50_flax	1376	3176	4552	9	6066	6075	33.5%
17_VHB_50_flax	1397	3205	4602	12	6110	6122	33.0%
18_Limestone_50 flax	1449	3287	4736	12	6321	6333	33.7%
19_Hempcrete_50 flax	1266	2991	4257	8	5622	5630	32.3%
20_Strawbale_50_ Flax (Minimum Energy Result)	1250	2971	4221	9	5556	5566	31.9%

5.4.4.2. Konya model with Mediterranean Climate and location data

The annual energy consumption results for 19 base scenarios and the case scenario (6^{th} wall option-adobe, 0.50-meter without insulation) are presented in Table 5.15 for Konya model with its own climate (Continental) and test climate (Mediterranean). The base scenarios represent the wall options with the same wall material for four façades.

Scenarios in this section has no ventilation because they are base case scenarios in which all openings are kept closed as seen in on-site measurements.

Table 5.15. Konya model with its own climate (Continental) and test climate (Mediterranean) ('-': decrease in energy consumption)

Base Scenarios of all Wall Options	Continental (Climate of Konya)			Mediterranean (Test Climate)			RATIO
	Cooling (kWh)	Heating (kWh)	Total (kWh)	Cooling (kWh)	Heating (kWh)	Total (kWh)	
01_Adobe_30_no ins	209	5736	5945	409	3570	3979	-33.1%
02_VHB_30_no ins	218	5982	6199	444	3677	4121	-33.5%
03_Limestone_30_no ins	262	7825	8087	749	4280	5029	-37.8%
04_Hempcrete_30_no_ins	175	3638	3812	136	2902	3037	-20.3%
05_Strawbale_30_no_ins	187	3435	3622	140	2878	3018	-16.7%
06_Adobe_50_no_ins (Konya Case Building)	171	4643	4814	211	3177	3388	-29.6%
07_VHB_50_no ins	186	4856	5042	260	3266	3526	-30.1%
08_Limestone_50_no ins	217	6555	6772	498	3809	4307	-36.4%
09_Hempcrete_50 no ins	157	3191	3348	98	2732	2830	-15.5%
10_Strawbale_50_no ins	163	3068	3232	95	2714	2809	-13.1%
11_Adobe_30_flax	166	4049	4215	155	3010	3165	-24.9%
12_VHB_30_flax	172	4095	4267	162	3037	3199	-25.0%
13_Limestone_30 flax	166	4287	4453	172	3082	3254	-26.9%
14_Hempcrete_30_flax	170	3449	3619	125	2840	2965	-18.1%
15_Strawbale_30_flax	180	3338	3518	127	2836	2963	-15.8%
16_Adobe_50_flax	148	3728	3875	110	2880	2990	-22.8%
17_VHB_50_flax	159	3803	3961	123	2915	3038	-23.3%
18_Limestone_50 flax	152	4088	4240	129	2989	3118	-26.5%
19_Hempcrete_50 flax	155	3120	3276	95	2709	2804	-14.4%
20_Strawbale_50_ Flax	162	3035	3197	93	2700	2793	-12.6%

According to Table 5.15, the existing building, i.e. case scenario with the 6th wall option (adobe, 0.50- meter without insulation) consumes energy for whole year of 4814 kWh with its own climate (Continental). Annual energy consumption of the same case scenario consumes 3388 kWh with test climate (Mediterranean). The annual energy consumption is decreases with the ratio of 29.6% when Konya model is transferred into Muğla.

The maximum increase regarding annual energy consumption is experienced for 3rd wall option (limestone, 0.30-meter without insulation) with the ratio of 37.8%. The annual energy consumption decreases from 8087 kWh to 5029 kWh.

The minimum changes in annual energy consumption are with the 10th wall options (strawbale, 0.50-meter without flax insulation), from 3232 kWh to 2829 kWh. Compared to changes with its own climate, the consumption decreases with the ratio of 13.1%. The energy consumption for cooling increases, whereas consumption for heating decreases for all scenarios.

CHAPTER 6

CONCLUSION

Worldwide environmental issues regarding global warming, depletion of resources and increasing energy demand raised the concerns about taking precautions in the construction sector. Energy efficiency has become the primary solution to tackle rapid resource consumption. The materials of building envelopes, their proper combinations and selection according to façade orientation are subjects of investigations on energy performance of buildings.

Energy efficient building design is a challenge for building professionals who are looking to ensure sustainability. There is a range of applications for natural building materials, most of which are implemented using conventional/traditional construction techniques. Yet, more quantitative research on industrialized natural building materials is needed. Case studies for investigating best performing solutions in efficient building design will lead to a better understanding of sustainable design strategies.

Developing design strategies with natural wall materials for providing highly energy efficient solutions require a different approach going beyond the rule of thumbs on conservative traditional earth construction practices. This study questions current use of natural wall materials and attracts attention to their use with today's construction techniques. Thermal mass, types of natural building materials, façade orientation, and local climate are used as the parameters for exploring several questions on natural wall materials. This thesis presents a comparative energy efficiency study with natural building materials in two adobe buildings from different climatic regions in Turkey.

6.1. Concluding Regarding Results

Based on the research questions stated in Chapter 1.2, this part presents conclusions drawn from the results of the study, presented in Chapter 5:

- **Do adobe buildings provide enough energy performance for Mediterranean and Continental climates? Is the adobe an appropriate material selected for energy performance in Mediterranean and Continental climates?**

The case buildings were designed in harmony with their climates. The case building in Muğla has the L-shape mass with larger exterior surfaces and gable roof, which is typical for hot-humid climates to provide shaded areas for windows and outdoor use, and to balance solar heat gain with shade protection on a seasonal basis. The case building in Konya has the compact form with flat roof, which is typical for cold climates to reduce radiant, conductive, and evaporative heat loss by minimizing exterior surface area. By going beyond their climate and shape relationship, the energy performance of adobe is scrutinized through the switch of climates per case buildings. Figure 6.1 shows the ratio of change on annual energy consumption (increase or decrease), when Muğla model (adobe, 0.30-meter without insulation) is simulated in Konya (Continental climate), and Konya model (adobe, 0.50-meter without insulation) is simulated in Muğla (Mediterranean climate), as explained in Chapter 5.4.4.

The results for Muğla model, simulated in the Continental climate, convey that the annual energy consumption rises up with the range from 30% to 35% for all scenarios. However, in the case of Konya model in Mediterranean climate, the amount of energy consumption drops with the range from 40% to 10% for all scenarios (30% and 40% for 1^{st}, 2^{nd}, 3^{rd}, 6^{th}, 7^{th} and 8^{th} (adobe, VHB, limestone, 0.30-meter and 0.50-meter without insulation), 20% and 25% for 11^{th}, 12^{th}, 13^{th}, 16^{th}, 17^{th}, 18^{th} (adobe, VHB, limestone, 0.30-meter and 0.50-meter with flax), 15% and 20% for 4^{th}, 5^{th} (hempcrete and strawbale, 0.30-meter without insulation), 9^{th} (hempcrete 0.50-meter without insulation), 14^{th}, 15^{th} (hempcrete and strawbale, 0.30-meter with flax) and 19^{th} (hempcrete, 0.50-meter with flax), and 10% and 15% for 20^{th} (strawbale, 0.50-meter with flax)).

Direct sunlight reaches with a bigger solar altitude angle on the surface of roof than walls. The roof is a significant building component in terms of energy performance, because of its higher energy absorption capability without shading. By this research on climate switch, specific correlations are examined for Muğla and Konya model with 1^{st} wall option (adobe, 0.30-meter without insulation) (Figure 6.2), (Figure 6.3).

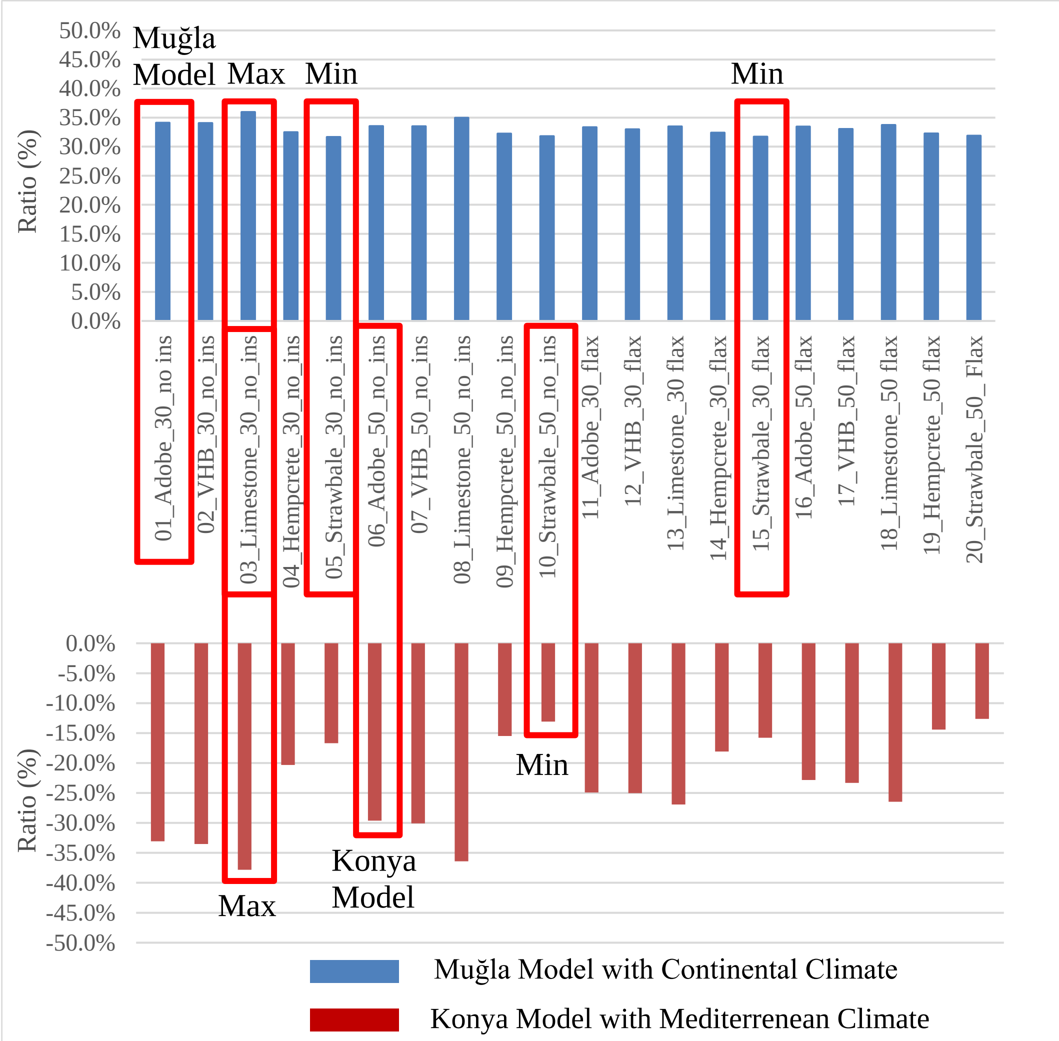


Figure 6.1. Ratio of change on annual energy consumption when climate switch is performed for Konya and Muğla models ('-': decrease in energy consumption)

- According to Table 5.14 and Table 5.15, the cooling energy consumption is decreased in Muğla model transferred to Konya between the range of 2000 kWh and 1300 kWh for 20 scenarios, and cooling energy consumption of transferred Konya model is increases between the range of 200 kWh and 100 kWh for 20 scenarios.
- Cooling energy consumption of Muğla model is less in Continental Climate than Mediterranean Climate for climatic conditions differences.
- Cooling energy consumption of Konya model decreased when it was expected to increase when transferred to Muğla. This is thought to be because the U-Value of the Konya model roof is better than the Muğla model (Table 4.2).

- Comparing to Konya and Muğla model in the same climate, for both climate Konya model consume less heating energy consumption even their wall option is the same.
- The energy consumed for heating increases for both models in the Continental climate.

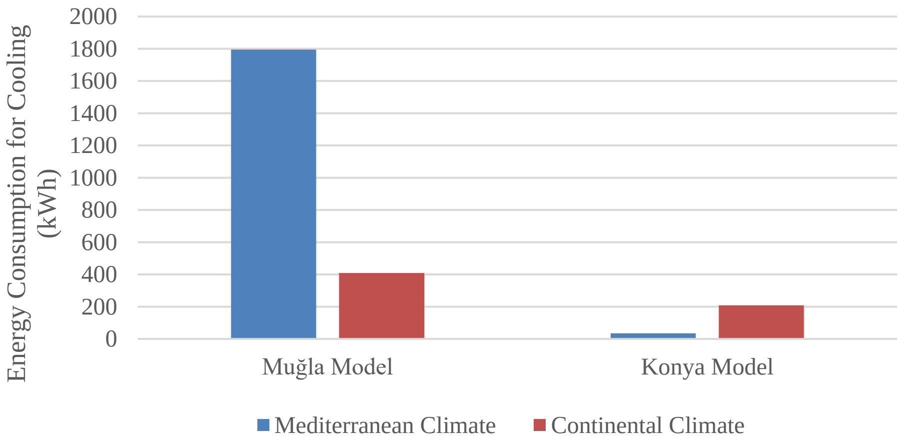


Figure 6.2. Energy consumption of cooling for Muğla and Konya models in Mediterranean and Continental Climates, both models have 1st wall option in walls

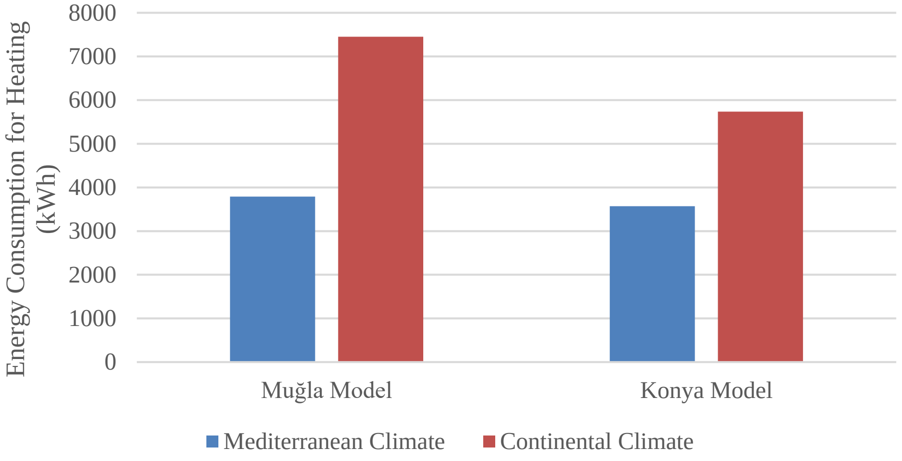


Figure 6.3. Energy consumption of cooling for Muğla and Konya models in Mediterranean and Continental Climates, both models have 1st wall option in walls

- **What is the most energy efficient natural wall material for the case buildings in Mediterranean and Continental climates?**

Simulation results indicate that the use of strawbale in all façades is the most desirable option in terms of energy savings in both winter and summer seasons for the case building in the Mediterranean climate. In the Continental climate, strawbale again provides the minimum energy consumption for heating, but for cooling 50 cm adobe with thermal insulation achieves the least energy consumption

- **Is it possible to make combinations of materials on different wall directions of the building?**

The use of wall options created with five main materials selected in this thesis on different façades of the case buildings enable us to design more energy efficient buildings in both climate zones. The simulation results show that the building with strawbale on all four façades have the best result in terms of minimum total energy consumption. However, in Konya, buildings are generally built with adobe in a traditional way especially in rural areas. If adobe is to be used, it is preferable only on the east façade, while strawbale should be chosen for the other three façades.

- **Which combination of wall options provide the least energy consumption?**

It can be inferred from the results that allocation of wall options into different orientations does not guarantee more energy efficiency for both case buildings. For the case building in Muğla (Mediterranean climate), the 20th wall option (strawbale, 0.50 m, with flax insulation) resulted in the lowest cooling heating and annual energy consumption (1154 kWh ,2973 kWh and 4126 kWh, respectively) when it is applied on all four façades while night time ventilation is on as shown in Table 5.9.

For the building in Konya (Continental climate), cooling energy consumption is minimum (99 kWh) when the 16th wall option (adobe, 0.50 m, with flax insulation) is selected when night-time ventilation is on (Table 5.13). Heating and annual energy consumptions are minimum (3038 kWh and 3145 kWh, respectively) when the 20th wall option (strawbale, 0.50 m, with flax insulation) is applied on all four façades while night-time ventilation is on as shown in Table 5.12.

In the results regarding orientation combinations, 16th wall option presents minimum cooling results when it is used in east and west façades (Table 5.13) and the minimum annual energy consumption is found when 20th wall option is applied in all façades. In traditional architecture, adobe is a widely used material in Konya. Therefore, if the adobe is to be used in Konya, it can be used in east and west façades and the other two wall façades can be built using the 20th wall option (strawbale, 0.50 m, with flax insulation). The energy consumption is, with 16th and 20th wall options, 3363 kWh.

Comparing the results with case scenarios, annual energy consumption decreases 26% when all façades use the 20th wall option in Muğla. For Konya, when 16th wall option is applied on east and west façades, and 20th wall option on north and south façades, annual energy consumption decreases 30%. If all façades use the 20th wall option, the annual energy consumption decreases 34.6%.

Table 6.1: Minimum energy consumption for Muğla and Konya model

	North East	South East	South West	North West	Annual	%	INFO
MUĞLA	01_Adobe_30 no ins	01_Adobe_30 no ins	01_Adobe_30 no ins	01_Adobe_30 no ins	5584	-	CASE SC. NTV OFF
MUĞLA	20_Strawbale 50_Flax	20_Strawbale 50_ Flax	20_Strawbale 50_Flax	20_Strawbale 50_Flax	4126	20	NTV ON
	East	**South**	**West**	**North**	**Annual**	**%**	**INFO**
KONYA	06_Adobe_50 no ins	06_Adobe_50 no ins	06_Adobe_50 no ins	06_Adobe_50 no ins	4814	-	CASE SC. NTV OFF
KONYA	16_Adobe 50_flax	20_Strawbale 50_ Flax	16_Adobe 50_flax	20_Strawbale 50_Flax	3363	30	NTV ON
KONYA	20_Strawbale 50_Flax	20_Strawbale 50_ Flax	20_Strawbale 50_Flax	20_Strawbale 50_Flax	3197	34	NTV ON

- **How does the material with high thermal mass behave in buildings in summertime? How does thermal mass affect energy consumption while night-time ventilation on or off? In which way?**

The wall options were calculated in terms of their thermal capacity and thermal mass in Chapter 5.1. They are classified as having low, medium, and high thermal mass. They are visualized in Figure 6.4, Figure 6.5, Figure 6.6 and Figure 6.7 with their energy consumption data according to its climates in order to observe which thermal mass consumes how much energy in summertime while night-time ventilation is on or off.

Considering the low, medium and high thermal mass according to numerical results in Table 5.1, 2nd 4th 5th 10th 12th 14th 15th wall options are determined as low thermal mass, 1st, 3rd, 7th, 9th, 11th, 13th, 17th, 1th and 20th wall options are determined as medium thermal mass and 6th, 8th, 16th and 18th wall options are determined as high thermal mass and they are coloured in Table 6.2. The light, medium and deep blue express as low, medium and high thermal mass, respectively.

For Muğla model, when the ventilation is turned on all night, most of the 20 wall options are close to the 1150 kWh limit when they are in the middle of the 1150-1500 kWh band. Medium thermal mass 3rd wall option (Limestone, 0.30 m thickness, no insulation) and high thermal mass 8th wall option (Limestone, 0.50 m, no insulation) which are in 1850-2200 kWh band, decreased to 1150-1500 kWh band.

2nd wall option (VHB, 0.30 m, no insulation) with low thermal mass, 1st wall option (adobe, 0.30 m, no insulation) with medium thermal mass, 7th (VHB, 0.50 m, no insulation), and 6th wall options with high thermal mass (adobe, 0.50 m, no insulation) decreased from 1850-1500 kWh to 1150-1500 kWh band. (Figure 6.2 and Figure 6.3).

Table 6.2. Wall options low, medium and high thermal mass in terms of their thermal capacity and time constant results

Case Buildings and Base Scenarios	Thermal Capacity [MJ/K]	Time Constant [h]
01_Adobe_30_no ins (Muğla Case Building)	56.25	15.63
02_VHB_30_no_ins	30.63	8.51
03_Limestone_30_no_ins	54.38	15.10
04_Hempcrete_30_no_ins	22.58	6.27
05_Strawbale_30_no_ins	10.28	2.85
06_Adobe_50_no_ins (Konya Case Building)	93.75	26.04
07_VHB_50_no_ins	47.63	13.23
08_Limestone_50_no_ins	90.38	25.10
09_Hempcrete_50_no_ins	33.14	9.20
10_Strawbale_50_no_ins	11.00	3.05
11_Adobe_30_flax	56.86	15.79
12_VHB_30_flax	31.23	8.68
13_Limestone_30 flax	54.98	15.27
14_Hempcrete_30_flax	23.18	6.44
15_Strawbale_30_flax	10.88	3.02
16_Adobe_50_flax	94.36	26.21
17_VHB_50_flax	48.23	13.40
18_Limestone_50 flax	90.98	25.27
19_Hempcrete_50 flax	33.74	9.37
20_Strawbale_50_ Flax	11.60	3.22

For Konya model, when the ventilation is closed during the night, most of the 20 wall options are found in the 150-210 kWh band. Whereas when the ventilation is turned on during the night, the consumption of summer season decreased to 90-150 kWh band. However, as seen in Figure 6.3 and Figure 6.4, only three wall options decrease from 210-270 kWh band to 150-210 kWh band. These are 2nd wall option with low thermal mass (VHB, 0.30 m, no insulation), 3rd wall option with medium thermal mass (Limestone, 0.30 m thickness, no insulation), and 8th wall option with high thermal mass (Limestone, 0.50 m, no insulation).

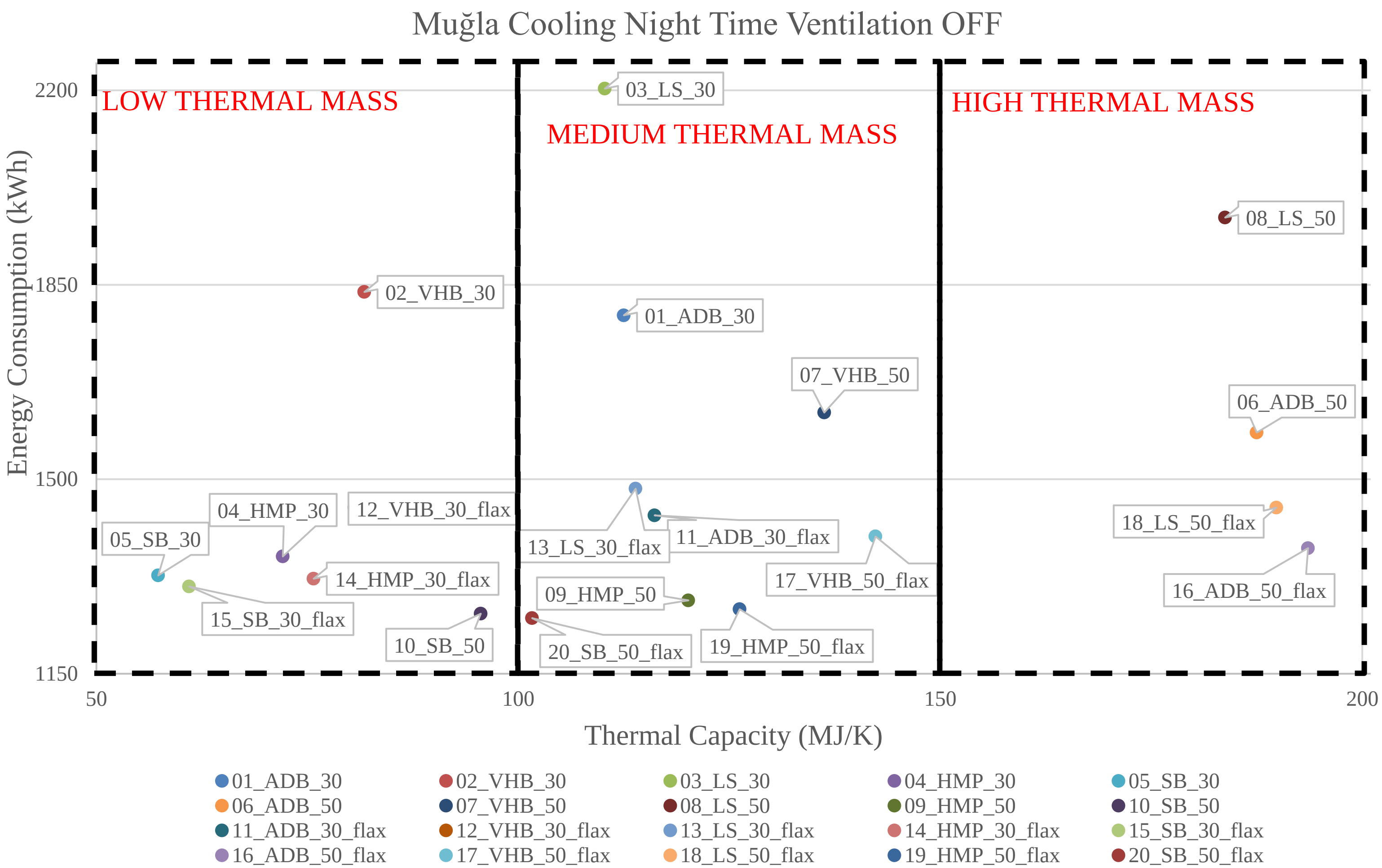


Figure 6.4. Relationship energy consumption for cooling and thermal capacity for Muğla model while night-time ventilation off

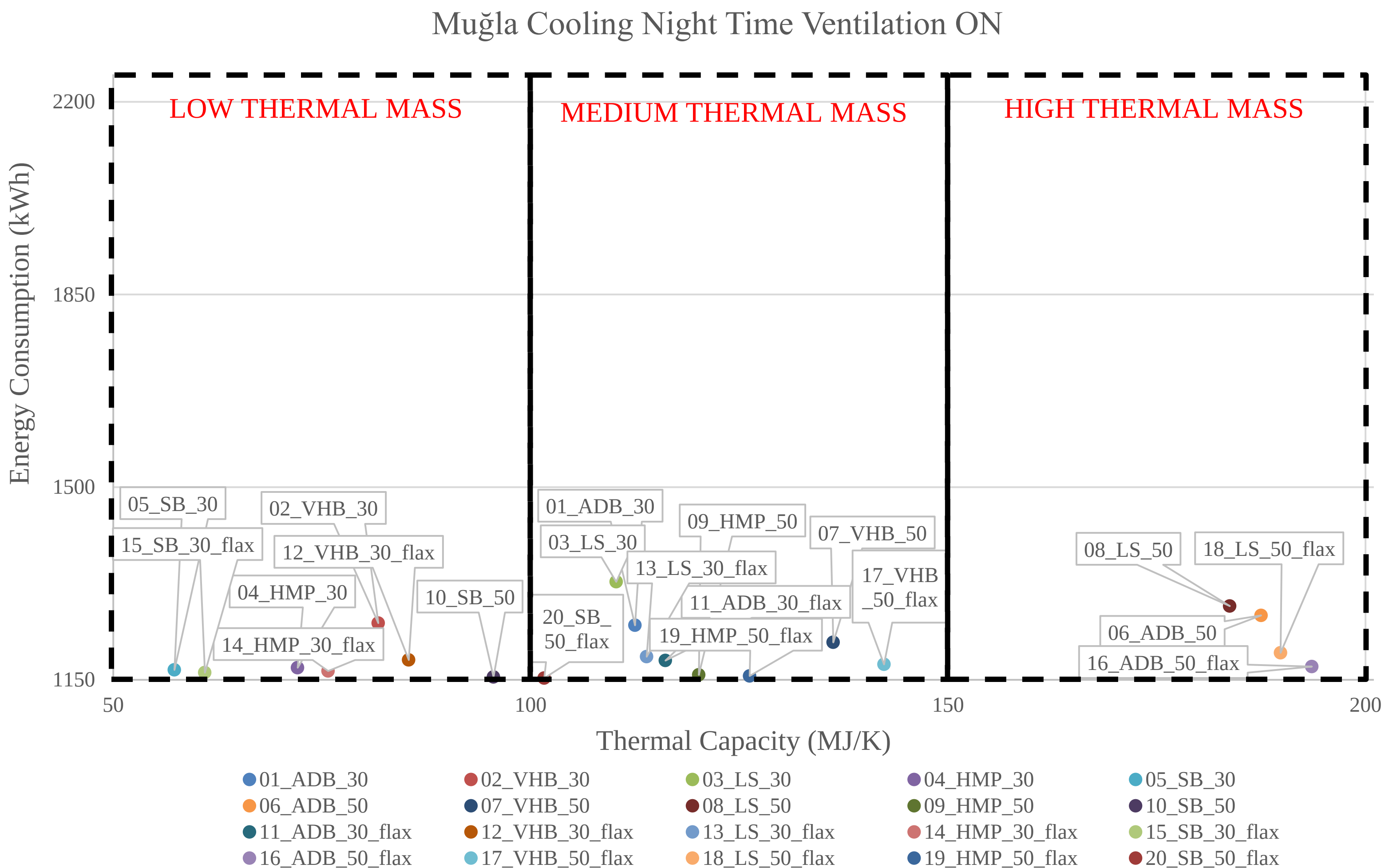


Figure 6.5. Relationship energy consumption for cooling and thermal capacity for Muğla model while night-time ventilation on

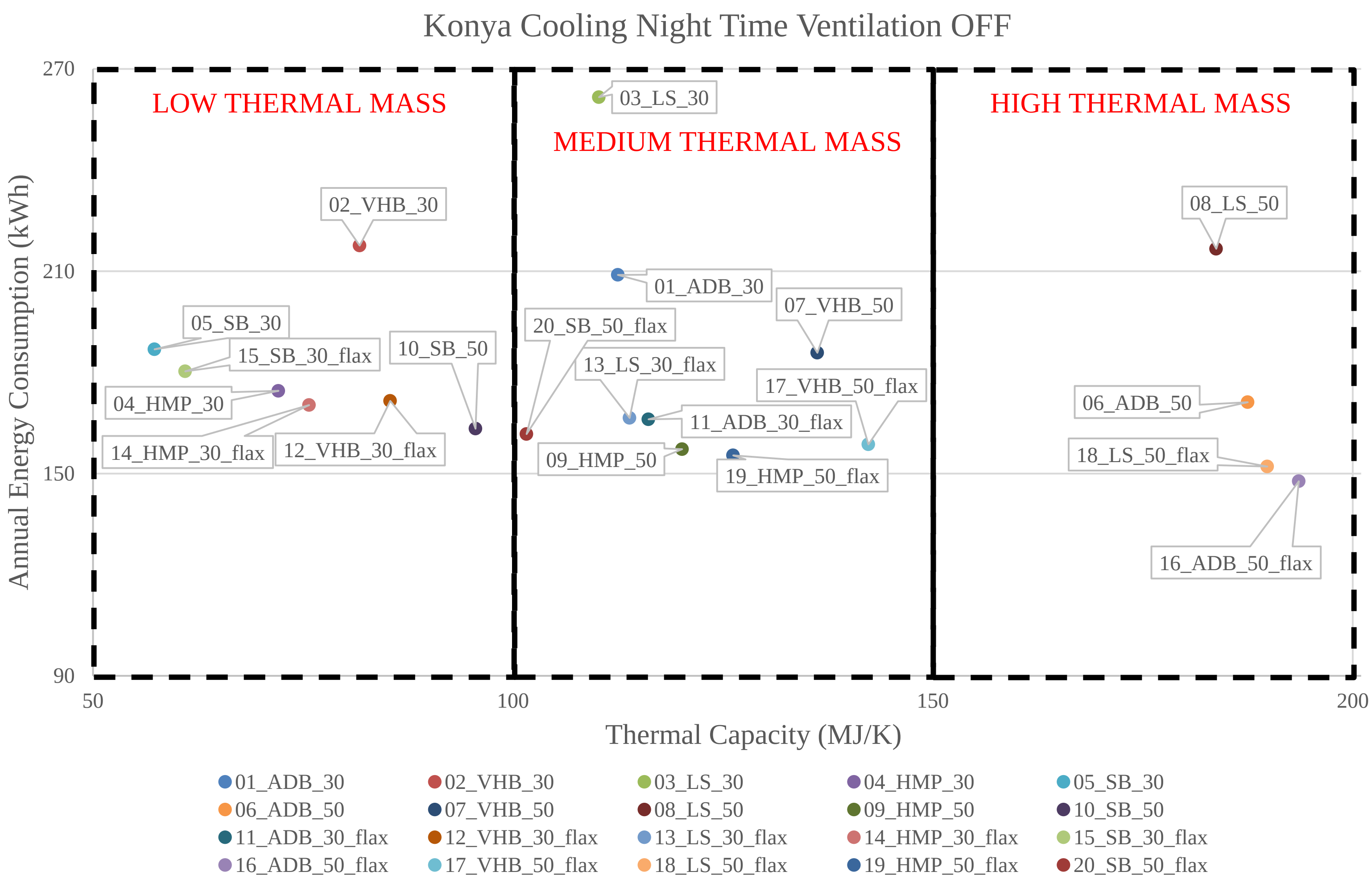


Figure 6.6. Relationship energy consumption for cooling and thermal capacity for Konya model while night-time ventilation off

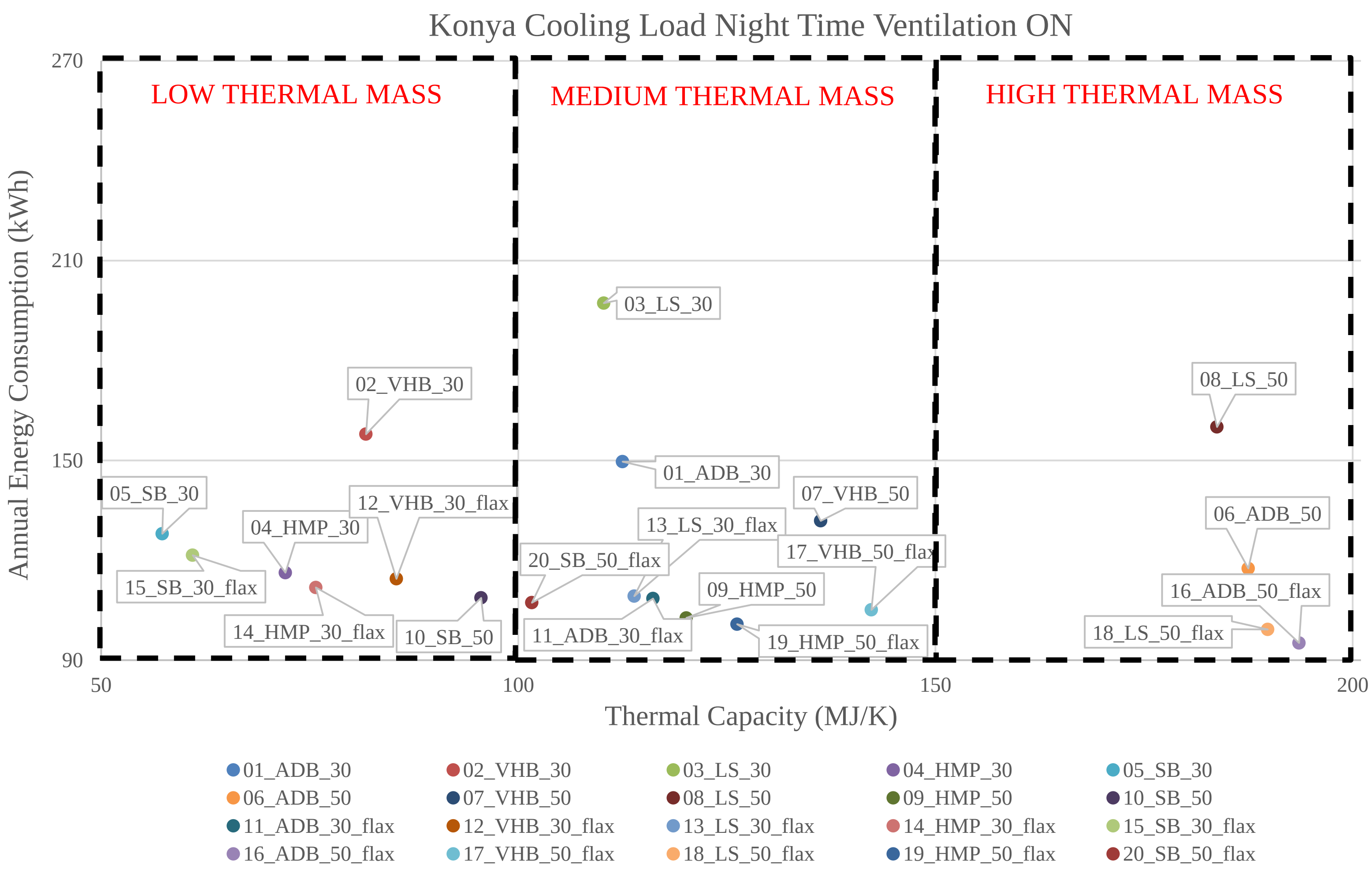


Figure 6.7. Relationship energy consumption for cooling and thermal capacity for Konya model while night-time ventilation on

- **What is the effect of night-time ventilation on energy consumption, and is the night-time ventilation effective on discharge accumulated daytime heat due to thermal mass?**

  It is observed from the simulation results that night-time ventilation is reducing cooling consumption in both climates. High diurnal temperature differences help lower indoor temperatures for Konya. However, this is not true for Muğla.

- **What is the effect of climate on energy consumption?**

  As a conclusion, in this study building walls is researched with different wall options. It is assumed that climate affects energy consumption, however, two case building's roof layers are different. The roof of Muğla case building has timber plank, water insulation and roof tile with 2.200 W/m^{2}K U-Value and it is a gable roof, whereas the roof of Konya case building has an earth roof with reeds with the thickness of 0.50 m approximately with 0.387 W/m^{2}K U-Value and it is flat. The simulations are taken for buildings with different climates. For instance, Muğla model is simulated with Konya climate and location data and Konya model is simulated with Muğla climate and location data.

- **Considering the U-Value and thermal mass, which is the most effective on energy consumption?**

  It is deduced from Figure 6.8 and Figure 6.9 that when u value increases, energy consumption also increases.

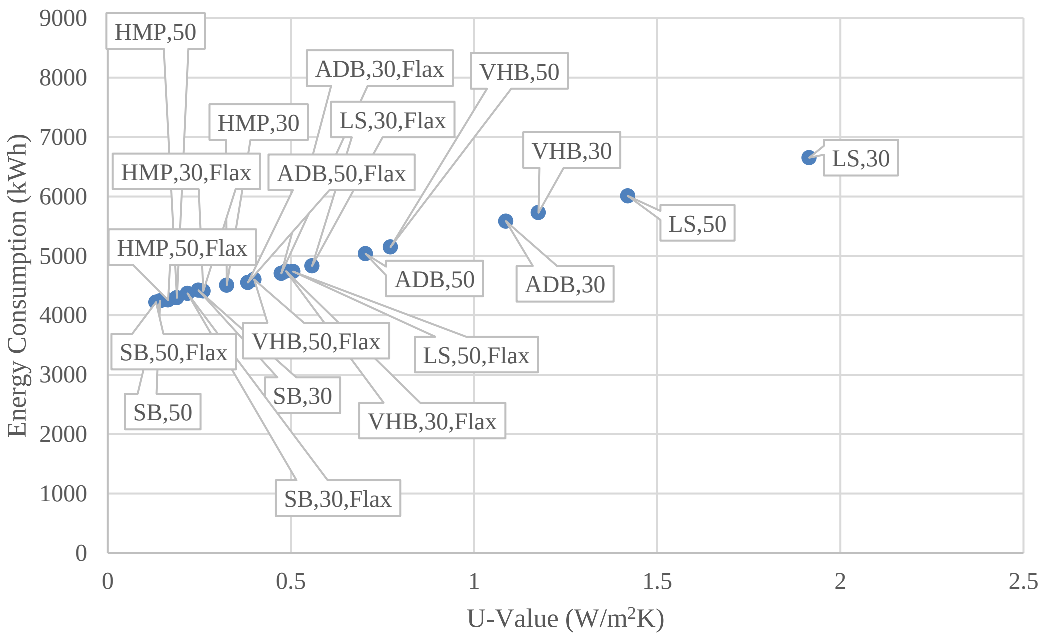


Figure 6.8. Relationship between U-Value and energy consumption in Muğla model

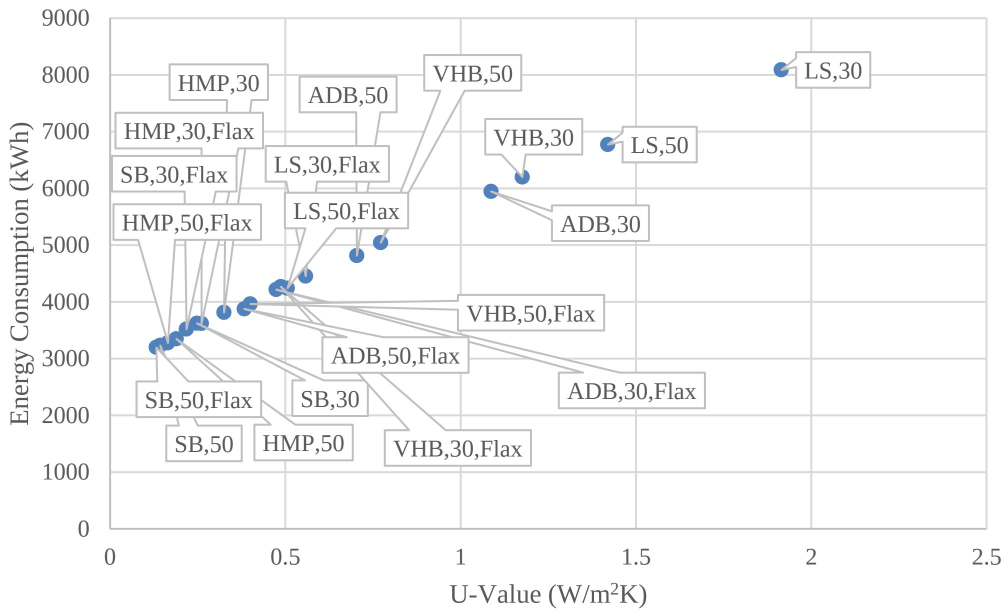


Figure 6.9. Relationship between U-Value and energy consumption in Konya model

- **How does the thickness insulation and material choice effect the energy consumption?**

In Figure 6.8 and Figure 6.9, allows comparing thickness and insulation in terms of materials, and Figure 6.10 and Figure 6.11, expressed comparison materials in terms of thickness and insulation, shows the energy consumption results with case scenarios and base scenarios.

Material

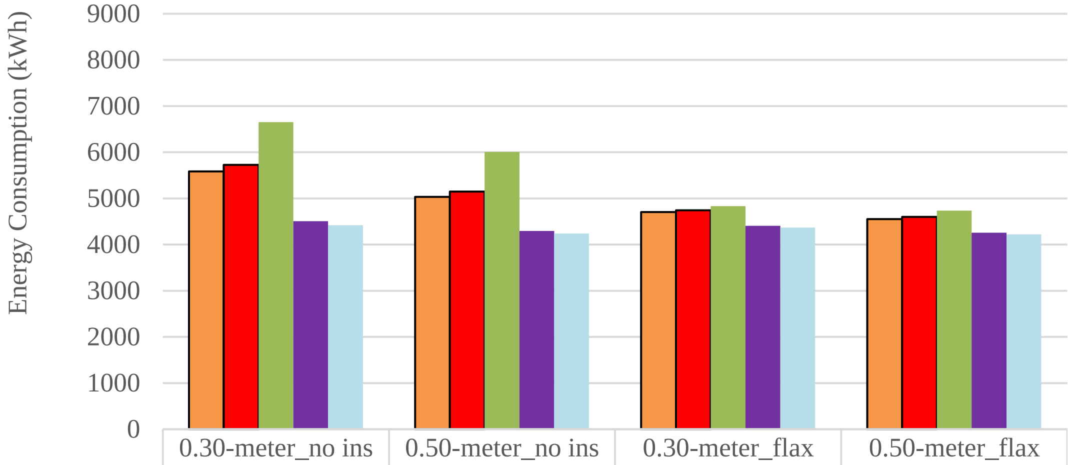
- For adobe, VHB and limestone, insulation is more efficient than thickness.
- For hempcrete and strawbale, thickness is more efficient than insulation.

Thickness

- Energy consumption decreases when thickness is increased.

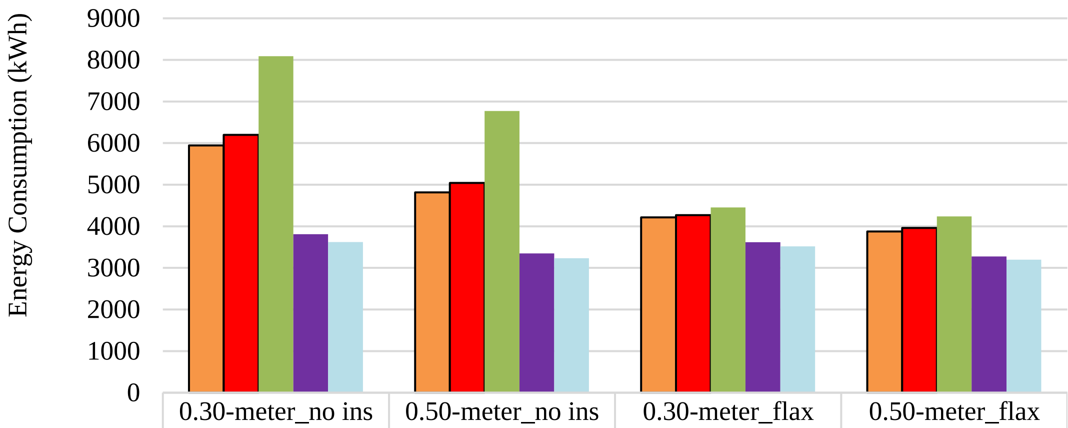
Insulation

- Energy consumption decreases when insulation is applied.



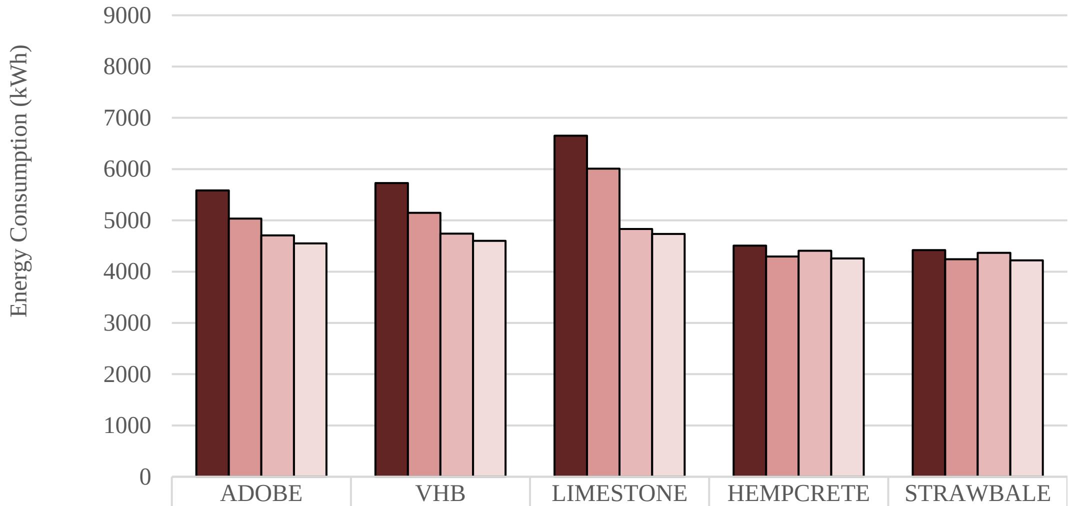
	0.30-meter_no ins	0.50-meter_no ins	0.30-meter_flax	0.50-meter_flax
ADOBE	5584	5035	4706	4552
VHB	5727	5149	4742	4602
LIMESTONE	6652	6009	4832	4736
HEMPCRETE	4507	4295	4408	4257
STRAWBALE	4421	4241	4368	4221

Figure 6.10. Annual energy consumption results for base scenario and case scenarios in Muğla



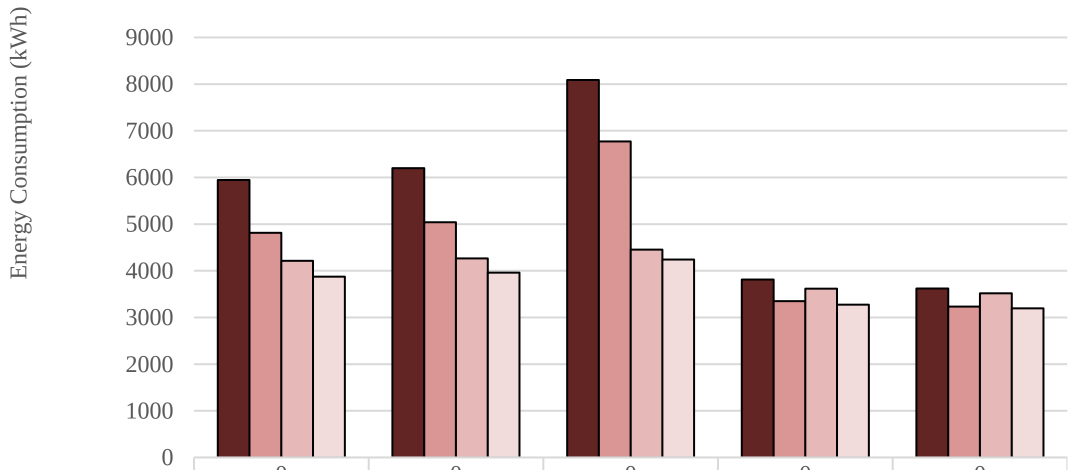
	0.30-meter_no ins	0.50-meter_no ins	0.30-meter_flax	0.50-meter_flax
ADOBE	5945	4814	4215	3875
VHB	6199	5042	4267	3961
LIMESTONE	8087	6772	4453	4240
HEMPCRETE	3812	3348	3619	3276
STRAWBALE	3622	3232	3518	3197

Figure 6.11. Annual energy consumption results for base scenario and case scenarios in Konya



	ADOBE	VHB	LIMESTONE	HEMPCRETE	STRAWBALE
0.30-meter_no ins	5584	5727	6652	4507	4421
0.50-meter_no ins	5035	5149	6009	4295	4241
0.30-meter_flax	4706	4742	4832	4408	4368
0.50-meter_flax	4552	4602	4736	4257	4221

Figure 6.12. Annual energy consumption results for base scenario and case scenarios in Muğla



	0	0	0	0	0
0.30-meter_no ins	5945	6199	8087	3812	3622
0.50-meter_no ins	4814	5042	6772	3348	3232
0.30-meter_flax	4215	4267	4453	3619	3518
0.50-meter_flax	3875	3961	4240	3276	3197

Figure 6.13. Annual energy consumption results for base scenario and case scenarios in Konya

6.2. General Concluding Remark

The impact analysis of different wall scenarios on energy consumption indicates that:

U-Value

- For both climates, U-value of wall options becomes more influential performance parameter than thermal mass on energy consumption (Figure 6.6 and Figure 6.7)
- Lower wall U-value is essential factor to consume less energy for both Konya and Muğla model, annually (Figure 6.6 and Figure 6.7).
- Strawbale allows the least annual energy consumption with the lowest thermal mass capacity and the best U-value for both Muğla and Konya model (Figure 6.6, Figure 6.7 and Table 6.2).

Material, Thickness and Insulation

- The most energy efficient natural building material is strawbale by which energy consumption is minimum for both climates. The energy performance of case buildings in Muğla and Konya using hempcrete, adobe, VHB and limestone decrease respectively (Figure 6.10 and Figure 6.11).
- The study reveals that thicker and insulated walls guarantee less consumption both in summer and winter in both climates.
    - When thickness increases energy consumption decreases (Figure 6.8 and Figure 6.9).
    - There is an inverse proportion between insulation and energy consumption. The presence of insulation enables less energy consumption (Figure 6.8 and Figure 6.9).
- The lowest annual energy consumption values are achieved by 20^{th} wall option with low thermal mass, i.e. 50 cm strawbale with flax both in Muğla and Konya. For cooling season in Konya, the lowest energy consumption values for cooling is achieved by 16^{th} wall option with high thermal mass, i.e. 50 cm adobe with flax in Konya, while 20^{th} wall option with low thermal mass, i.e. strawbale with 50 cm with flax provides the minimum consumption in Muğla (Table 6.1).

Night-Time Ventilation

- Considering the energy consumption for both summer season of climates, the case building in Muğla requires more energy than the case building in Konya, while night-time ventilation is either on or off (Figure 6.4, Figure 6.5, Figure 6.6 and Figure 6.7).
- Night-time ventilation always causes to decrease in energy consumption in this study for all scenarios (Figure 6.4, Figure 6.5, Figure 6.6 and Figure 6.7).

Thermal Mass

- Any meaningful relationship between thermal mass and energy consumption is not determined.

Climate Switch

- Limestone is affected to a larger extend by the outside temperature and humidity fluctuations compared to other materials, whereas strawbale is the least effected material (Figure 6.1).

6.3. Further Study

The following further studies would be conducted in the light of the results:

- Energy consumption is the primary factor that needs attention in this research. For future study, environmental performance can be studied. CO_2 footprint would be added as a factor for determining the minimum solutions.
- This study is conducted on an unoccupied case building, and scenarios are defined for unoccupied case buildings. Therefore, this study achieves to investigate the energy consumption in buildings. For further study, scenarios would be identified with occupied case buildings.
- In this research, ambient temperature data was collected via on-site measurements and simulation tool. Decrement factor is essential for thermal mass and thermal comfort. It would be calculated for each natural building material if inner and outer surface temperatures of north wall on case buildings would be gathered trough monitoring campaign.

- The material properties of adobe change according to the location of earth source, since there is no homogenies type and ingredients of earth. Yet, this study accepted the same characteristics of earth for both Muğla and Konya cases. This may one of the reasons for fluctuations seen in monitoring and simulation results (Figure 5.7 for Muğla and Figure 5.8 for Konya).

6.4. Recommendations

In this study, adobe buildings constructed with traditional methods were examined in terms of energy efficiency. On the other hand, this thesis tested the industrialized natural building materials whose production stage is standardized. Natural building materials are valuable because of their low environmental impact, low energy consumed during their production and positive impact on human health. Nowadays, while positive effects of natural building materials are expected to be more in use in buildings, one of the important reasons that they do not receive sufficient attention is that these materials have not yet been sufficiently industrialized, and therefore not widespread. In this study, energy consumption values of the buildings produced with natural building materials were simulated. Owing to these results, the use of natural building materials in buildings is not only an important parameter for public health, but also quantitative results make it a logical choice in terms of designing energy efficient buildings, and opening the path of industrialization of these materials supports the aim of this thesis.

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