THERMAL COMFORT ANALYSIS OF HISTORICAL MOSQUES. CASE STUDY: THE ULU MOSQUE, MANİSA, TURKEY

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ABSTRACT

THERMAL COMFORT ANALYSIS OF HISTORICAL MOSQUES.
CASE STUDY: THE ULU MOSQUE, MANİSA, TURKEY

Mosques are sanctuary places for Muslims where they can communicate with each other and perform their religious activities. Mosques differ from other building types in terms of occupancy period during a day with their unique function and intermittent operating schedule.

Historical mosques with cultural heritage value, contain lots of artworks and represent Turkish culture for centuries. These mosques are originally built and serve without heating, cooling and mechanical ventilation systems.

In this thesis, a systematic approach on monitoring and evaluating the microclimate and thermal comfort of historical mosques has been developed. This approach consists of two phases: detailed data collection and developing a dynamic building energy model.

As a case study, The Ulu Mosque was monitored between 2015 and 2018. Thermal comfort evaluation of the mosque during worship periods were conducted based on the method provided by EN ISO 7730 standard. A dynamic Building Energy Performance Software, is used to model the mosque, and the model was calibrated by hourly indoor temperature data. The calibrated model, which meets ASHRAE 14 requirements, is used to develop retrofitting proposals. Thirteen different scenarios were proposed to improve thermal comfort during worship periods. The results were then evaluated according to EN 16883 standard in terms of the conservation of cultural heritage. Electric radiator heating with intermittent operating schedules was obtained as the best options to protect cultural heritage, while decreasing dissatisfaction level from 45% to 10% in winter months. Additionally, comparing with continuous operating schedule, intermittent operation saves 46.9% energy.

ÖZET

TARİHİ CAMİLERDE ISIL KONFOR ANALİZİ. ALAN ÇALIŞMASI: ULU CAMİ, MANİSA, TÜRKİYE

Camiler, Müslümanların ibadetlerini yerine getirdikleri ve birbiriyle iletişim kurabildikleri sosyal merkezlerdir. Camiler, Ay ve Güneş'in hareketlerini referans alan değişken ibadet vakitleri ve doluluk oranlarıyla diğer yapı tiplerinden farklıdırlar.

Tarihi camiler aynı zamanda kültürel değere de sahiptirler. Bir müze gibi birçok sanat eserini muhafaza edebilirler ve Türk kültürünü temsil ederler. Çoğunlukla ısıtma veya soğutma sistemleri yoktur, sadece doğal havalandırma ile serinletilirler.

Bu tez çalışmasında, tarihi yapının iç ve dış ortam ikliminin izlenmesi ve değerlendirilmesi için sistematik bir yaklaşım sunulmuştur. Bu yaklaşım iki aşamadan oluşur. İlk aşama ayrıntılı veri toplama, ikincisi ise toplanan verilere dayalı bir sanal bina performans modeli oluşturmaktır.

Alan çalışması olarak, Ulu Cami'de 2015-2018 yılları arasında farklı dönemlerde ölçme ve izleme gerçekleştirilmiştir. Caminin ibadet vakitlerinde ısıl konfor değerlendirmesi, EN ISO 7730 standardının sağladığı yöntemle yapılmıştır. Sanal modelin oluşturulmasında dinamik bina ısıl performans yazılımı kullanılmıştır. Daha sonra model ölçülen iç ortam sıcaklık verilerine göre ASHRAE 14 standardının gereksinimlerini karşılayacak şekilde kalibre edilmiş ve toplanan veriler, mevcut yapısal problemler ve Cami'nin tasarım özellikleri dikkate alınarak değerlendirilmiştir.

Namaz vakitlerinde caminin mevcut ısıl konfor düzeyinin yetersiz olduğu belirlenmiş, ısıl konfor memnuniyet düzeyinin artırılması için on üç farklı senaryo önerilmiştir. Bu senaryolar modele uygulanmış ve EN 16883 standardına göre kültürel mirasın korunması açısından değerlendirilmiştir. Sonuç olarak, kesikli çalışma programında elektrikli radyatör ile ısıtma uygulaması hem ısıl konfor hem de kültürel mirasın korunması açılarından en iyi seçenek olarak değerlendirilmiştir. Bu senaryo ile kış aylarında kişisel memnuniyetsizlik seviyesi %45'ten %10'a düşürülürken, sürekli çalışma programlarına göre %46.9 oranında enerji tasarruf sağlanmaktadır.

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A	Average of the measured values	(-)
CV (RMSE)	Coefficient of variant of root mean square error	(%)
f	Clothing surface factor	(-)
h	Convective heat transfer coefficient	(W/m^2K)
I	Thermal resistance	(m^2K/W)
M	Metabolic rate	(W/m^2)
MBE	Mean bias error	(%)
n	number of observations	(-)
o	Measured value	(-)
P	Partial water vapor	(Pa)
PMV	Predicted mean vote	(-)
PPD	Predicted percentage of dissatisfied	(%)
RH	Relative humidity	(%)
RMSE	Root-mean-square-error	(%)
t	Temperature	(℃)
s	Simulated value	(-)
$\bar{t}_r$	Mean radiant temperature	(℃)
v	Velocity	(m/s)
W	Mechanical power	(W/m^2)
3D	3 dimensional	(-)
2D	2 dimensional	(-)

Subscripts

a	Air
l	Local
c	Convection
cl	Clothing
r	Relative

CHAPTER 1

INTRODUCTION

1.1. Problem Statement

Socrates at 400's BC had ideas about climatic sustainability and how a house should be built to ensure thermal comfort. On the other hand, thermal comfort was not a practical issue until the industrial revolution. For heating, a fire pit in the middle of the houses was used. When the weather is hot hand-held fans could be useful for relief. While heating technologies were improved at the 18^{th} century, cooling technologies had to wait two centuries more (Szokolay, 1985). At 1923, Houghton and Yaglou were used "comfort zone" term for the first time and described it as "*a thermal condition in which little or no effort is required by occupants to adjust their bodies to surrounding environmental conditions*" (Houghton and Yaglou, 1923; Panchyk, 1984). Following the World War II, the number of studies on "thermal comfort" were increased, and many disciplines from engineering to architecture, physiology, medicine, and geography brought their findings together in an interdisciplinary manner (Auliciems and Szokolay, 1997).

Owing to the fact that people spend more than 90% of their lifetimes in controlled environments where mechanical heating, cooling and ventilation system (HVAC) are used, tremendous amount of articles have been published on thermal comfort analysis of these controlled environments (Zomorodian et al., 2016).

As expected, some of the natural features of historical constructions have the ability to provide an adequate level of thermal comfort for their inhabitants. Construction materials, thermal mass, moisture cushioning, location, general form and exterior wall openings affect hydrothermal performance of historical buildings. Furthermore, some parts of building design could lead to low and high-pressure areas that could create natural ventilation. In addition, occupants of historical buildings change indoor climatic conditions with interventions such as opening/closing windows and doors when they are hot/ cold.

The biggest challenge on improving thermal conditions of historical buildings is to preserve cultural heritage. Therefore, each retrofit intervention to be performed should not only aim obtaining better thermal comfort but also not to be harmful on the heritage value of the building. EN 16883 “Conservation of cultural heritage” standard which is a guideline to enhance energy performance of historical buildings, states that “*Interventions to a historical building should respect the architecture, appearance, structure and historical artistic value of the building. Any measures that harm these elements should be avoided. A systematic evaluation should consider not only technical and economic aspects but also the physical and historical features of the building*” (EN 16883, 2017).

The mosques are places of worship and are only being visited during specific periods. Therefore, heating and cooling systems of the mosques are operated intermittently. For this reason, heating and cooling strategies must be carefully designed. Although many studies encountered in thermal comfort of living and working areas, dwellings, offices, classrooms and schools; according to the author’s knowledge, there are few studies exist on thermal comfort of historical mosques.

1.2. Aim and Objectives of the Study

The primary aim of this thesis is to evaluate thermal comfort conditions of historical mosques that do not have any HVAC system. The objectives are;

- to determine monthly average thermal comfort conditions,
- to propose retrofitting scenarios to improve thermal comfort,
- to evaluate the proposed scenarios based on thermal comfort improvement and protection of heritage value together.

The Ulu Mosque in Manisa, Turkey, is selected as case study for thermal comfort evaluation. The thesis examines the following questions:

- What is the plan of the Ulu Mosque and which construction materials are determined for the building?
- What is the occupancy schedule?
- How can we create a dynamic building energy model which is close to the reality?
- What is the need for thermal comfort in a historical mosque?

• What is needed to develop restoration strategies for historical mosques without disturbing the cultural heritage value?

1.3. Limitations and Assumptions

The thesis is conducted in two stages with some restrictions and assumptions. One of the problems to model a historical building is lack of material knowledge. Even though the restoration project exists, material properties of a historical building are not known precisely, and it is not allowed to take samples to determine. Therefore, assumptions should be made with reference to the period in which the building was constructed.

The dynamic building energy simulation tools that can be used for developing and analyzing the building models are designed for modern buildings with uniform construction in general. Therefore, it would be difficult to model historical buildings which have variable wall thicknesses. For the Ulu Mosque, the average wall thicknesses are calculated and used in the software.

The number of scenarios for improving thermal comfort is limited due to the importance of historical buildings including architectural and aesthetic values.

Throughout the measurement period, some of the temperature and relative humidity data were missing from August 2nd to 13th, 2017 because of the technical problems of dataloggers such as failure or low battery.

1.4. Content of the Study

The thesis consists of six chapters. First chapter introduces the problem, goals, objectives, assumptions and limitations of the study. The literature survey that presents a brief summary of thermal comfort analysis in contemporary and historical buildings and mosques, are given in Chapter 2. In Chapter 3, methodology is presented. The methodology contains introduction to dynamic building energy performance software, "DesignBuilder", calibration procedure, thermal comfort model defined by EN ISO 7730 standard, case building, the Ulu Mosque-Manisa-Turkey and measurement procedure. Results of the measurements, modeling, calibration and simulations are given in Chapter 4. Results derived from the study and suggestions for further studies are discussed in Chapter 5. Conclusions are given in Chapter 6.

CHAPTER 2

LITERATURE SURVEY

In this chapter, literature survey is presented into three sections: Thermal comfort, historical buildings and mosques.

2.1. Thermal Comfort

Thermal comfort is described as "*the condition of human's feeling express the thermal environment*" and it is a function of two group variables: personal and environmental. Personal variables depend on personal behavior and choices which are physical activity level and clothing insulation. Environmental variables are indoor radiant temperature, relative humidity, air temperature and air velocity where the occupant is situated (Fig. 2.1). Those parameters are used into a mathematical model for predicting thermal comfort and thermal dissatisfaction levels which was presented by Fanger as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), respectively (Fanger, 1970). PMV and PPD methods are used to evaluate thermal conditions of buildings and to compare HVAC systems, operating strategies and insulation options.

International Organization for Standardization (ISO) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) were standardized ergonomics of the thermal environment with analytical determination based on Fanger's PMV and PPD methods which were established by the researcher with over 1000 subject in a controlled climatic chamber (EN ISO 7730, 2005; ASHRAE 55, 2013).

PMV is described as an index that predicts the mean value of the votes of a large group, has a 7-point thermal sensation scale which is based on the heat balance of the body with the environment that could be affected from air temperature, air velocity and humidity, mean radiant temperature, physical activity level and clothing insulation (EN ISO 7730, 2005). Thermal sensation scale based on 7 ratings from -3 to +3. It describes occupants' feeling about the indoor temperature as -3 for cold, -2 for cool, -1 for slightly cool, 0 for neutral, +1 for slightly warm, +2 for warm and +3 for hot as given in Fig. 2.2 (Fanger, 1970).

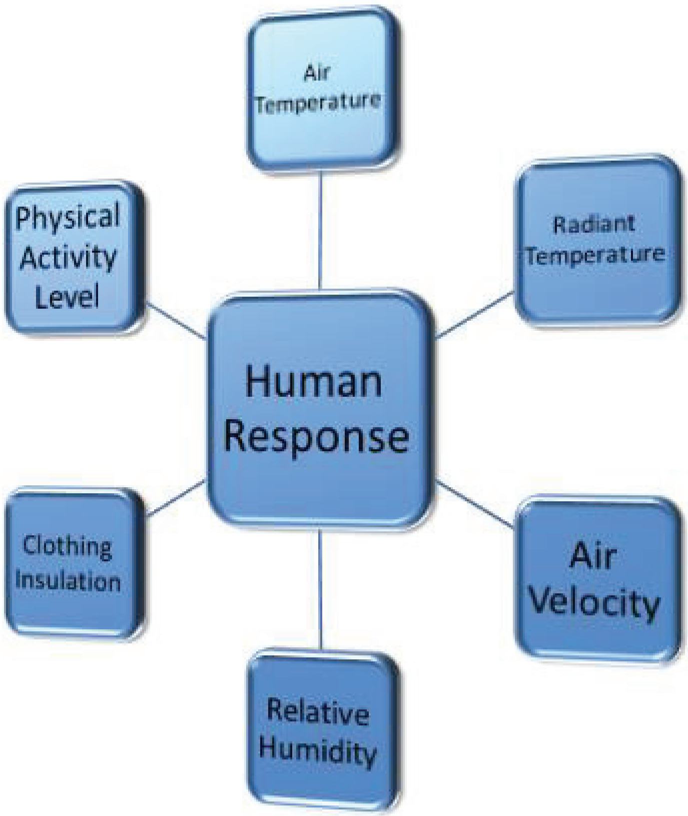


Figure 2.1. Thermal comfort variables (EN ISO 7730, 2005)

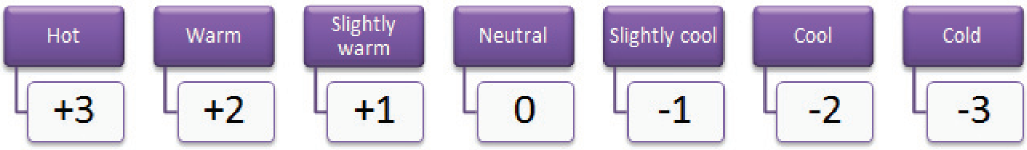


Figure 2.2. Seven-point thermal sensation scales (Fanger, 1970)

The PPD establishes a quantitative prediction of the percentages of thermally dissatisfied people who feel too warm or too cool. PPD is a function of PMV and it could be seen how PPD changes when the PMV changes between ± 3 (Fig. 2.3). Indoor environment is accepted as "comfortable" if 85% of the occupants are satisfied meaning 15% dissatisfaction (EN ISO 7730, 2005).

Atmaca and Gedik (2019) investigated indoor thermal comfort levels in two mosques based on international standards. The PMV and PPD levels were calculated from measurement results to compare and monitor thermal comfort level in the mosques that both have natural and the same mechanical ventilation system while having different heating/cooling systems. The results showed that entrance zone of both mosques had the lowest thermal comfort values. The authors suggested that creating intermediate zone between indoor and outdoor zones would decrease thermal dissatisfaction. The mosque with air-conditioning system had better thermal comfort level compared to the mosque with traditional building envelope and heating-cooling system.

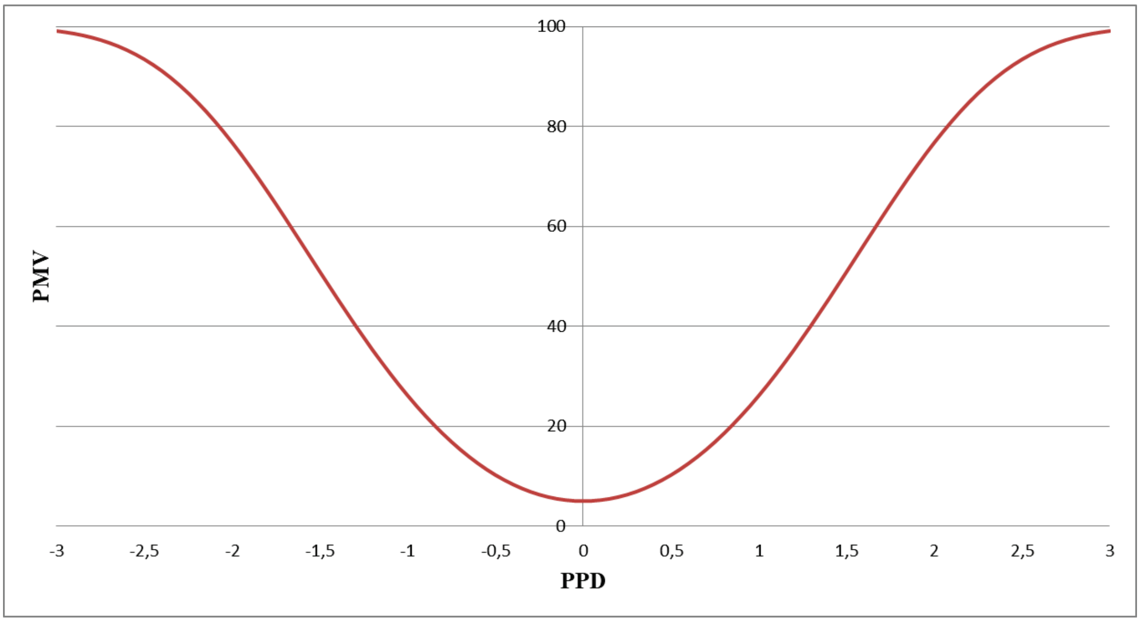


Figure 2.3. PPD as a function of PMV (EN ISO 7730, 2005)

Fanger and Toftum (2002) investigated that the PMV model seems to over-estimate the sensation of warmth in non-air-conditioned buildings in warm climates. The answer situated beyond model agreed well with high-quality field studies in buildings with HVAC systems, in cold, temperate and warm climates. In contrast to that, in non-air-conditioned buildings in warm climates, occupants might vote comfort less than the PMV predicts because of the occupants' low expectations. Then, an extension of the PMV model that states an expectancy factor is recommended for non-air-conditioned buildings in warm climates. Besides, Wang et al. (2018) presented an uncertainty analysis for subjective thermal comfort votes, which were analyzed in terms of thermal sensation, humidity sensation, draught sensation and thermal satisfaction. They were obtained that the standard uncertainty of subjective thermal comfort vote would decrease with the increasing number of subjects above 40.

Living a long time in a specific region or the past thermal experience caused generation of thermal adaptation. Yang et al. (2015) studied the application of PMV in the hot-humid climate 440 feedback of occupants were analyzed. The PMV and the adaptive thermal comfort methods were applied to estimate thermal preferences of the occupants and compared with the surveys. The authors concluded that PMV method was over or under-estimated occupants' actual thermal sensation which affected from the physiological response and the contribution accommodate themselves to the environment due to psychological adaptation.

2.2. Historical Buildings

Many historical buildings have complex geometry because of their domed ceiling, round towers and different wall thicknesses. There is no insulation on the walls and no mechanical ventilation system due to the lack of technology at the times those were built (Windström, 2012; Webb, 2017). Moreover, their structure has been damaged by natural climatic effects such as rain, wind and temperature during the centuries (Wu et al., 2014).

Intervention strategies for the restoration of historical buildings should preserve the historical and artistic value of the building. Semprini et al. (2017) proposed an HVAC plant for the ancient historical church to enhance thermal comfort and reduce energy consumption without affecting the historical value and artistic perception of the building. The energy model was created by DesignBuilder software and the results showed that the proposed HVAC plant gave a pleasant indoor temperature level during daytime.

Turcanu et al. (2016) examined a historical roman church and tested different heating strategies to improve thermal comfort. Computational fluid dynamics software was used to simulate fluid flow and heat transfer. Underfloor heating system with mechanical ventilation resulted as the optimum solution to provide thermal comfort while conserving cultural values with respect to the static heaters.

2.3. Mosques

In recent years, numerous reports and articles have been published on the improvement of thermal comfort in different types of buildings such as offices, public and residential buildings (Atmaca and Gedik, 2019). Although each type of buildings has its own occupancy and operational schedule, the mosques similar to other religious buildings have intermittent occupation and the occupation period changes throughout the year which is unique (Jaafar et al., 2017).

Bughrara et al. (2017) conducted a study to determine thermal comfort condition in a naturally ventilated historical mosque via a dynamic building energy simulation tool in order to improve thermal comfort by underfloor heating system. The measurements were taken in the mosque and were used to calibrate the model. The model results indicated that underfloor heating system is the best way to enhance thermal comfort level in the mosque.

Thermal comfort and energy efficiency studies for the mosques concentrated on zoning the area. Depending on the number of occupants, the number of heated/cooled zones could be changed. On the other hand, intermittent heating/cooling would be a more efficient way than continuous operation in terms of thermal comfort and energy consumption. Furthermore, installing and air-conditioning system with over capacity would be also helpful to reach the comfort level faster. Budaiwi and Abdou (2013) investigated the impact of operational zoning and oversized HVAC systems in mosques with intermittent operation. The zoning is required because of the different occupancy levels for each prayer time. While occupancy rate could reach 100% at Friday time or Tarawih, occupancy rate for other prayer times could decrease dramatically. The study contains 132 mosques which are classified into six categories in terms of the mosque's floor type, capacity, aspect ratio, etc. It is assumed that occupants wear thin clothes and perform light activities. The study was concluded that to build up an oversized HVAC system would be the fastest way to obtain thermal comfort with intermittent operation, especially for the Friday time prayers. It helps to cool the area in an energy efficient way with zoning for 1-hour usage in daily routine prayer in the hot-humid climates.

Al-Homoud et al. (2009) investigated thermal comfort level on three different mosques both for daily routines and Friday time. Thermal comfort temperature range was considered as 20-24°C for cold season and 23-26.5°C for hot season while relative humidity range was 30–60% for all seasons. The study concluded that zoning with intermittent operation decreased energy consumption and achieved an acceptable thermal comfort level. Similar to that, Azmi and Kandar (2019) studied separate spatial zoning system for high and low occupancy to improve thermal comfort and save energy. In regular prayer times because of low occupancy, it was efficient to be created a small zone near the qibla wall where the pray was performed behind the Imam.

There are number of studies examining thermal comfort in historical mosques. However, there is no study for historical mosques by focusing thermal comfort on only prayer times in temperate climates and also performing risk assessment study aiming to preserve cultural heritage to the author’s knowledge.

CHAPTER 3

MATERIALS AND METHODS

The methodology of the thesis consists of three main phases: detailed data collection, development of a dynamic building energy model, and propose and analyze retrofitting strategies. The first phase involves long-term measurements of indoor and outdoor climatic conditions (temperature and relative humidity), collection of data on structural characteristics of the building, thermal properties of building materials, heating/cooling system, ventilation strategies, and number of occupants and occupation time. The second phase is to model the building to reflect its formal, structural and occupancy characteristics. The model is then calibrated by hourly indoor air temperature data. The calibrated model (baseline), which meets ASHRAE 14 requirements, can be used to evaluate indoor climate of the mosque and, to develop and analysis of retrofitting proposals. If thermal comfort analysis of the baseline model case points out the need to improve thermal comfort, third phase discusses retrofitting strategies and simulation of these strategies. Simulation results are compared based mainly on thermal comfort and protection of cultural heritage assets along with energy consumption data of the proposed strategies. Fig. 3.1 gives the flow diagram of the methodology.

3.1. Detailed Data Collection

Data collection process includes collecting existing data and an indoor and outdoor climatic data measurement campaign. Existing data is collected from architectural and restoration projects, reports, books, surveys and personal communications with staff of the mosque. The data obtained from those sources are structural characteristics of the building, thermal properties of building materials, heating/cooling system, ventilation strategies, and number of occupants and occupation time.

Long-term measurements of indoor and outdoor climatic data (temperature and relative humidity) are conducted by mini dataloggers (HOBO U12) (Fig. 3.2). The properties of dataloggers are given in Table 3.1 (Onset, 2017).

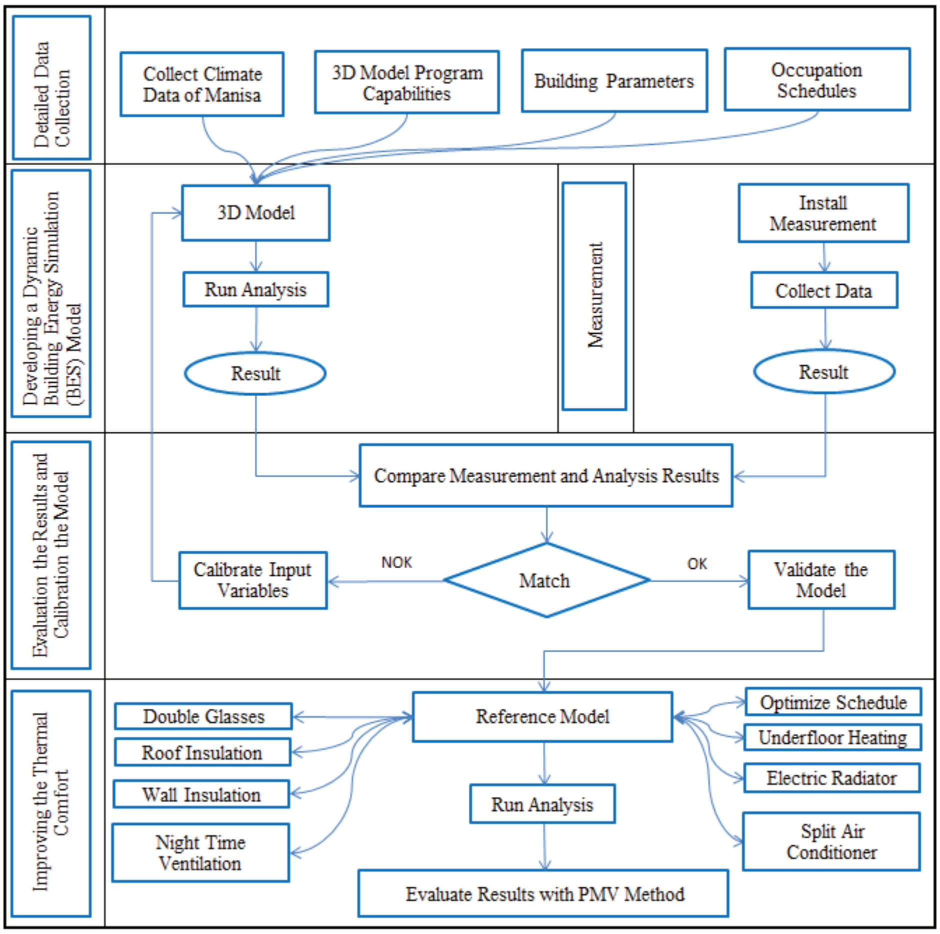


Figure 3.1. Flow diagram of the methodology

Figure 3.2. HOBO U12 data logger (Source: Onset, 2017)

Table 3.1. Properties of datalogger HOBO U12 (Onset, 2017)

Parameter	Temperature (T) (°C)	Relative Humidity (RH) (%)
Measurement range	(-20)-70	5-10
Accuracy	± 0.35	± 2.5

Five dataloggers were installed in the prayer hall (Fig. 3.3) while one datalogger was located outside to the courtyard. Temperature (T) and relative humidity (RH) measurements were recorded every 10 minutes in four different periods: April 4th, 2016-March 11th, 2018. The dataloggers were positioned at different heights to protect them any human interaction as shown in Table 3.2.

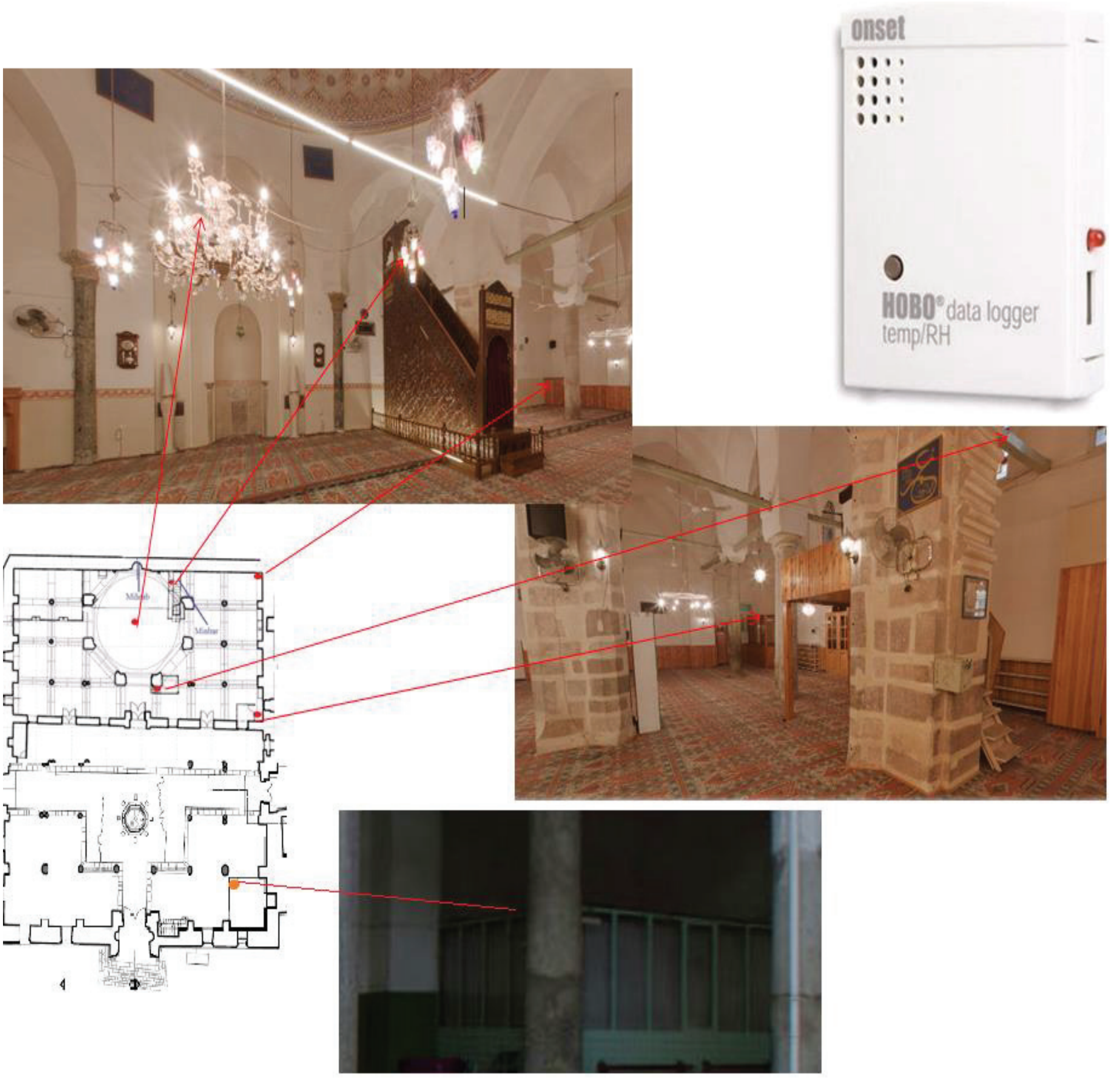


Figure 3.3. Locations of dataloggers

Table 3.2. Heights of dataloggers

Datalogger locations	Height (cm)
Above imam* room	230
Next to muezzin** place	440
Right corner of qibla*** wall	130
Mimber****	410
Chandelier	245
Outside	245

* Imam leads Islamic worship services.

** Muezzin is the person appointed at a mosque to lead and recite the call to prayer for every event of prayer and worship in the mosque.

*** The qibla is the direction of Kaaba in Mecca that should be faced when a Muslim prays.

**** Mimber is a short flight of steps used as a platform by a imam in a mosque.

3.2. Developing a Dynamic Building Energy Simulation (BES) Model

The mosque is modeled and calibrated to determine thermal comfort conditions at the baseline. Then, the proposed retrofit interventions to improve thermal comfort are simulated by this model. DesignBuilder (v.5.0.3.007) (2017) software is chosen for BES modeling because of the integration with Energy Plus which enables to complete the simulation within the DesignBuilder interface and the results could be displayed and analyzed effectively in different intervals.

First, the architectural drawing of the mosque is transferred to the software by AutoCAD LT 2008 (2017). Two-dimensional dwg. data is scaled and transformed into dxf. to draw model into DesignBuilder with higher accuracy. Fig. 3.4 shows how 2D dwg. data scaled and transformed into dxf. to draw model into DesignBuilder with higher accuracy.

Afterward, the two-dimensional file is called up with DesignBuilder software. Height and thickness values are uploaded to the software and the mosque is modeled in three dimensions with building materials, construction technology, number of users, occupancy schedule, window and door components. Fig. 3.5 shows the BES model of the mosque.

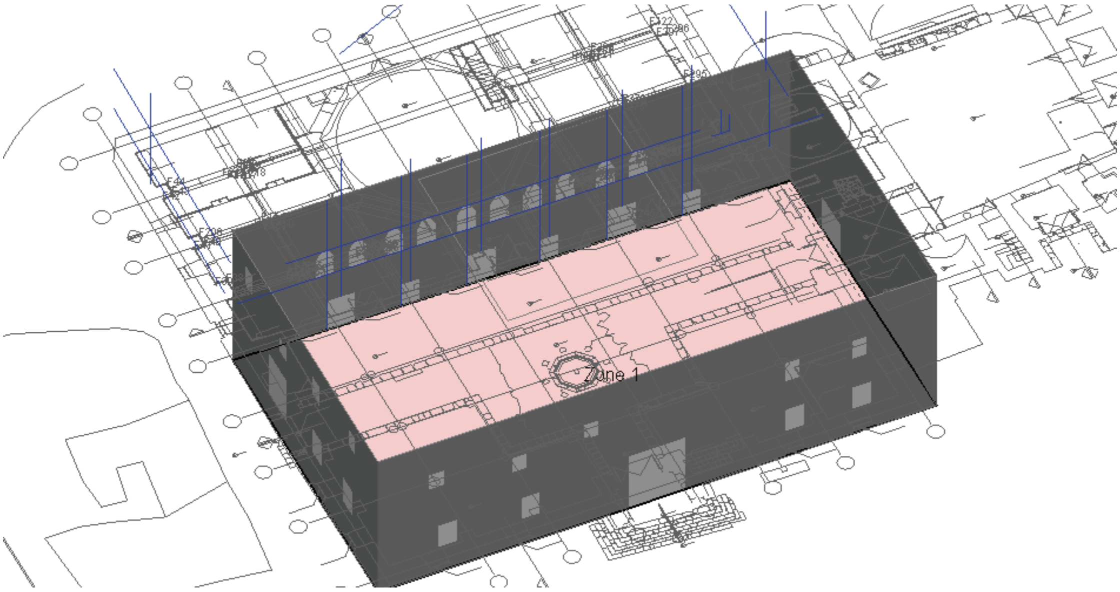


Figure 3.4. 2D dxf. data used to draw model into DesignBuilder

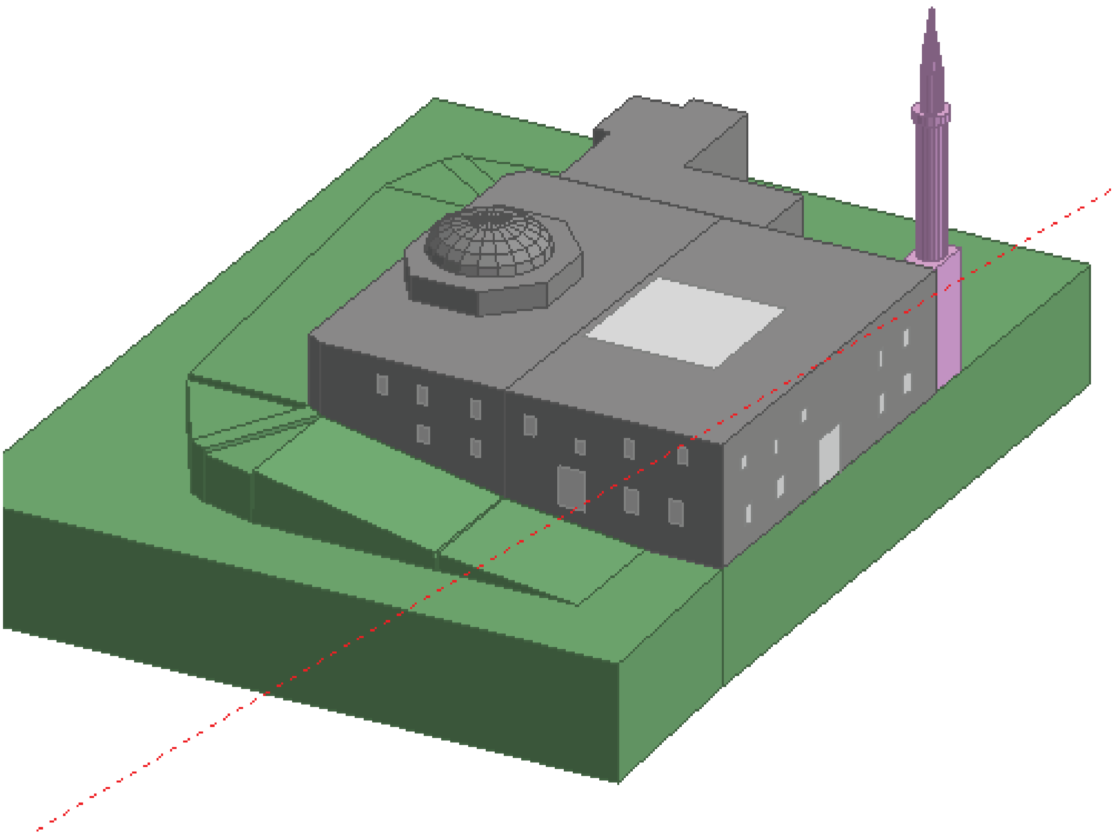


Figure 3.5. BES model of the Ulu Mosque

Like the most of historical buildings, the Ulu Mosque has different geometries and irregularities on the wall form. Therefore, during the design process, some assumptions were taken to simplify the geometry of the building. The assumptions are as follows:

- The minaret is a tower and used for calling Muslims to prayer by muezzin, is considered adiabatic to reduce the simulation time. It is shown in Fig. 3.5 with purple color.
- DesignBuilder v.5.0 does not have properties for irregular wall drawings. Therefore, the average thicknesses of the walls were calculated and drawn as a straight line.
- The mosque occupancy rate is 5% for dawn-prayer 10% for mid-day to night prayer and 100% for Friday time and Tarawih which refers to additional prayer performed during Ramadan after the Isha.
- There is no heating/cooling system in the mosque. Ventilation is performed by fans (mechanical) or windows (natural) during prayer times in summer.
- The windows and doors in courtyard are transformed into the holes because they are always open.
- The orientation to the North direction of the mosque is taken from Google Map by drawing a perpendicular line to the North direction and is applied with the same angle to the model as 171° (Fig.3.6).

Figure 3.6. Orientation of the mosque (Source: Google Maps, 2017)

- Metabolic rate of the occupants is taken as 70 W/m^2 assuming sedentary behavior which means that any time a person is sitting, lying down, standing still or waiting (EN ISO 7730, 2005).
- Clothing is an important parameter on thermal comfort since it creates an insulation layer. It is crucial to determine the occupants' clothing value called "clo" which is given in Table 3.3 (EN ISO 7730, 2005).
- Three different clothing styles are chosen for winter, spring and summer months. Additionally, for the morning prayers, thicker cloths are chosen for winter and spring since prayer time is quite early.

3.3. Calibration

The developed model is calibrated by measured T data in order to match the behavior of the model and the building.

The criteria of calibration are based on error indices which are Mean Bias Error (MBE), Root Mean Square Error (RMSE) and Coefficient of Variant of Root Mean Square Error (CV (RMSE)). The error indices are used to estimate the acceptable error range between the simulated data and the measured data, and calculated by Eq.s 3.1-3.3. As a result, the analysis assumes that the model reflects the actual results as the MBE value and CV (RMSE) value are below of acceptance limits as shown in Table 3.4 (ASHRAE Guideline 14, 2002).

$$MBE = \frac{\sum_{i=1}^{n} Residual_i}{n} \tag{3.1}$$

$$RMSE = \left[\frac{\sum_{i=1}^{n} |s_i - o_i|^2}{n}\right]^{1/2} \tag{3.2}$$

$$CV(RMSE) = \frac{RMSE}{A} \tag{3.3}$$

3.4. Thermal Comfort Analysis

Once the model is calibrated according to ASHRAE 14, Fanger's PMV and PPD methods are used to determine thermal comfort of the mosque. PMV and PPD values are calculated by Eq.s 3.4-3.8.

$$\text{PMV}=[0{,}303.\exp(-0{,}036.\text{M})+0{,}028].$$
$$\begin{cases}[(\text{M}-\text{W})-3{,}05.10^{-3}.[5\,733-6{,}99.(\text{M}-\text{W})-\text{P}_\text{a}]-0{,}42.[(\text{M}-\text{W})-58{,}15] \\ -1{,}7.10^{-5}.\ \text{M}.(5867-\text{P}_\text{a})-0{,}0014.\ \text{M}.(34-\text{t}_\text{a}) \\ -3{,}96.\ 10^{-8}.\ \text{f}_{\text{cl}}\ .\left[(\text{t}_{\text{cl}}+273)^4-(\bar{\text{t}}_\text{r}+273)^4\right]-\ \text{f}_{\text{cl}}.\text{h}_\text{c}.(\text{t}_{\text{cl}}-\text{t}_\text{a})\end{cases} \quad (3.4)$$

$$\text{t}_{\text{cl}}=35{,}7-0{,}028.(\text{M}-\text{W})-\text{I}_{\text{cl}}.\ \{3{,}96.10^{-8}.\ \text{f}_{\text{cl}}.\left[(\text{t}_{\text{cl}}+273)^4-(\bar{\text{t}}_\text{r}+273)^4\right]+\text{f}_{\text{cl}}.\text{h}_\text{c}.(\text{t}_{\text{cl}}-\text{t}_\text{a})\ \} \quad (3.5)$$

$$\text{h}_\text{c}=\begin{cases}2{,}38.|\text{t}_{\text{cl}}-\text{t}_\text{a}|^{0{,}25} & \text{for } 2{,}38.\ |\text{t}_{\text{cl}}-\text{t}_\text{a}|^{0{,}25}>12{,}1.\sqrt{\text{v}_{\text{ar}}} \\ 12{,}1.\sqrt{\text{v}_{\text{ar}}} & \text{for } 2{,}38.\ |\text{t}_{\text{cl}}-\text{t}_\text{a}|^{0{,}25}<12{,}1.\sqrt{\text{v}_{\text{ar}}}\end{cases} \quad (3.6)$$

$$\text{f}_{\text{cl}}=\begin{cases}1{,}00+1{,}290\text{l}_{\text{cl}} & \text{for } \text{l}_{\text{cl}}\le 0{,}078\text{m}^2\ \text{K/W} \\ 1{,}05+0{,}645\text{l}_{\text{cl}} & \text{for } \text{l}_{\text{cl}}>0{,}078\text{m}^2\text{K/W}\end{cases} \quad (3.7)$$

$$\text{PPD}=100-95.\exp(-0{,}03353.\text{PMV}^4-0{,}2179.\ \text{PMV}^2) \quad (3.8)$$

After that, it is investigated whether the model's thermal condition meets the recommended threshold values specified in EN ISO 7730 (2005) for the occupants given Table 3.5. If the desired thermal comfort is not achieved in the current situation of the building, various attempts to improve the thermal comfort level are made. The interventions can be done considering the historical values of the building.

3.5. Retrofitting Strategies

The main aim of retrofitting strategies is to improve thermal comfort of the mosque by proposing different scenarios. The developed scenarios are classified as passive and active retrofitting scenarios. While passive retrofitting strategies are changing the windows with double glazing and low emissivity glass, night time ventilation, roof insulation and wall insulation, active scenarios are implementing an underfloor heating system, electric radiator and split air-conditioning system. The active and passive scenarios are simulated using calibrated model, then PMV and PPD values are obtained.

Table 3.3. Thermal insulation and metabolic rate for prayers

Mid-day prayer, afternoon prayer, after-sunset prayer, night prayer (May and September dawn-prayer)					
Seasons	**Month**	**Clotting**	**Clothing insulation* (clo)**	**Total clothing insulation (clo)**	**Metabolic rate** (W/m^2)**
Summer	June July August	Panties	0.03	0.49	70
		Singlet	0.04		
		Normal trousers	0.25		
		Socks	0.02		
		Short sleeves	0.15		
Spring and Autumn	April May September October	Panties	0.03	1.03	70
		Thick sweater	0.35		
		Normal trousers	0.25		
		Thick angle socks	0.05		
		Jacket	0.035		
Fall	November December January February March	Panties	0.03	1.28	70
		Thick sweater	0.35		
		Normal trousers	0.25		
		Thick angle socks	0.05		
		Coat	0.6		
Dawn-prayer					
Seasons	**Month**	**Clotting**	**Clothing insulation* (clo)**	**Total clothing insulation (clo)**	**Metabolic rate** (W/m^2)**
Summer	June July August	Panties	0.03	0.49	70
		Singlet	0.04		
		Normal trousers	0.25		
		Socks	0.02		
		Short sleeves	0.15		
Spring and Autumn	April May September October	Panties	0.03	1.28	70
		Thick sweater	0.35		
		Normal trousers	0.25		
		Thick angle socks	0.05		
		Coat	0.6		
Fall	November December January February March	Panties	0.03	1.48	70
		Thick sweater	0.35		
		Normal trousers	0.25		
		Thick angle socks	0.05		
		Coat	0.6		
		Vest	0.2		

*Taken from EN ISO 7730 (2005) page: 20 table C2 for clothing insulation

** Taken from EN ISO 7730 (2005) page: 18 table B1 for metabolic rate

Table 3.4. Acceptance limits for calibration (ASHRAE Guideline 14, 2002)

Reference	Monthly criteria (%)		Hourly criteria (%)	
	MBE	**CV (RMSE)**	**MBE**	**CV (RMSE)**
ASHRAE Guideline 14	5	15	10	30

Table 3.5. Recommended threshold values for PMV (EN ISO 7730, 2005)

Category	PPD (%)	PMV
A	< 6	-0.2 < PMV < + 0.2
B	< 10	-0.5 < PMV < + 0.5
C	< 15	-0.7 < PMV < + 0.7

Besides thermal comfort analysis, the effect of retrofit interventions on heritage value is also evaluated to find the most appropriate solutions for the components of building's envelope based on the EN 16883 "Conservation of cultural heritage- Guidelines for improving the energy performance of historic buildings" standard (2017). The standard utilizes a five-level assessment criteria as presented in Table 3.6. Finally, the results are compared with the baseline model based on four measures: heritage value protection, thermal comfort, energy consumption and energy cost.

Table 3.6. Five-level assessment scale (EN 16883, 2017)

Assessment scale				
High risk	Low risk	Neutral	Low benefit	High benefit

CHAPTER 4

CASE STUDY

The Ulu Mosque Complex which is located on the northern skirts of Spil Mountain in Manisa-Turkey was built in 1366 by Architect Emet Bin Osman with the order of Ishak Celebi who is the grandson of Saruhan Bey and the third bey of Saruhan Emirates (Saruhanoğluları). The complex consists of a mosque, a madrasah, a tomb and a courtyard. Besides, there is a bath on the 80 m north-east side of the complex (Fig. 4.1) (TC Ministry of Culture and Tourism, 2017).

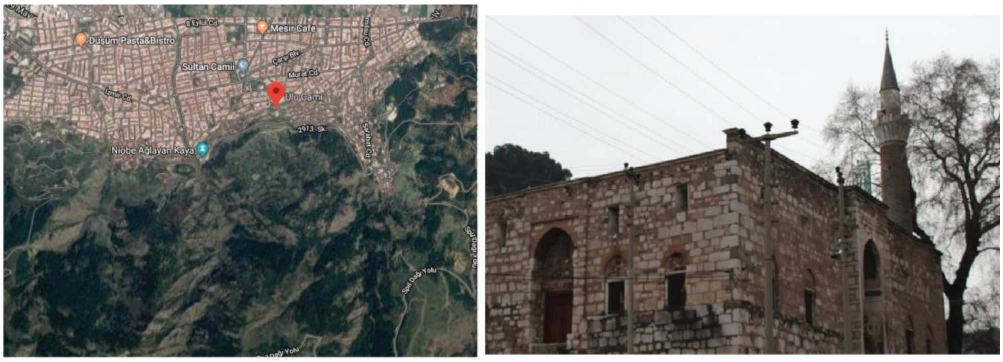


Figure 4.1. Location of the Ulu Mosque complex-Manisa-Turkey
(Source: Google Maps, 2017)

The madrasah, which is named as "Fethiye Medresesi," was built by the same architect about ten years later than the mosque and it was built as a single eyvan and two floors on the west side of the mosque (Fig. 4.2.a). There is a fountain in courtyard behind the north-facing crown door (Fig. 4.2.b) and a tomb which was entered with a gate on the southern wall between the mosque and the madrasah. It is believed that there are four sarcophagi which were belonged to Ishak Celebi and his family (Fig. 4.2.c). The bath is known as "Çukur Hamam" and it is thought that it was built to bring income to the municipality (Fig. 4.2.d). The bath was restored in 2006 by Governorate of Manisa (TC Ministry of Culture and Tourism, 2017).

The mosque is located in the eastern part of the complex and has a single minaret. It has a transverse rectangular plan and is covered with large dome that sits on squinches carrying an octagonal base. It consists of approximately two equal size spaces: courtyard and prayer hall. Both spaces consist of twenty-eight divisions; seven of them are longitudinally four in the transverse direction. Nine of these compartments were covered with a dome of 11 m in diameter and seated on octagonal columns, while the ceiling of the courtyard was left open (Fig. 4.3).

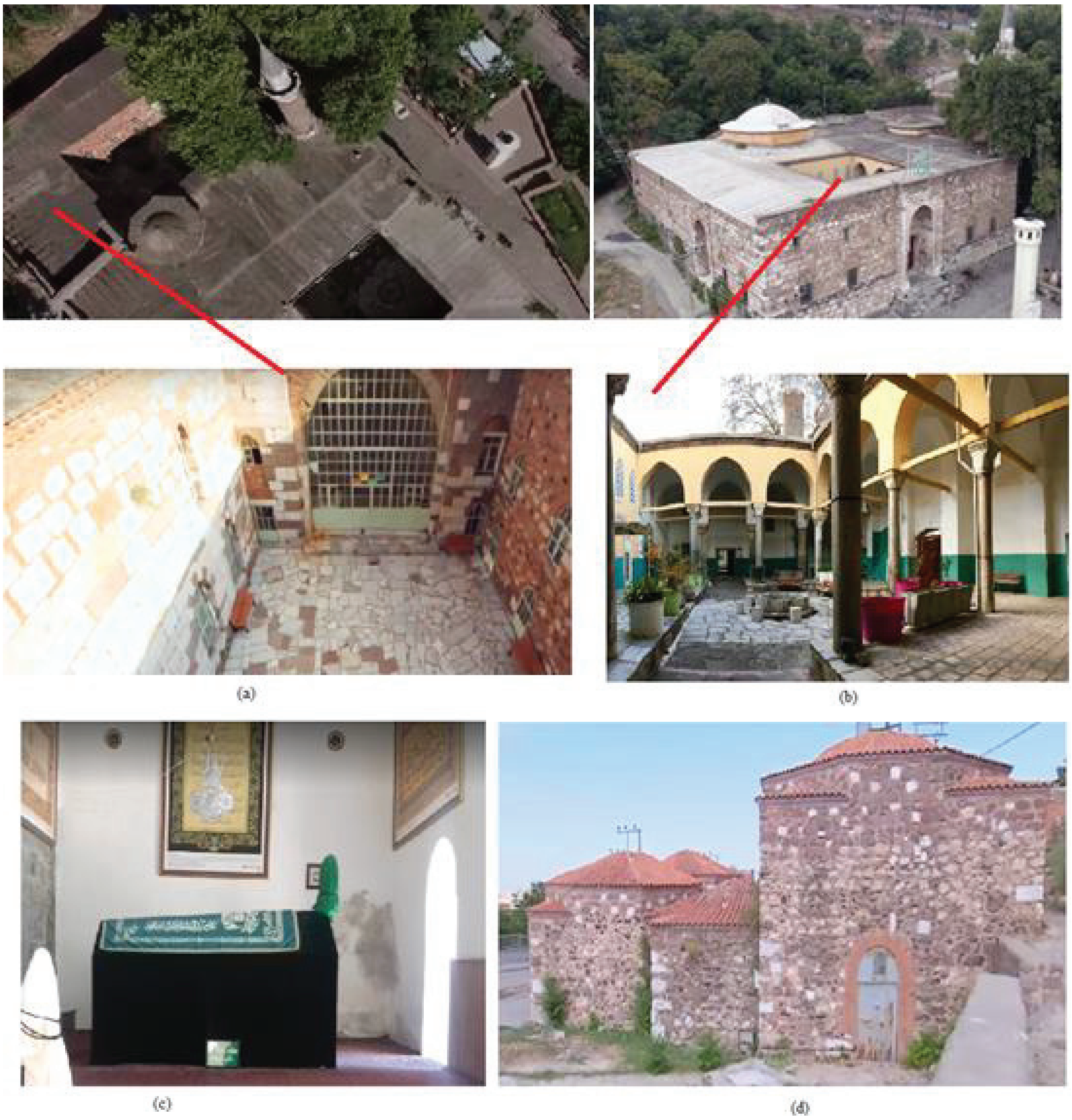


Figure 4.2. The Ulu Mosque complex a) Fethiye Madrasah, b) Courtyard, c) Tomb, d) Çukur Hamam (Source: Google Maps, 2017)

The mimber of the mosque is decorated with artifacts which were made with the technique of kundekari as presented in Fig. 4.4. It is one of the masterpieces of the Turkish timber carvings during the period of Beyliks. Door of the mimber is protected at Manisa Museum. The Ulu Mosque has the capacity of 550 people during prayer referring to the carpet design which indicates borders between prayers.

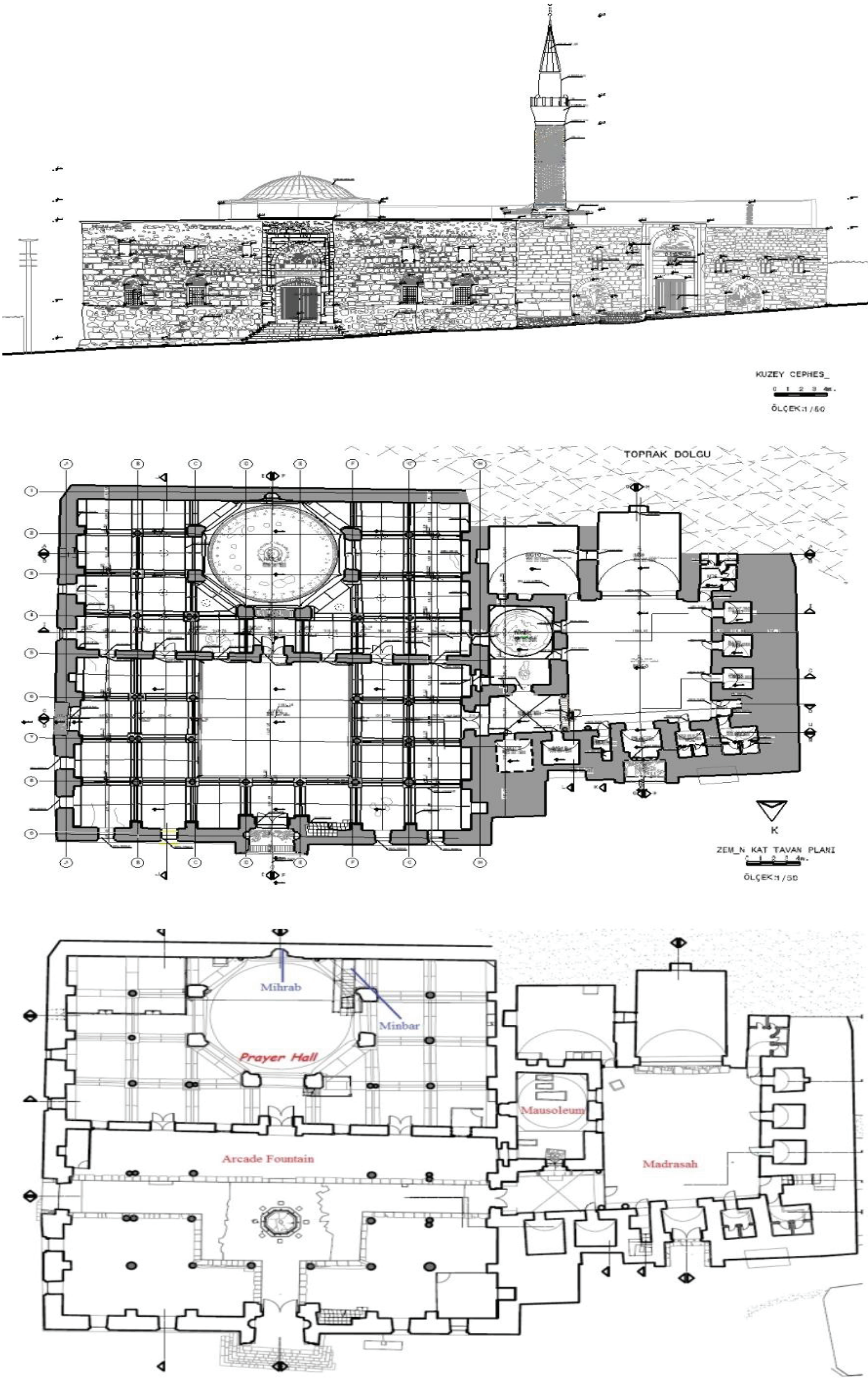


Figure 4.3. Plan of the Ulu Mosque (Adaptation from the drawings of relays: IZTECH Architectural Restoration Department, 2015)

Figure 4.4. Interior view of the Ulu Mosque (Source: Mekan 360, 2017)

Figure 4.5. Fan locations in the prayer hall a) wall type fans, b) ceiling fans, c) portable fans

Figure 4.6. Entrance to the prayer hall

There is no mechanical heating/cooling system in the prayer hall. In summer, ventilation is provided by twenty-nine fans which are located on the walls (9), ceiling (18) and two of them are portable (Fig. 4.5).

There are twelve windows at the entrance wall, five windows on the west wall and one window at the east wall. There are no windows on the qibla wall of the building. The entrance door and two windows next to the door is used kept open for natural ventilation when necessary as seen Fig. 4.6. Rest of the windows are fixed, cannot be opened.

The materials of building components, thicknesses, thermo-physical properties are obtained from restoration project if available (IZTECH Architectural Restoration Department, 2015). If not, assumptions were made based on walk-through inspections, then the assumed parameters were validated by calibration results. Table 4.1 shows overall heat transfer coefficients, thicknesses and position of each building component. Giving the fact that the thicknesses of the walls are different, for modeling purposes, the thicknesses of the walls were fixed by keeping the volume as constant as possible.

Table 4.1. Thermo-physical properties, thicknesses, positions and layers of building components

Building components	Overall heat transfer coefficient (U) (W/m^2K)	Thickness (cm)	Position	Layer
External walls	1.525	130	Outermost Innermost	Granite
		3		Plaster
Floor	1.349	25	Outermost Innermost	Sand and gravel
		2		Flooring wood blocks (Assumption)
		0.5		Carpet/textile flooring (Assumption)
Roof	2.168	0.5	Outermost Innermost	Concrete slab (Assumption)
		20		Brick
		0.5		Plaster
Windows	6.121	4		Single clear
Doors	1.685	35		Pine wood

The mosque prayer times were taken for each month and calculated an average time because every month has different time schedule due to the difference in sunrise and sunset for each day, as it is seen in Table 4.2.

The occupancy rates in the mosque were determined by observing the number of participation in five prayer times and Friday time, and by interviewing the Imam. Occupancy rate is taken as 5% for dawn-prayer, 10% for mid-day, afternoon, after-sunset and night prayers. During Tarawih at Ramadan and Friday time, the occupancy rate is assumed as 100% (Fig. 4.7).

Table 4.2. Daily prayer time according to the months

Prayer time		Dawn-prayer (Fajr Time)	Mid-day prayer (Dhuhr)	Afternoon-prayer (Asr)	After-sunset prayer (Maghrib)	Night-prayer (Isha)
Months	January	06:57	13:30	16:04	18:24	19:52
	February	06:36	13:34	16:33	18:58	20:22
	March	05:57	13:29	16:52	19:28	20:51
	April	05:03	13:20	17:02	19:57	21:26
	May	04:13	13:16	17:09	20:26	22:06
	June	03:47	13:21	17:16	20:47	22:37
	July	04:06	13:26	17:21	20:45	22:30
	August	04:48	13:25	17:12	20:15	21:48
	September	05:26	13:15	16:47	19:29	20:53
	October	05:55	13:06	16:14	18:42	20:05
	November	06:25	13:05	15:47	18:08	19:34
	December	06:49	13:15	15:42	18:01	19:30

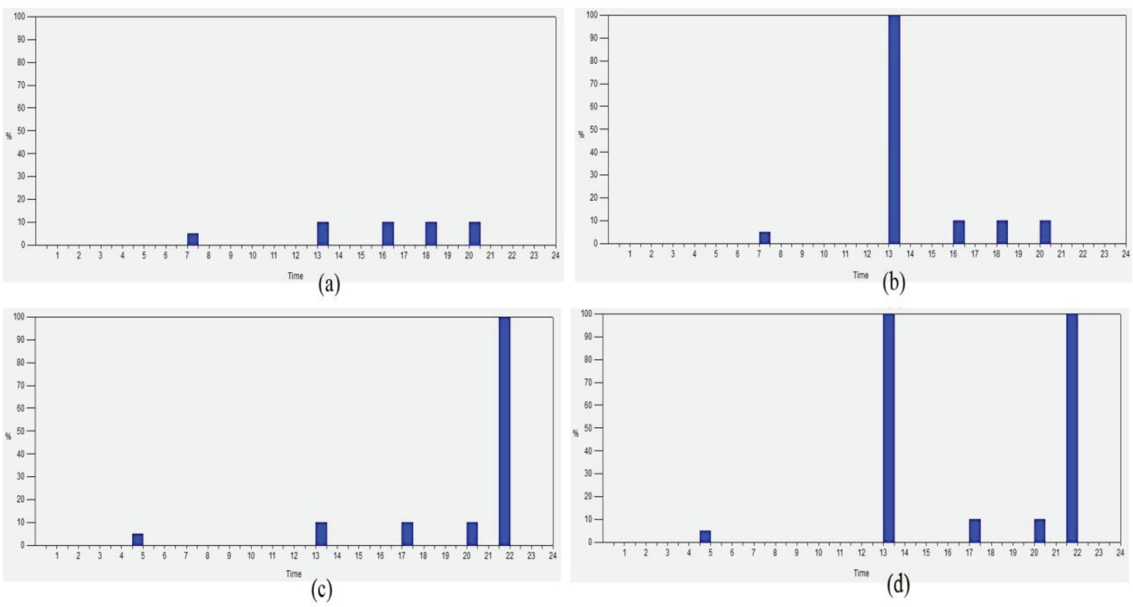


Figure 4.7. Occupancy rates of the mosque according to a) daily prayers, b) prayers on Friday, c) daily prayers in Ramadan, d) prayers on Friday in Ramadan

CHAPTER 5

RESULTS AND DISCUSSION

In this chapter, first T and RH data recorded throughout the measurement campaign are presented. Then, the BES model and calibration results which were used to determine thermal comfort conditions of the mosque (baseline model) are given. According to the baseline model, thermal comfort analysis and retrofit scenarios were developed and simulated. Simulation results were evaluated based on thermal comfort, risk on cultural heritage and energy consumption.

5.1. Data Analysis

Thermal condition of the mosque is highly influenced by the outdoor weather since there is no heating/cooling system. Therefore, collection of outdoor T and RH data is as important as indoor data.

5.1.1. Outdoor Environment Analysis

Outdoor T and RH data were collected by one datalogger located at the courtyard, between April 20th, 2016 and March 11th, 2018 with 10 minute-intervals and presented in Fig. 5.1. Monthly average values of T and RH are also given in Table 5.1. The outdoor T data is distributed from 1.1°C to 38.6°C with an average of 20°C.

5.1.2. Indoor Environment Analysis

Five dataloggers were located in the prayer hall to collect T and RH data during the measurement campaign (Fig.5.2).

Minimum, maximum and average T and RH values collected from dataloggers located on above the imam room, mimber, muezzin place, chandelier and right corner of qibla wall are shown in Fig.s 5.3-5.12, respectively and also given in Table 5.2.

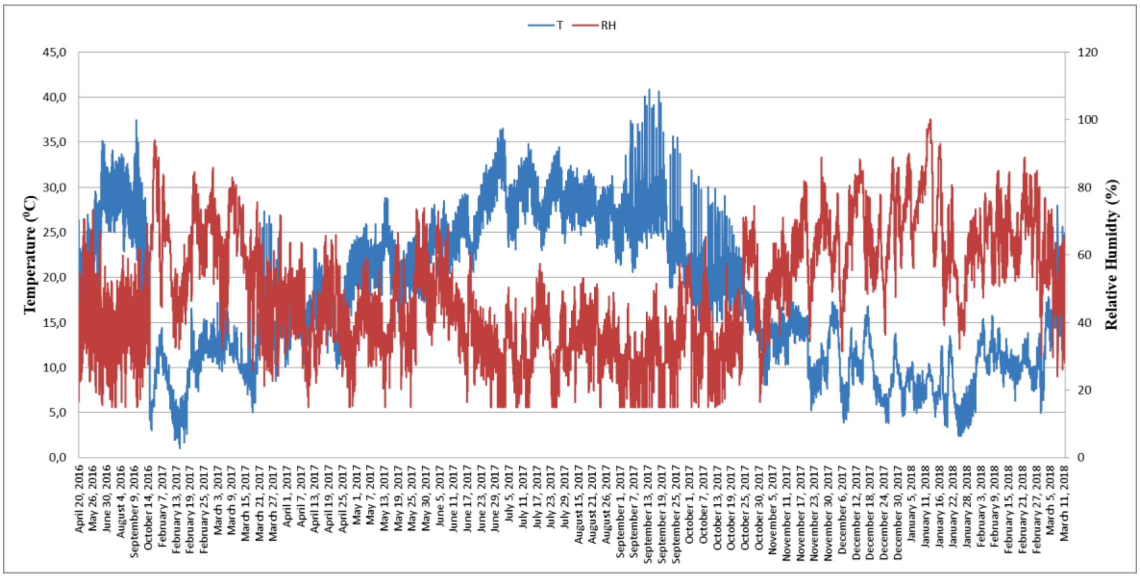


Figure 5.1. Outdoor T and RH measurements from April 20th, 2016 to March 11th, 2018

Table 5.1. Measured outdoor values

Measurement		T (°C)			RH (%)		
Max/Min/Avg.		Min.	Avg.	Max.	Min.	Avg.	Max.
2016	Apr-16	13.6	19.2	26.4	16.6	36.4	54.7
	May-16	14.2	20.8	28.4	22.5	46.2	73.3
	Jun-16	18.8	27.5	35.2	15.4	37	66.7
	Jul-16	25	29.3	34.1	15	34.3	52.5
	Aug-16	22.8	29.1	33.7	15	40	59.9
	Sep-16	16.6	25.3	37.4	15	37.7	61.9
	Oct-16	14.5	21.6	28.8	26.4	41.3	69
2017	Feb-17	1	8.7	16.5	32.2	63.3	94
	Mar-17	5	12.9	27.4	21	56.5	85.8
	Apr-17	9.9	16.4	24.2	15	41.3	66
	May-17	15.1	21.3	28.9	15	43.2	73.9
	Jun-17	19.4	26	35.4	15	40.9	73
	Jul-17	23.0	29.3	36.5	15	32.1	57.4
	Aug-17	21.7	27.6	32.1	15	36.6	53
	Sep-17	18.4	26.2	40.9	15	30.6	57.4
	Oct-17	12.3	19	31.9	15	40.5	74.4
	Nov-17	5.2	12.4	17.7	21.9	58.4	88.9
	Dec-17	3.8	10.1	17.3	31.4	65.1	88.8
2018	Jan-18	2.4	7.2	13.5	32.1	68.3	100
	Feb-18	5	10.8	15.8	45.4	67.6	88.9
	Mar-18	4.9	14.3	28.0	23.9	54.8	76.9

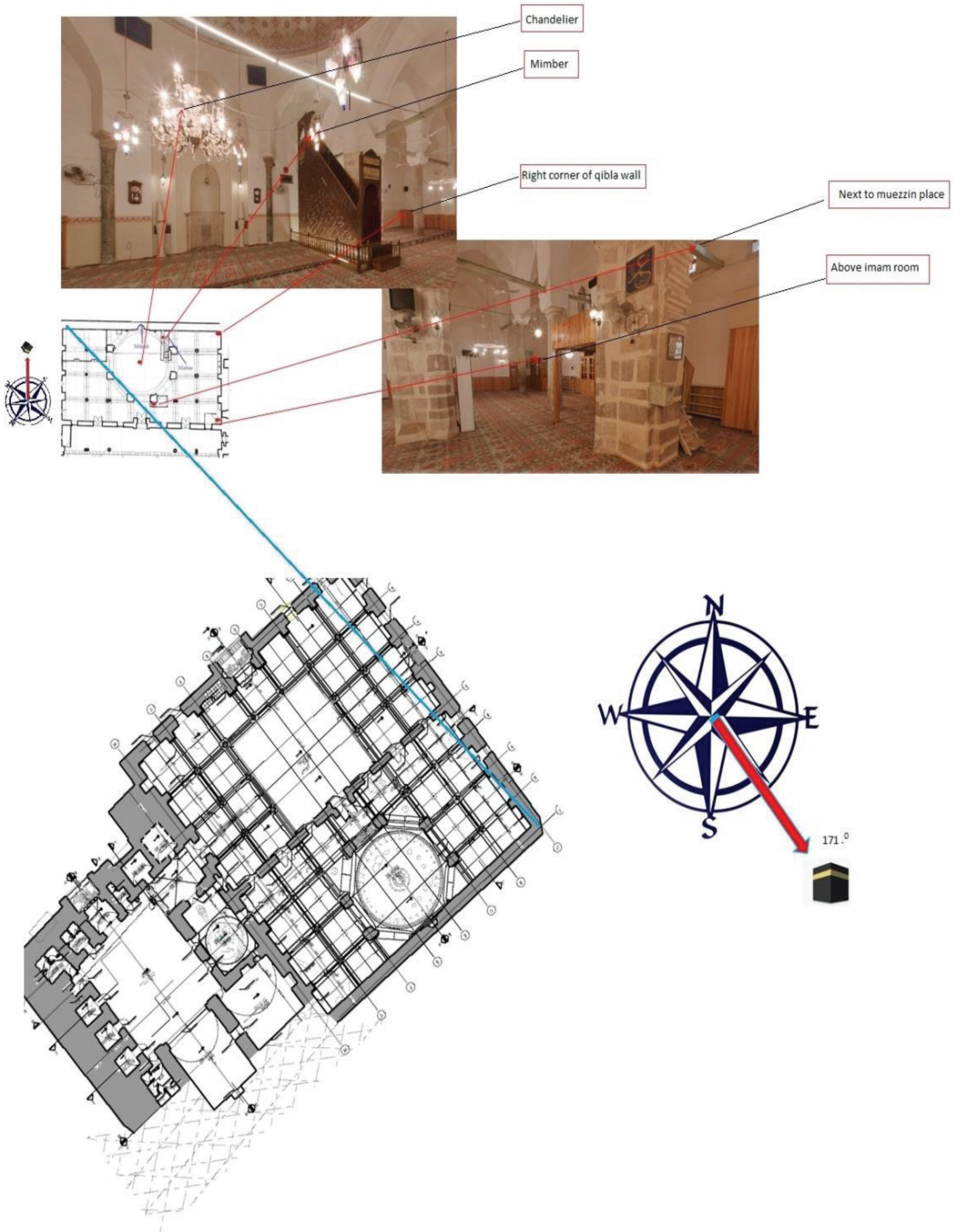
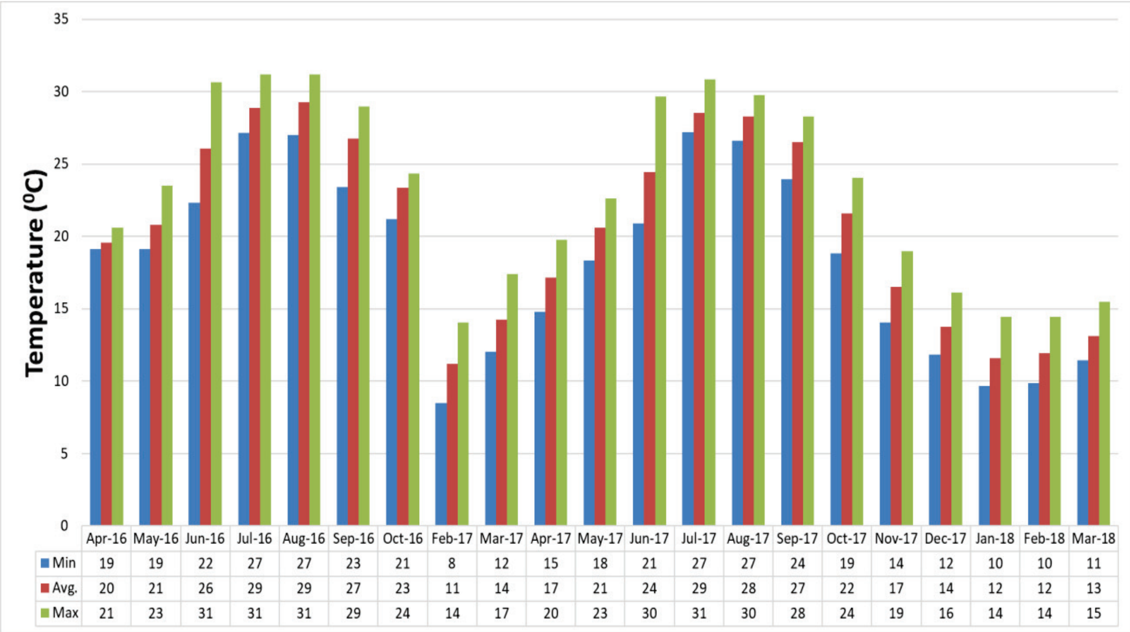
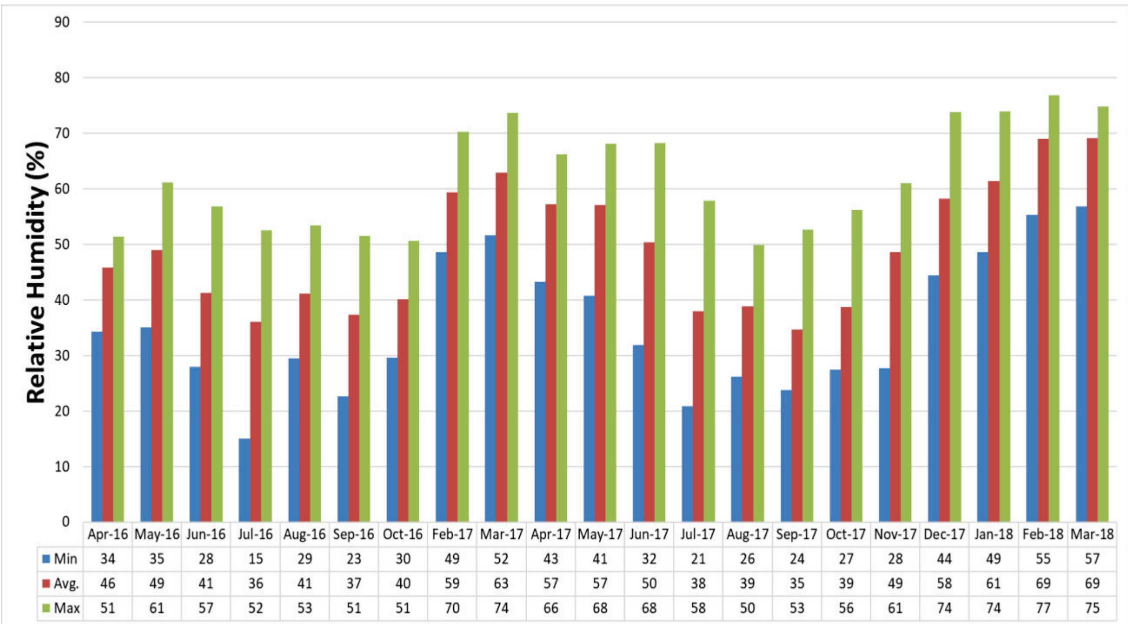


Figure 5.2. Datalogger locations in the prayer hall



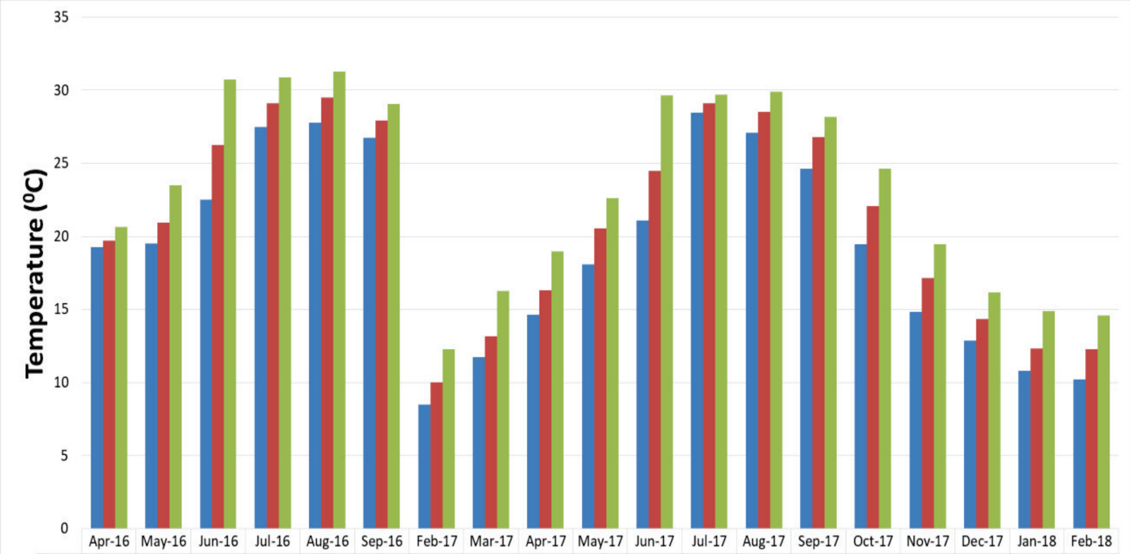
	Apr-16	May-16	Jun-16	Jul-16	Aug-16	Sep-16	Oct-16	Feb-17	Mar-17	Apr-17	May-17	Jun-17	Jul-17	Aug-17	Sep-17	Oct-17	Nov-17	Dec-17	Jan-18	Feb-18	Mar-18
Min	19	19	22	27	27	23	21	8	12	15	18	21	27	27	24	19	14	12	10	10	11
Avg.	20	21	26	29	29	27	23	11	14	17	21	24	29	28	27	22	17	14	12	12	13
Max	21	23	31	31	31	29	24	14	17	20	23	30	31	30	28	24	19	16	14	14	15

Figure 5.3. Measured T data above the imam room



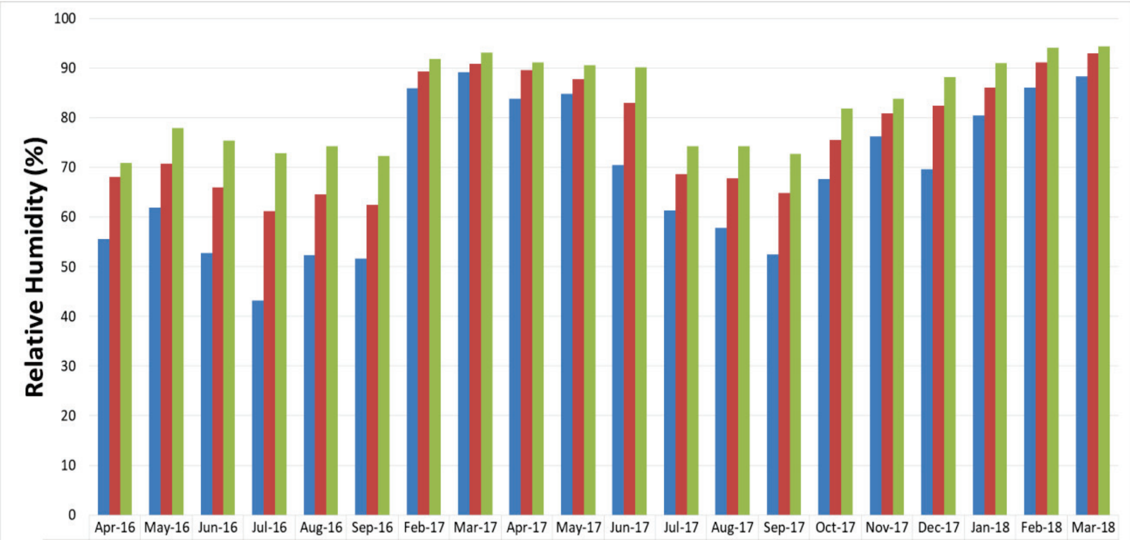
	Apr-16	May-16	Jun-16	Jul-16	Aug-16	Sep-16	Oct-16	Feb-17	Mar-17	Apr-17	May-17	Jun-17	Jul-17	Aug-17	Sep-17	Oct-17	Nov-17	Dec-17	Jan-18	Feb-18	Mar-18
Min	34	35	28	15	29	23	30	49	52	43	41	32	21	26	24	27	28	44	49	55	57
Avg.	46	49	41	36	41	37	40	59	63	57	57	50	38	39	35	39	49	58	61	69	69
Max	51	61	57	52	53	51	51	70	74	66	68	68	58	50	53	56	61	74	74	77	75

Figure 5.4. RH measurements above the imam room



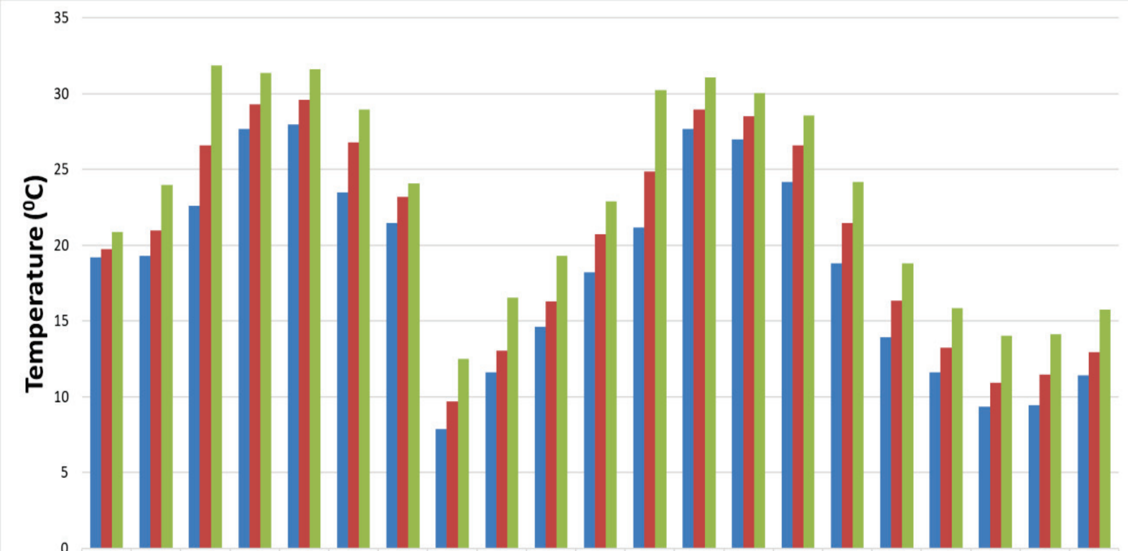
	Apr-16	May-16	Jun-16	Jul-16	Aug-16	Sep-16	Feb-17	Mar-17	Apr-17	May-17	Jun-17	Jul-17	Aug-17	Sep-17	Oct-17	Nov-17	Dec-17	Jan-18	Feb-18
Min	19	20	23	27	28	27	8	12	15	18	21	28	27	25	19	15	13	11	10
Avg.	20	21	26	29	30	28	10	13	16	21	24	29	29	27	22	17	14	12	12
Max	21	24	31	31	31	29	12	16	19	23	30	30	30	28	25	19	16	15	15

Figure 5.5. Measured T data at mimber



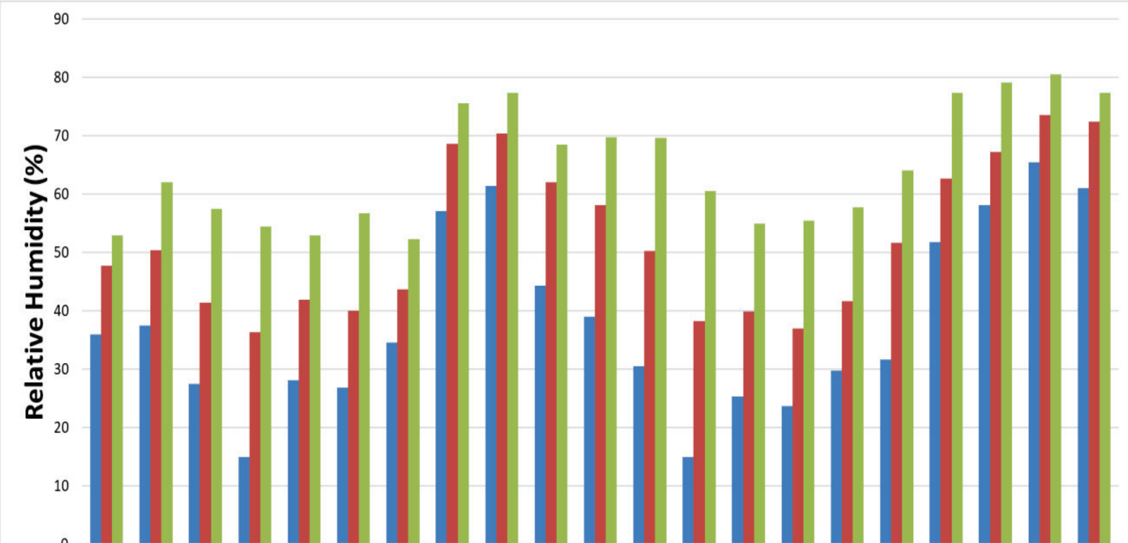
	Apr-16	May-16	Jun-16	Jul-16	Aug-16	Sep-16	Feb-17	Mar-17	Apr-17	May-17	Jun-17	Jul-17	Aug-17	Sep-17	Oct-17	Nov-17	Dec-17	Jan-18	Feb-18	Mar-18
Min	56	62	53	43	52	52	86	89	84	85	70	61	58	53	68	76	70	81	86	88
Avg.	68	71	66	61	65	62	89	91	90	88	83	69	68	65	76	81	83	86	91	93
Max	71	78	76	73	74	72	92	93	91	91	90	74	74	73	82	84	88	91	94	94

Figure 5.6. Measured RH data at mimber



	Apr-16	May-16	Jun-16	Jul-16	Aug-16	Sep-16	Oct-16	Feb-17	Mar-17	Apr-17	May-17	Jun-17	Jul-17	Aug-17	Sep-17	Oct-17	Nov-17	Dec-17	Jan-18	Feb-18	Mar-18
Min	19	19	23	28	28	23	21	8	12	15	18	21	28	27	24	19	14	12	9	9	11
Avg.	20	21	27	29	30	27	23	10	13	16	21	25	29	29	27	21	16	13	11	11	13
Max	21	24	32	31	32	29	24	12	17	19	23	30	31	30	29	24	19	16	14	14	16

Figure 5.7. Measured T data at the next to muezzin place



	Apr-16	May-16	Jun-16	Jul-16	Aug-16	Sep-16	Oct-16	Feb-17	Mar-17	Apr-17	May-17	Jun-17	Jul-17	Aug-17	Sep-17	Oct-17	Nov-17	Dec-17	Jan-18	Feb-18	Mar-18
Min	36	37	28	15	28	27	35	57	61	44	39	31	15	25	24	30	32	52	58	65	61
Avg.	48	50	41	36	42	40	44	69	70	62	58	50	38	40	37	42	52	63	67	74	72
Max	53	62	57	55	53	57	52	76	77	69	70	70	61	55	55	58	64	77	79	81	77

Figure 5.8. Measured RH data at the next to muezzin place

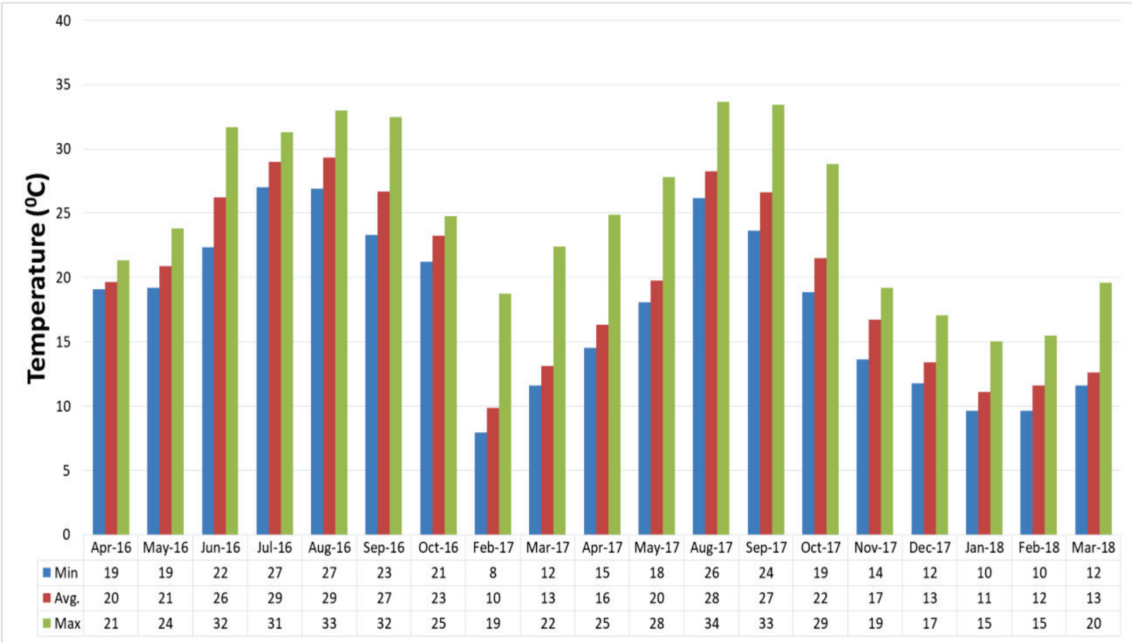


Figure 5.9. Measured T data of chandelier

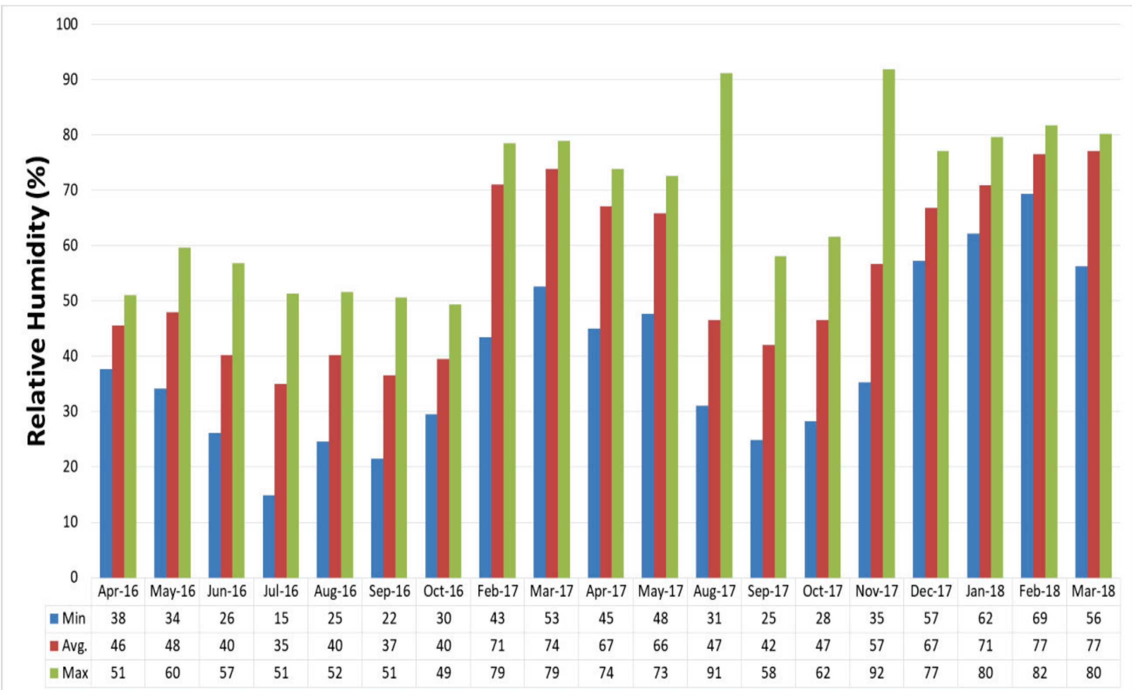
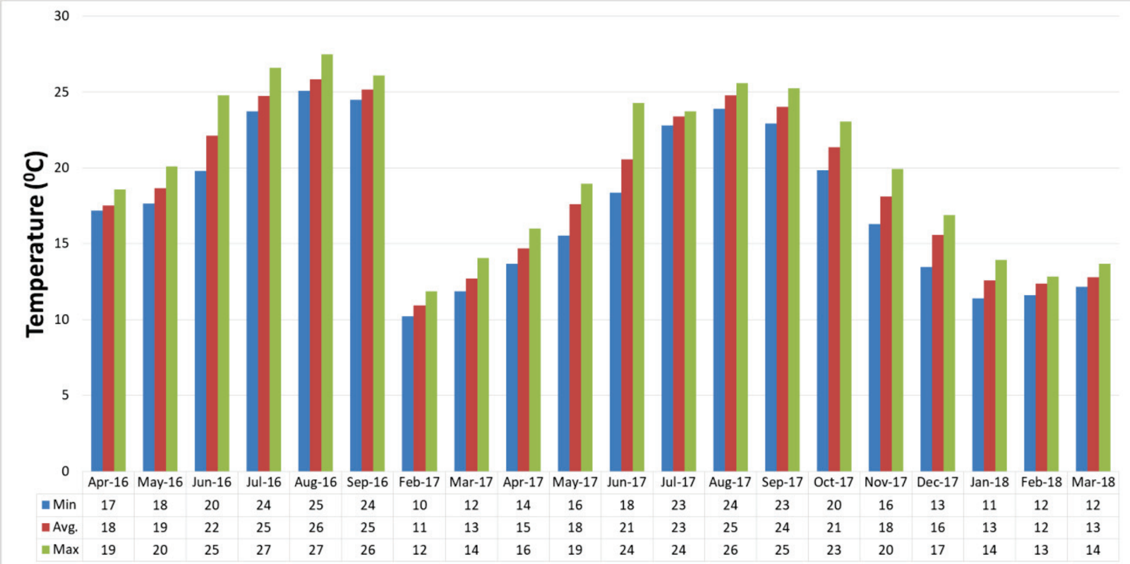
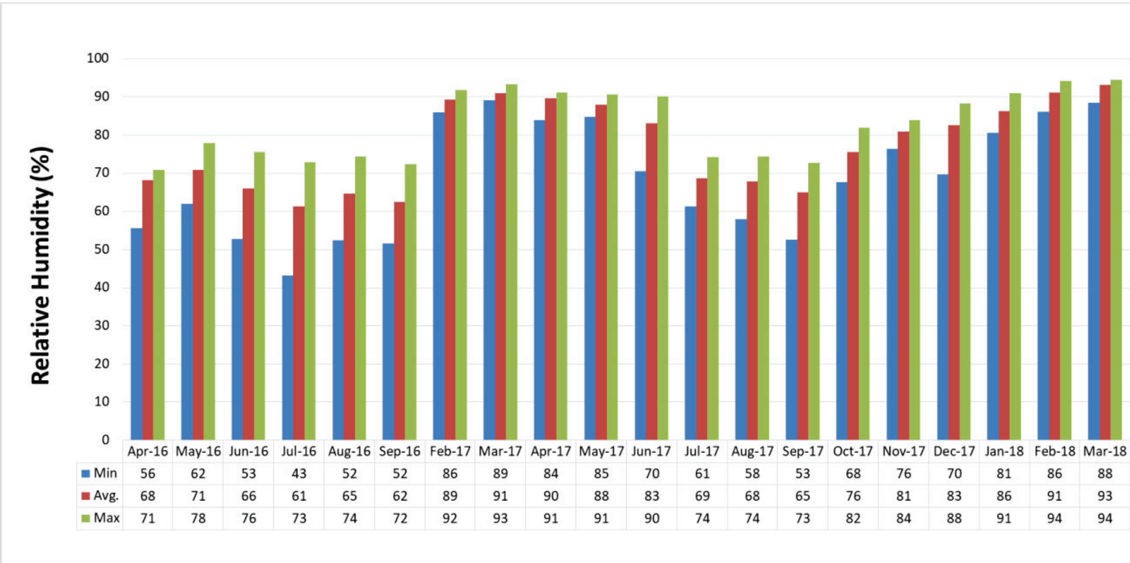


Figure 5.10. Measured RH data of chandelier



	Apr-16	May-16	Jun-16	Jul-16	Aug-16	Sep-16	Feb-17	Mar-17	Apr-17	May-17	Jun-17	Jul-17	Aug-17	Sep-17	Oct-17	Nov-17	Dec-17	Jan-18	Feb-18	Mar-18
Min	17	18	20	24	25	24	10	12	14	16	18	23	24	23	20	16	13	11	12	12
Avg.	18	19	22	25	26	25	11	13	15	18	21	23	25	24	21	18	16	13	12	13
Max	19	20	25	27	27	26	12	14	16	19	24	24	26	25	23	20	17	14	13	14

Figure 5.11. Measured T data of right corner of qibla wall



	Apr-16	May-16	Jun-16	Jul-16	Aug-16	Sep-16	Feb-17	Mar-17	Apr-17	May-17	Jun-17	Jul-17	Aug-17	Sep-17	Oct-17	Nov-17	Dec-17	Jan-18	Feb-18	Mar-18
Min	56	62	53	43	52	52	86	89	84	85	70	61	58	53	68	76	70	81	86	88
Avg.	68	71	66	61	65	62	89	91	90	88	83	69	68	65	76	81	83	86	91	93
Max	71	78	76	73	74	72	92	93	91	91	90	74	74	73	82	84	88	91	94	94

Figure 5.12. Measured RH data of right corner of qibla wall

The lowest temperature recorded in February while the highest temperature was encountered in August. Except for the right corner of qibla wall, the values, collected from data loggers are quite similar and identical. It is shown in the Fig. 5.13 that green line referring to the average values collected from datalogger at right corner of qibla wall is approximately 3°C lower than the others.

In order to understand the effect of outdoor climate on indoor environment, measured T and RH values are represented from April 20th, 2016 to March 11th, 2018 in Fig. 5.14 and 5.15. Even though, the indoor environment is highly affected from outside T, thick and massive walls made of stones, provide high thermal inertia, delays the variations in T between inside and outside of the building.

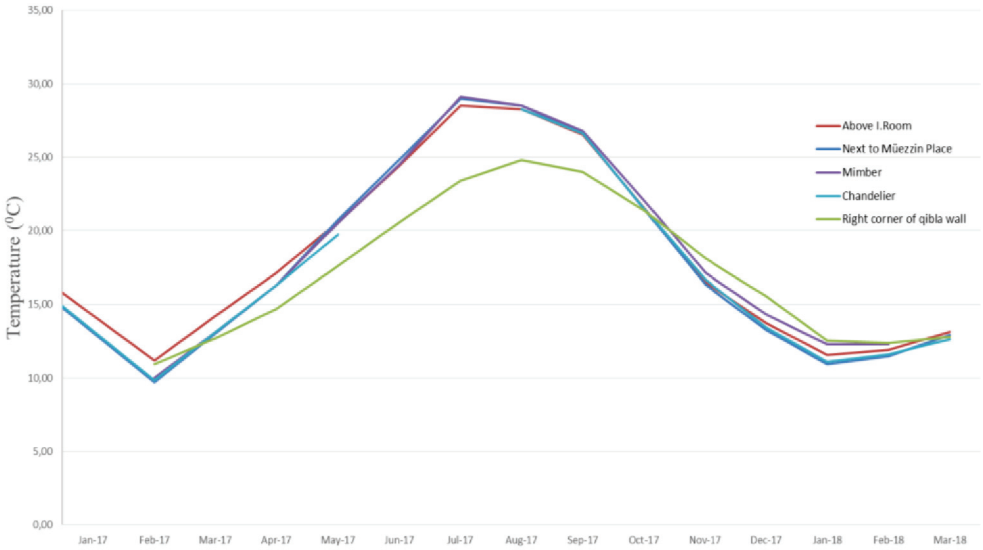


Figure 5.13. Comparison of indoor T data

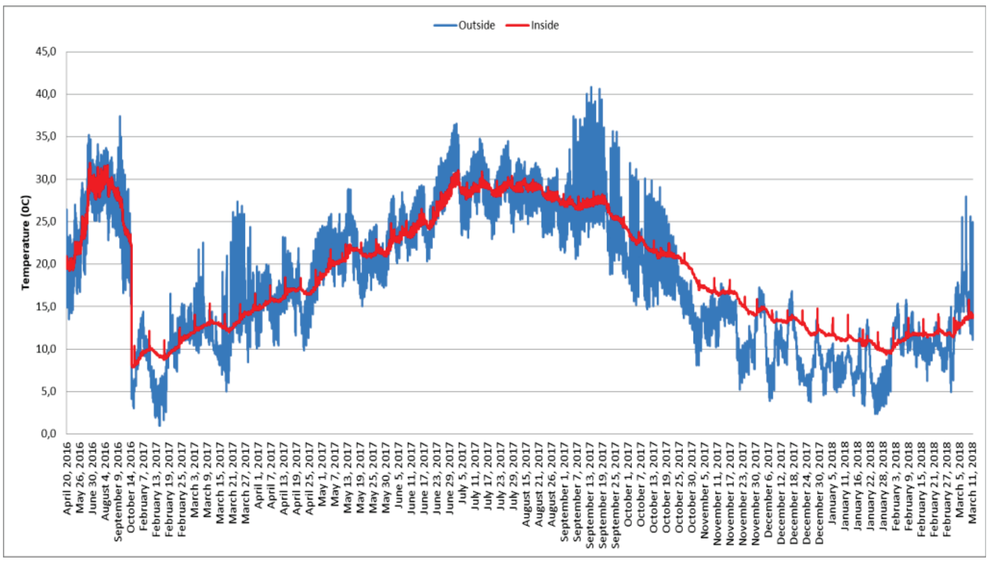


Figure 5.14. Comparison of indoor and outdoor T data

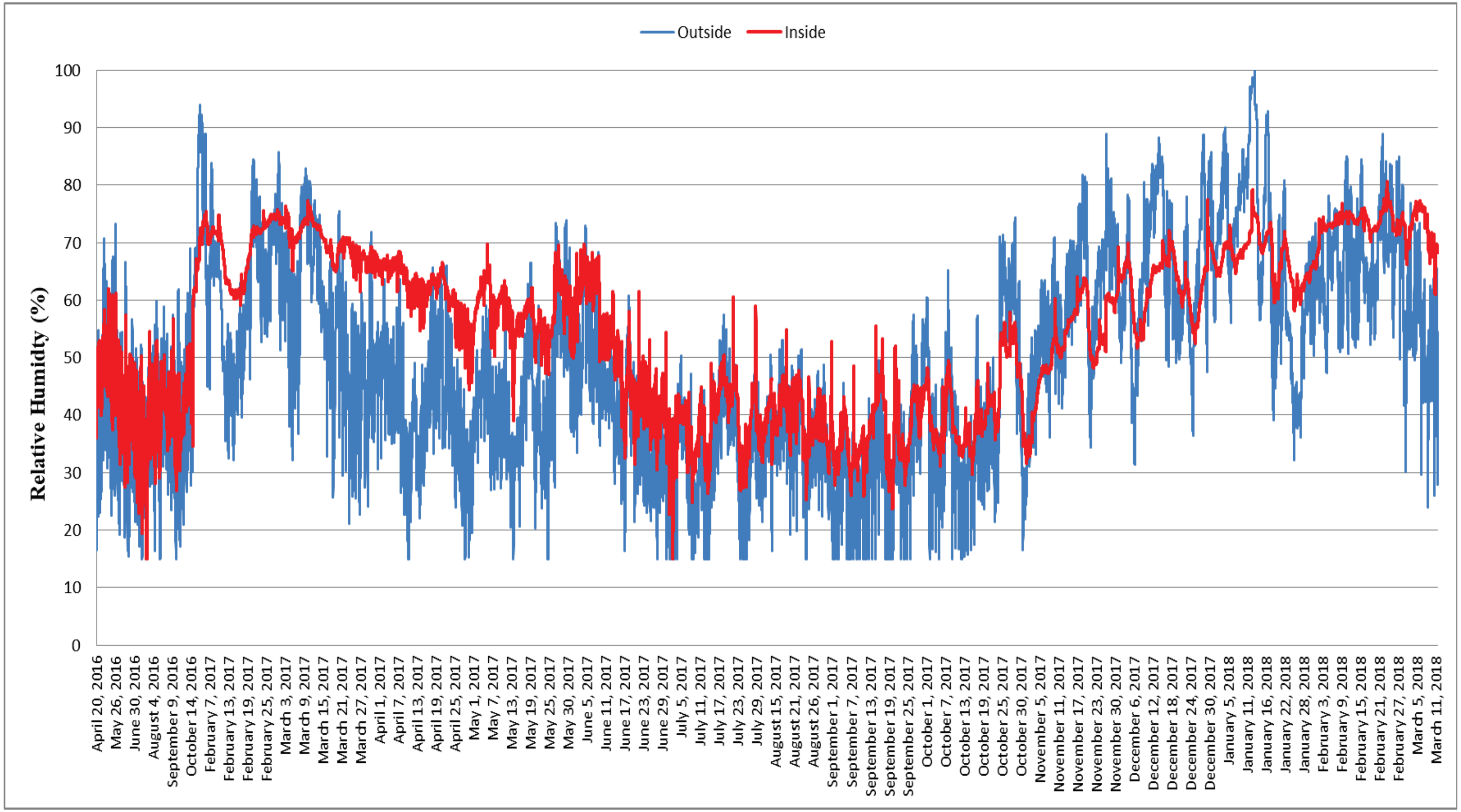


Figure 5.15. Comparison of indoor and outdoor RH data

Table 5.2. Monthly averages of indoor and outdoor T and RH data

Hobo Location		Above I. Room						Outside					
Measurement		Temperature (˚C)			Relative Humidity (%)			Temperature (˚C)			Relative Humidity (%)		
Max/Min		Min	Avg.	Max	Min	Avg.	Max	Min	Avg.	Max	Min	Avg.	Max
2016	Apr-16	19.1	19.6	20.6	34.3	45.8	51.4	13.6	19.2	26.4	16.6	36.4	54.7
	May-16	19.1	20.8	23.5	35.1	48.9	61.1	14.2	20.8	28.4	22.5	46.2	73.3
	Jun-16	22.3	26.1	30.6	28.0	41.3	56.9	18.8	27.5	35.2	15.4	37.0	66.7
	Jul-16	27.1	28.9	31.2	15.0	36.0	52.5	25.0	29.3	34.1	15.0	34.3	52.5
	Aug-16	27.0	29.3	31.2	29.5	41.1	53.4	22.8	29.1	33.7	15.0	40.0	59.9
	Sep-16	23.4	26.7	29.0	22.6	37.3	51.5	16.6	25.3	37.4	15.0	37.7	61.9
	Oct-16	21.2	23.4	24.3	29.6	40.1	50.6	14.5	21.6	28.8	26.4	41.3	69.0
2017	Feb-17	8.5	11.2	14.0	48.6	59.4	70.2	1.0	8.7	16.5	32.2	63.3	94.0
	Mar-17	12.0	14.3	17.4	51.6	62.9	73.6	5.0	12.9	27.4	21.2	56.5	85.8
	Apr-17	14.8	17.1	19.8	43.3	57.2	66.2	9.9	16.4	24.2	15.0	41.3	66.0
	May-17	18.3	20.6	22.6	40.8	57.1	68.1	15.1	21.3	28.9	15.0	43.2	73.9
	Jun-17	20.9	24.4	29.7	31.9	50.3	68.3	19.4	26.0	35.4	15.0	40.9	73.0
	Jul-17	27.2	28.5	30.9	20.9	38.0	57.8	23.0	29.3	36.5	15.0	32.1	57.4
	Aug-17	26.6	28.3	29.8	26.2	38.8	49.9	21.7	27.6	32.1	15.0	36.6	53.0
	Sep-17	24.0	26.5	28.3	23.8	34.7	52.7	18.4	26.2	40.9	15.0	30.6	57.4
	Oct-17	18.8	21.6	24.1	27.5	38.6	56.2	12.3	19.0	31.9	15.0	40.5	74.4
	Nov-17	14.0	16.5	19.0	27.7	48.5	60.9	5.2	12.4	17.7	21.9	58.4	88.9
	Dec-17	11.8	13.8	16.1	44.4	58.2	73.8	3.8	10.1	17.3	31.4	65.1	88.8
2018	Jan-18	9.7	11.6	14.4	48.6	61.4	73.9	2.4	7.2	13.5	32.1	68.3	100
	Feb-18	9.9	11.9	14.4	55.4	69.0	76.8	5.0	10.8	15.8	45.4	67.6	88.9
	Mar-18	11.4	13.1	15.5	56.8	69.1	74.8	4.9	14.3	28.0	23.9	54.8	76.9

Hobo Location		Right corner of qibla wall						Mimber					
Measurement		Temperature (˚C)			Relative Humidity (%)			Temperature (˚C)			Relative Humidity (%)		
Max/Min		Min	Avg.	Max	Min	Avg.	Max	Min	Avg.	Max	Min	Avg.	Max
2016	Apr-16	17.2	17.5	18.6	55.6	68.1	70.9	19.3	19.7	20.6	45.4	55.8	59.2
	May-16	17.6	18.6	20.1	61.9	70.8	77.9	19.5	20.9	23.5	49.0	57.3	66.6
	Jun-16	19.8	22.1	24.8	52.8	66.0	75.5	22.5	26.2	30.7	37.3	49.5	59.2
	Jul-16	23.7	24.7	26.6	43.2	61.3	72.9	27.5	29.1	30.9	28.0	43.9	58.5
	Aug-16	25.1	25.8	27.5	52.3	64.6	74.3	27.8	29.5	31.3	38.8	49.0	58.7
	Sep-16	24.5	25.2	26.1	51.6	62.4	72.4	26.7	27.9	29.1	37.5	47.5	58.6
	Oct-16	-	-	-	-	-	-	-	-	-	-	-	-
2017	Feb-17	10.2	10.9	11.9	86.0	89.3	91.9	8.5	10.0	12.3	61.4	70.5	78.1
	Mar-17	11.9	12.7	14.1	89.2	90.9	93.2	11.7	13.1	16.2	70.1	74.4	80.8
	Apr-17	13.7	14.7	16.0	83.9	89.6	91.2	14.6	16.3	19.0	57.7	69.1	75.2
	May-17	15.6	17.6	18.9	84.8	87.9	90.7	18.1	20.5	22.6	53.6	66.0	76.7
	Jun-17	18.4	20.6	24.3	70.5	83.1	90.2	21.1	24.5	29.6	42.0	59.3	74.7
	Jul-17	22.8	23.4	23.7	61.3	68.7	74.3	28.5	29.1	29.7	32.2	42.8	50.3
	Aug-17	23.9	24.8	25.6	57.9	67.9	74.3	27.1	28.5	29.9	35.5	47.6	60.2
	Sep-17	22.9	24.0	25.3	52.5	64.9	72.7	24.6	26.8	28.2	33.1	44.0	61.9
	Oct-17	19.8	21.4	23.0	67.7	75.5	81.9	19.5	22.1	24.6	37.4	46.6	63.8
	Nov-17	16.3	18.1	19.9	76.3	80.9	83.9	14.8	17.1	19.5	38.0	55.3	68.7
	Dec-17	13.5	15.6	16.9	69.6	82.5	88.3	12.9	14.3	16.2	54.6	64.1	74.1
2018	Jan-18	11.4	12.6	13.9	80.5	86.2	91.0	10.8	12.3	14.9	59.1	66.8	77.1
	Feb-18	11.6	12.4	12.8	86.1	91.1	94.1	10.2	12.3	14.6	63.9	71.4	76.4
	Mar-18	12.1	12.8	13.7	88.4	93.1	94.4	-	-	-	-	-	-

Hobo Location		Next to Müezzin Place						Chandelier					
Measurement		Temperature (˚C)			Relative Humidity (%)			Temperature (˚C)			Relative Humidity (%)		
Max/Min		Min	Avg.	Max	Min	Avg.	Max	Min	Avg.	Max	Min	Avg.	Max
2016	Apr-16	19.2	19.8	20.9	36.0	47.8	53.0	19.1	19.6	21.3	37.7	45.7	51.1
	May-16	19.3	21.0	24.0	37.4	50.4	62.0	19.2	20.9	23.8	34.2	48.1	59.6
	Jun-16	22.6	26.6	31.9	27.5	41.4	57.5	22.3	26.2	31.7	26.2	40.2	56.8
	Jul-16	27.7	29.3	31.4	15.0	36.4	54.5	27.0	29.0	31.3	15.0	35.1	51.4
	Aug-16	28.0	29.6	31.6	28.1	41.9	52.9	26.9	29.3	33.0	24.7	40.2	51.6
	Sep-16	23.5	26.8	29.0	26.9	40.1	56.7	23.3	26.7	32.5	21.6	36.6	50.7
	Oct-16	21.5	23.2	24.1	34.6	43.8	52.3	21.2	23.3	24.8	29.6	39.6	49.4
2017	Feb-17	7.9	9.7	12.5	57.1	68.7	75.6	8.0	9.9	18.7	43.5	71.1	78.5
	Mar-17	11.6	13.0	16.5	61.5	70.4	77.4	11.6	13.1	22.4	52.6	73.8	78.9
	Apr-17	14.6	16.3	19.3	44.4	62.0	68.5	14.5	16.3	24.9	45.1	67.1	73.8
	May-17	18.2	20.7	22.9	39.0	58.1	69.8	18.1	19.8	27.8	47.7	65.9	72.6
	Jun-17	21.2	24.9	30.3	30.5	50.3	69.7	-	-	-	-	-	-
	Jul-17	27.7	29.0	31.1	15.0	38.2	60.6	-	-	-	-	-	-
	Aug-17	27.0	28.5	30.1	25.3	39.8	54.9	26.2	28.3	33.7	31.2	46.6	91.2
	Sep-17	24.2	26.6	28.6	23.7	37.0	55.5	23.6	26.6	33.4	24.9	42.1	58.1
	Oct-17	18.8	21.5	24.2	29.8	41.7	57.8	18.8	21.5	28.8	28.3	46.6	61.6
	Nov-17	13.9	16.3	18.8	31.6	51.7	64.0	13.6	16.7	19.2	35.4	56.7	91.9
	Dec-17	11.6	13.3	15.9	51.7	62.7	77.4	11.8	13.4	17.0	57.3	66.8	77.1
2018	Jan-18	9.4	10.9	14.0	58.1	67.3	79.2	9.6	11.1	15.1	62.3	70.9	79.7
	Feb-18	9.5	11.5	14.1	65.4	73.5	80.6	9.6	11.6	15.5	69.4	76.6	81.8
	Mar-18	11.4	12.9	15.8	61.1	72.5	77.3	11.6	12.6	19.6	56.3	77.2	80.3

5.2. Developing a Dynamic Building Energy Simulation (BES) Model

To be able to create a BES model of the Ulu Mosque, architectural plans and dimensions were obtained from the Department of Architectural Restoration of Izmir Institute of Technology and during walk-through inspections. Using input data and drawings, the mosque was modelled by DesignBuilder software (v. 5.0) (Fig. 5.16). The mosque was modeled with surrounding buildings and trees to evaluate the shading effects.

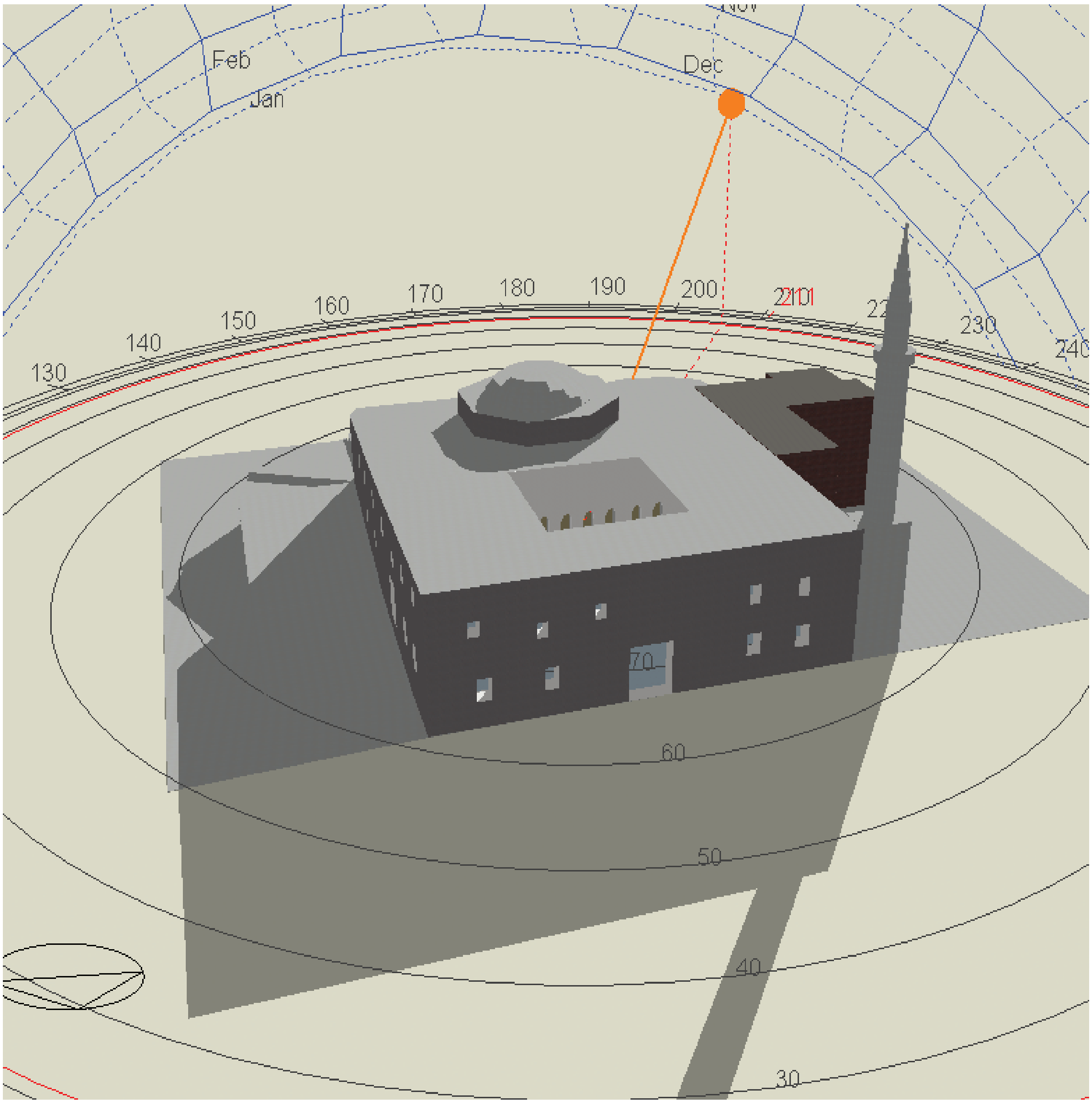


Figure 5.16. BES model of the mosque

The model consists of three inner-zones which were connected to each other and behave as single zone, and one outer zone for the courtyard. The materials of walls, windows, doors and domes were selected from the database of DesignBuilder software. The model had positioned as real circumstances with mihrap 171° directed to Qibla.

5.3. Calibration Results

The developed model which is called "baseline model" was calibrated by measured T data. Calibration was carried out until an acceptable calibration is achieved with respect to ASHRAE 14 (2002).

The comparison of hourly measurements and simulation data of prayer hall T is given in Figure 5.17. Trend of T values are identical.

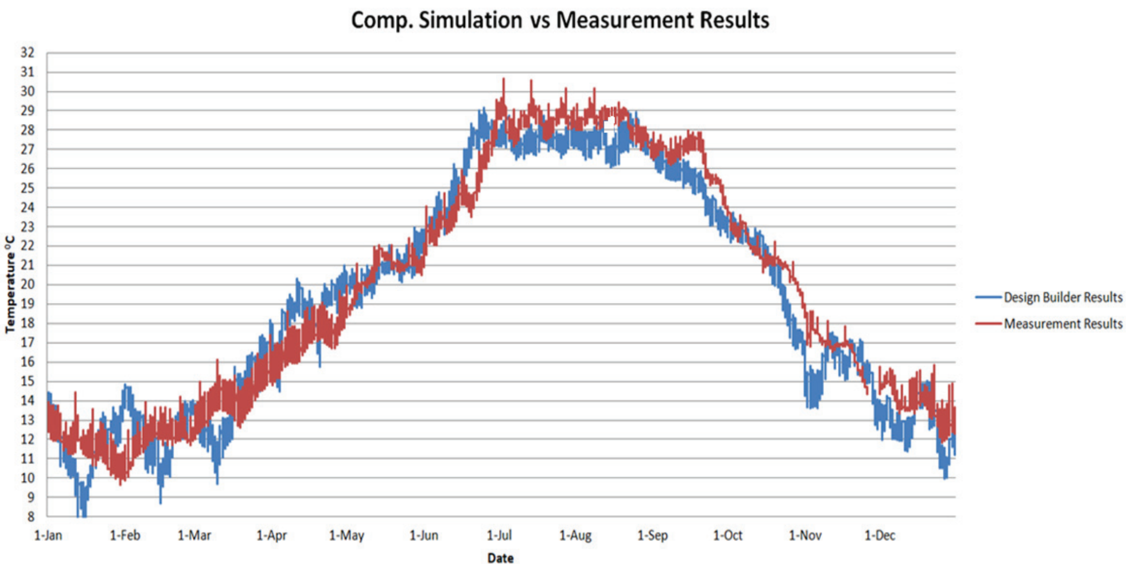


Figure 5.17. Hourly measured and simulated T data of prayer hall

The upper limits for Mean Bias Error (MBE) and Coefficient of Variant of Root Mean Square Error (CV (RMSE)) in hourly calibration process are defined as ±10% and ±30%, respectively in ASHRAE 14 (2002).

Calculated monthly error values for prayer hall are given in Table 5.3. All error values for MBE and CV(RMSE) are within the limits.

Table 5.3. Calculated error values for the BES model

Months	NMBE	CV(RMSE)
	(%)	
January	0.30	16.44
February	3.99	13.12
March	2.95	12.56
April	7.17	10.23
May	0.11	2.62
June	4.42	6.16
July	3.85	4.29
August	3.31	4.84
September	5.03	5.56
October	3.70	6.67
November	6.22	9.31
December	7.84	11.01
ASHRAE 14	**10**	**30**

5.4. Thermal Comfort Analysis

Thermal comfort analysis of the baseline model and retrofitting strategies to improve thermal comfort of Ulu Mosque were presented in this section. The analysis was conducted for the prayer hall and cover five prayer times a day during the year.

5.4.1. Thermal Comfort Analysis of the Baseline Model

Once the calibration was completed, energy simulation analysis was run through the program. Then, the data were collected, separated with respect to the prayer times and averaged. PMV and PPD values were calculated by Eq.s 3.4 and 3.8, respectively. All results are listed in Table 5.4.

5.4.1.1. PMV Analysis

Based on the calculation of PMV values on prayer times, occupants of the mosque feel cool in winter and almost neutral in summer. In summer season, occupants might appreciate the thermal comfort level of the building. Because, the PMV is between -0.57 and 0.33 (Fig. 5.18).

Table 5.4. PMV and PPD values (baseline model)

Baseline Model											
Months	Pray Time	Air Temperature	Relative Humidity	PMV	PPD	Months	Pray Time	Air Temperature	Relative Humidity	PMV	PPD
-	-	[°C]	[%]		[%]	-	-	[°C]	[%]		[%]
January	Dawn Prayer	10.39	60.54	-1.30	41.01	January	Mid-Day Prayer	11.03	57.36	-1.59	55.32
February	Dawn Prayer	10.86	58.38	-1.21	36.87	February	Mid-Day Prayer	11.76	54.20	-1.46	49.16
March	Dawn Prayer	12.23	55.70	-0.98	27.16	March	Mid-Day Prayer	13.62	50.50	-1.15	35.03
April	Dawn Prayer	17.72	50.73	-0.36	9.00	April	Mid-Day Prayer	18.17	48.93	-0.68	16.47
May	Dawn Prayer	20.27	46.10	0.07	5.43	May	Mid-Day Prayer	20.58	45.61	-0.21	6.48
June	Dawn Prayer	25.13	41.47	0.05	12.85	June	Mid-Day Prayer	25.23	33.47	0.00	8.79
July	Dawn Prayer	27.16	38.19	-0.23	6.62	July	Mid-Day Prayer	27.60	37.95	-0.09	6.17
August	Dawn Prayer	27.02	44.50	-0.24	7.14	August	Mid-Day Prayer	27.44	44.06	-0.11	6.72
September	Dawn Prayer	24.85	38.98	-0.06	7.62	September	Mid-Day Prayer	25.05	38.64	-0.02	8.17
October	Dawn Prayer	20.64	44.82	0.12	7.63	October	Mid-Day Prayer	20.77	44.40	-0.16	8.34
November	Dawn Prayer	14.32	63.58	-0.59	13.60	November	Mid-Day Prayer	15.52	58.96	-0.76	18.14
December	Dawn Prayer	12.20	61.68	-1.01	27.57	December	Mid-Day Prayer	12.76	58.89	-1.29	40.38
January	Afternoon Prayer	11.79	54.65	-1.49	50.49	January	After-Sunset Prayer	10.90	57.55	-1.58	54.86
February	Afternoon Prayer	12.47	52.00	-1.37	44.30	February	After-Sunset Prayer	12.80	50.76	-1.31	41.74
March	Afternoon Prayer	13.98	48.60	-1.08	31.83	March	After-Sunset Prayer	14.46	46.94	-1.01	28.67
April	Afternoon Prayer	18.75	46.54	-0.56	13.21	April	After-Sunset Prayer	18.55	47.31	-0.56	13.69
May	Afternoon Prayer	20.92	44.68	-0.14	6.04	May	After-Sunset Prayer	20.93	44.87	-0.12	6.08
June	Afternoon Prayer	26.10	39.09	0.29	15.22	June	After-Sunset Prayer	26.16	38.93	0.33	15.75
July	Afternoon Prayer	27.85	37.52	0.05	5.79	July	After-Sunset Prayer	28.17	36.58	0.18	6.55
August	Afternoon Prayer	27.82	42.83	0.07	6.14	August	After-Sunset Prayer	27.95	42.16	0.13	6.57
September	Afternoon Prayer	25.57	36.98	0.15	8.19	September	After-Sunset Prayer	25.62	36.75	0.17	8.69
October	Afternoon Prayer	21.39	39.80	-0.01	6.88	October	After-Sunset Prayer	21.11	43.35	-0.07	8.46
November	Afternoon Prayer	15.79	59.38	-0.70	16.52	November	After-Sunset Prayer	16.07	58.04	-0.66	15.27
December	Afternoon Prayer	12.66	60.03	-1.28	40.03	December	After-Sunset Prayer	13.09	58.52	-1.23	37.39
January	Night Prayer	11.60	55.03	-1.50	51.14						
February	Night Prayer	11.54	55.69	-1.45	48.80						
March	Night Prayer	13.49	50.79	-1.12	33.58						
April	Night Prayer	18.45	47.84	-0.57	13.95						
May	Night Prayer	20.73	45.04	-0.15	6.18						
June	Night Prayer	25.05	37.72	0.00	12.72						
July	Night Prayer	28.00	36.75	0.11	6.10						
August	Night Prayer	28.32	41.08	0.24	8.12						
September	Night Prayer	25.49	36.89	0.14	8.65						
October	Night Prayer	21.02	43.98	-0.08	8.77						
November	Night Prayer	15.39	60.21	-0.73	17.78						
December	Night Prayer	12.23	61.78	-1.32	42.22						

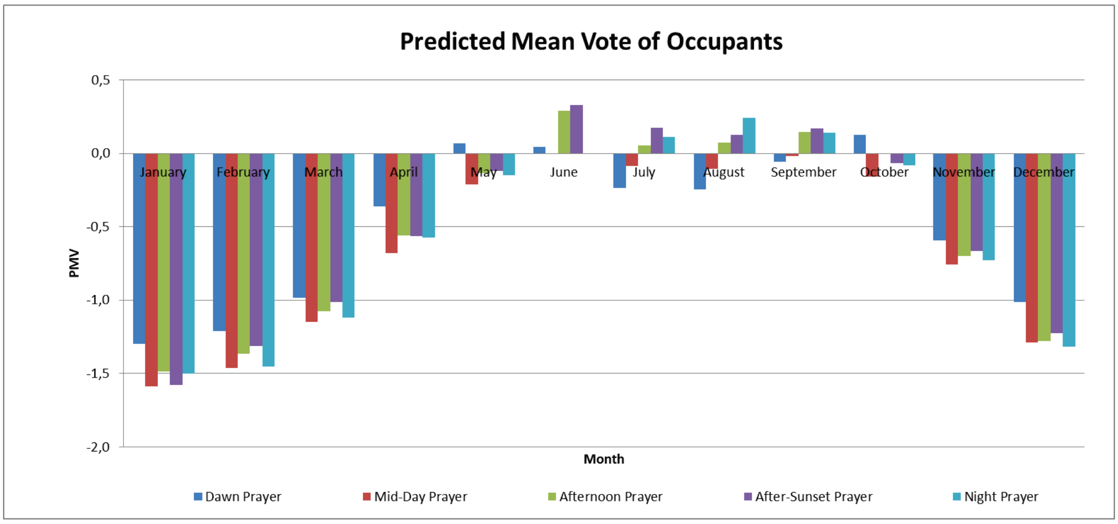


Figure 5.18. PMV values (baseline model)

5.4.1.2. PPD Analysis

The PPD are functions of PMV, establish a quantitative prediction. PPD values primarily indicate that thermal comfort problems appear during winter season. As can be seen from the Fig. 5.19, dissatisfaction level reaches to 55.3% in January mid-day parayer time.

From December to March, the lowest PPD is seen for dawn prayer times compared to the other prayer times in the same month because of the thick clothes chosen by occupants.

Although PPD starts to decrease in March, it is still outside the threshold limits. It reaches acceptable range from April to October. May has lowest PPD as 5.4% in dawn prayer times.

Occupants feel comfortable thermally from May to October since PPD is below 15%.

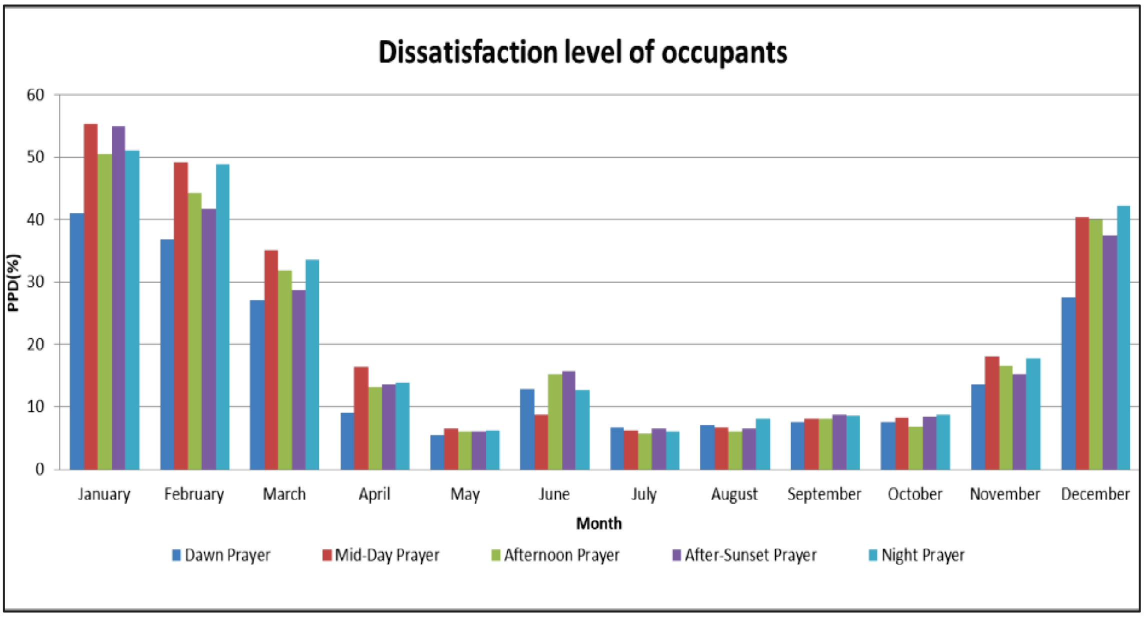


Figure 5.19. PPD levels of occupants

5.4.2. Thermal Comfort Analysis of the Retrofitting Strategies

As a result of the baseline model analysis, the satisfaction from the indoor thermal comfort is low in winter. To increase the satisfaction level during winter, various retrofitting scenarios are developed. The retrofitting scenarios can be classified as active and passive strategies.

5.4.2.1. Passive Retrofitting Strategies

Passive design strategy is the strategy to achieve thermal comfort without consuming any energy source such as electricity or natural gas (Bughrara, 2016). In the Thesis, four passive retrofit which are windows with double glazing and low emissivity glass, nighttime ventilation, roof insulation, and wall insulation, were developed.

5.4.2.1.1. Windows with Double Glazing and Low Emissivity Glass

Low-emissivity glass has the ability to minimize the amount of infrared and ultraviolet light which enters interior directly. It consists of a microscopical coat that reflects heat. Besides, double glazing property creates isolation to reduce heat transfer from the warm pane to the cold pane. In Table 5.5, physical properties of the glass existing in the building and offered for the scenario are given.

Table 5.5. Physical properties of glass

Physical Properties	**Baseline Model**	**Scenario**
Glazing Type	Clear single	Double
Thickness (mm)	6	3
SHGC (Solar Heat Gain Coefficient)	0.819	0.697
Direct Solar Transmission	0.775	0.633
Light Transmission	0.881	0.771
Gap	-	13 mm air
U Value (W/m²K)	**5.778**	**2.253**

Double-glazed windows with low emissivity glass were simulated and PPD levels are presented in Fig. 5.20 along with the baseline model results. As can be seen from the figure that improvement in satisfaction level is as low as 0.5%.

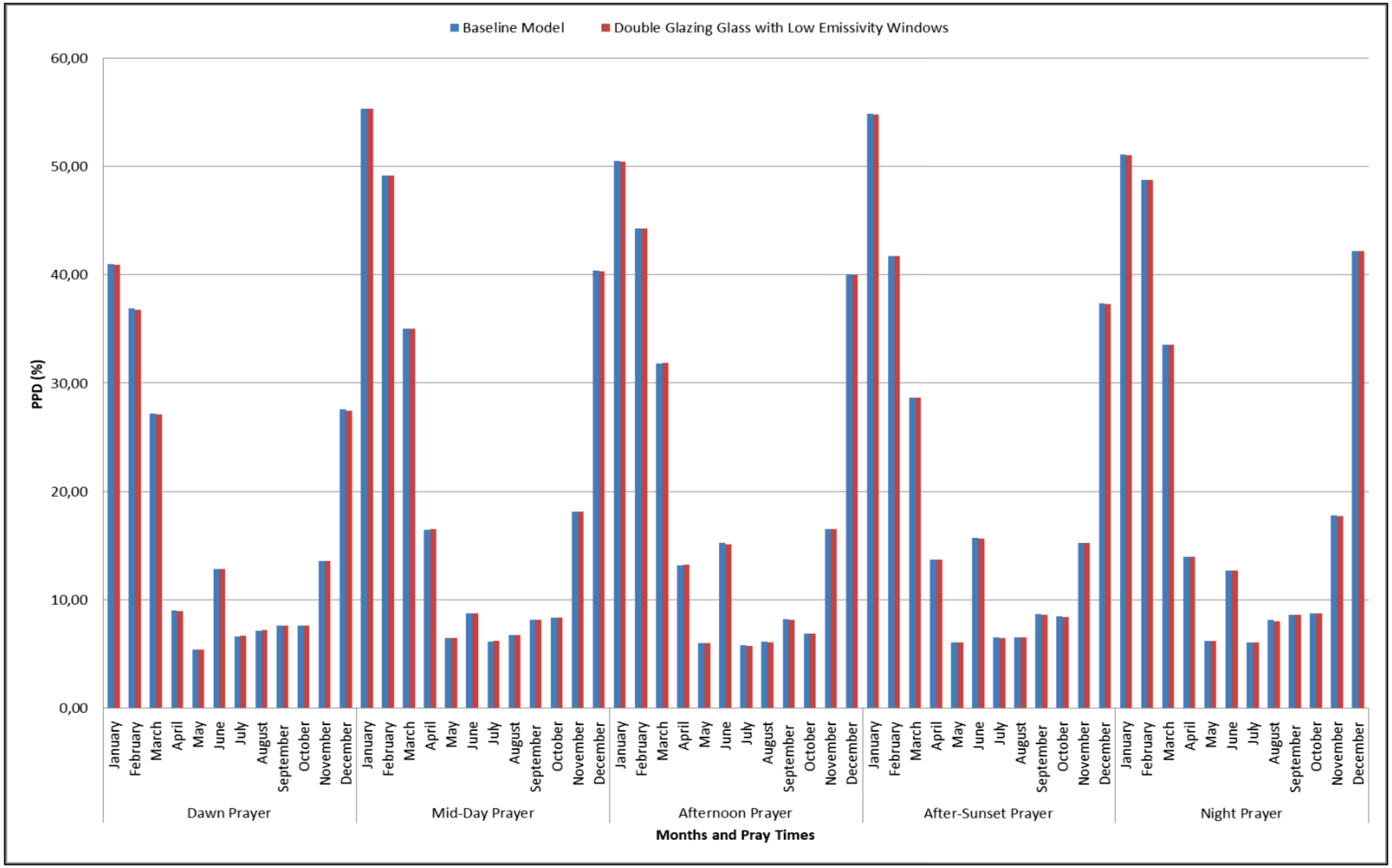


Figure 5.20. Comparison of PPDs between windows with double glazing and low emissivity glass and baseline model

5.4.2.1.2 Night Time Ventilation

Nighttime ventilation is a simple application by opening the windows at night time to cool inside during summer when the outdoor temperature is lower than indoor.

In the Thesis, nighttime ventilation strategy was used in summer season by opening all windows from 09:00 p.m. to 06:00 a.m. from May to October. Fig. 5.21 illustrates a comparison between nighttime ventilation and baseline model. For dawn prayer in summer, night time ventilation increases PPD around 5%. The reason of that even if nighttime ventilation helps to decrease T around 1°C, it increases RH around 4%. Therefore, it results an increase in discomfort in early morning hours. The other prayer times, no effect of nighttime ventilation was observed.

5.4.2.1.3. Roof Insulation

An insulation material for the dome and roof of the prayer hall is presented to decrease heat transfer and increase indoor T for the cold season.

The khorasan mortar with a 2.5 cm thickness is used as insulation material and an overall heat transfer coefficient is obtained as 1.963 W/m^2K (Bughrara, 2016). Khorasan mortar is an artificial high strength stone. It is developed in Asia and used as an antique building material in Western Asia, the Middle East and Anatolia as construction material by early architects (Akman et al., 1986).

On the other hand, khorasan mortar application should be carefully handled since additive khorasan mortar may cause chemical and physical incompatibilities with other materials of the structure. Therefore, this approach should be supported by laboratory tests.

Fig. 5.22 compares PPD levels of khorasan mortar application to the roof with the baseline model. The results show that PPD level is decreased barely around 0.5-1% with khorasan mortar.

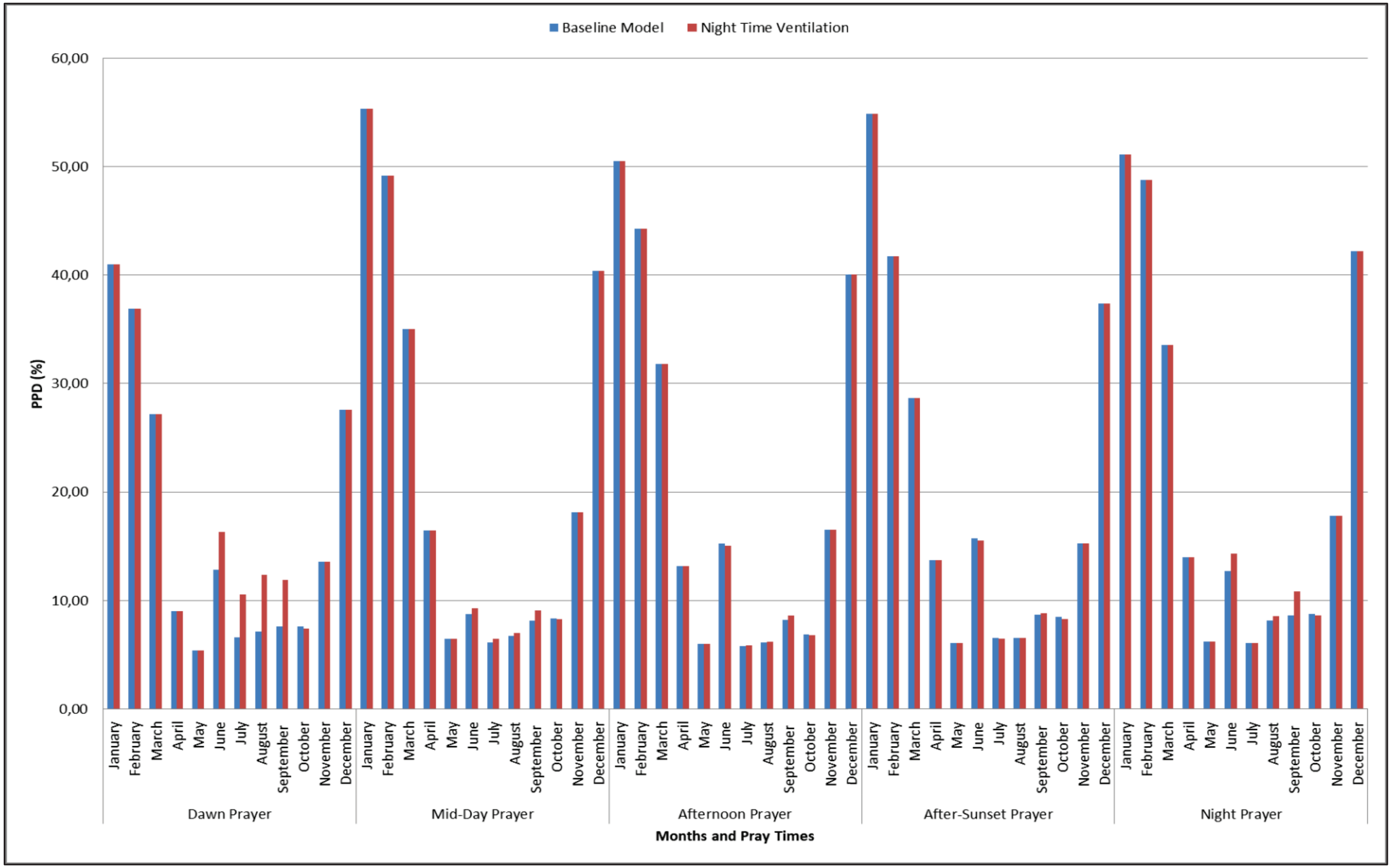


Figure 5.21. Comparison of PPDs between night time ventilation and baseline model

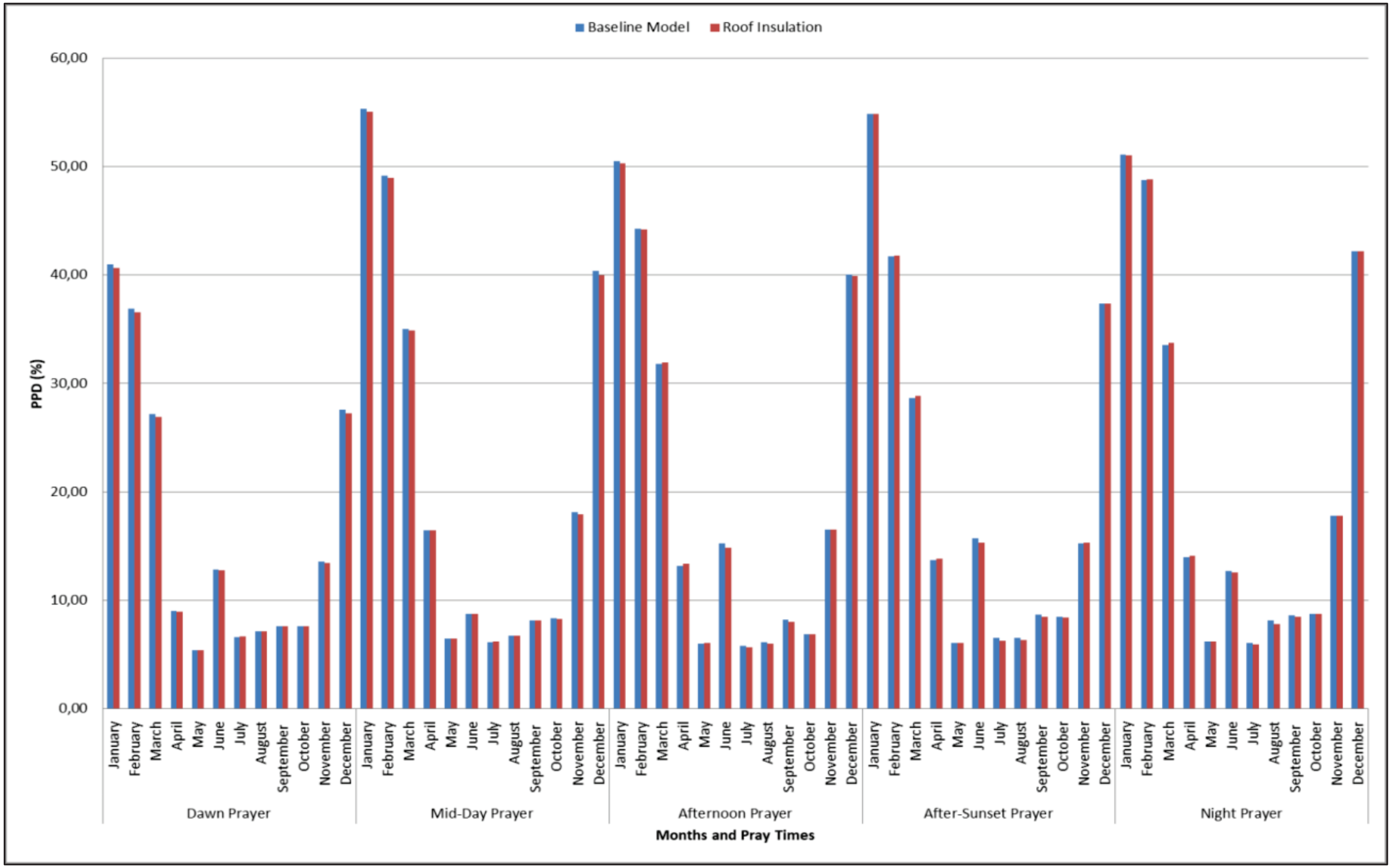


Figure 5.22. Comparison of PPDs between roof insulation and baseline model

5.4.2.1.4. Wall Insulation

The design of the construction of external walls has significant importance to ensure keeping the optical appearance of historical authenticity (Murgula and Pukhkal, 2015). In this retrofit scenario, an insulation material was applied to the walls to increase thermal comfort in winter season. Wood fiber board (9 cm) and wool (9 cm) insulation is applied outside of the prayer hall's stone walls. Then, a hemp-lime render is applied as two 10 mm coats which could be colored (Fig. 5.23) (Homebuilding, 2019). With insulation, overall heat transfer coefficient of the wall is decreased to 0.273 W/m²K.

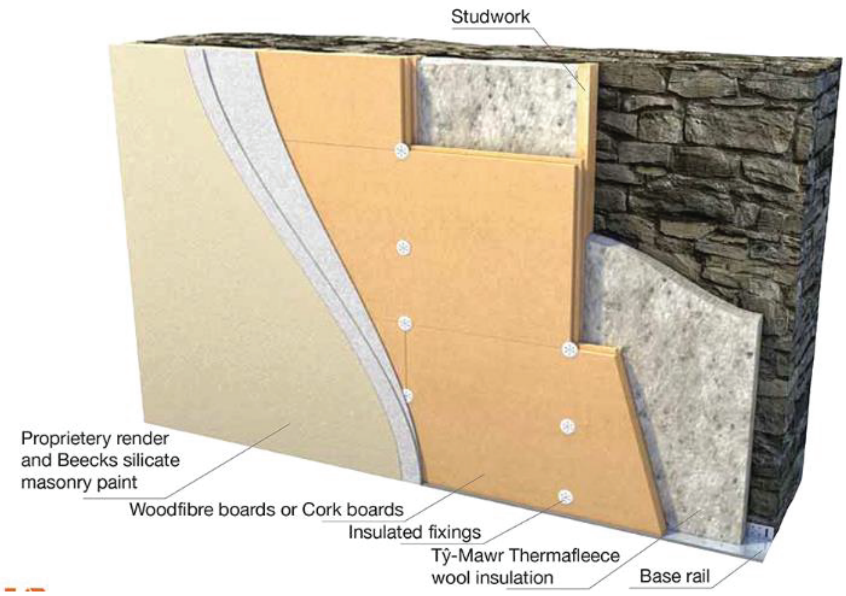


Figure 5.23. An example of an insulation system from Ty-Mawr
(Source: Homebuilding, 2019)

As it is seen the Fig. 5.24, wall insulation affects thermal comfort of occupants and increases PPD by 2% (yearly average). The PPD level increases approximately 3% in winter while maximum increase is encountered as 3.45% in December for night prayers. The PPD has minor decrease only in March for afternoon, after sun-set and night prayers as -0.06, -0.15 and 0.19%, respectively.

Without heating/cooling system, wall insulation has no or negligible benefit for the Ulu mosque. Contributions of wall insulation with heating/cooling system will be evaluated in active retrofit strategies.

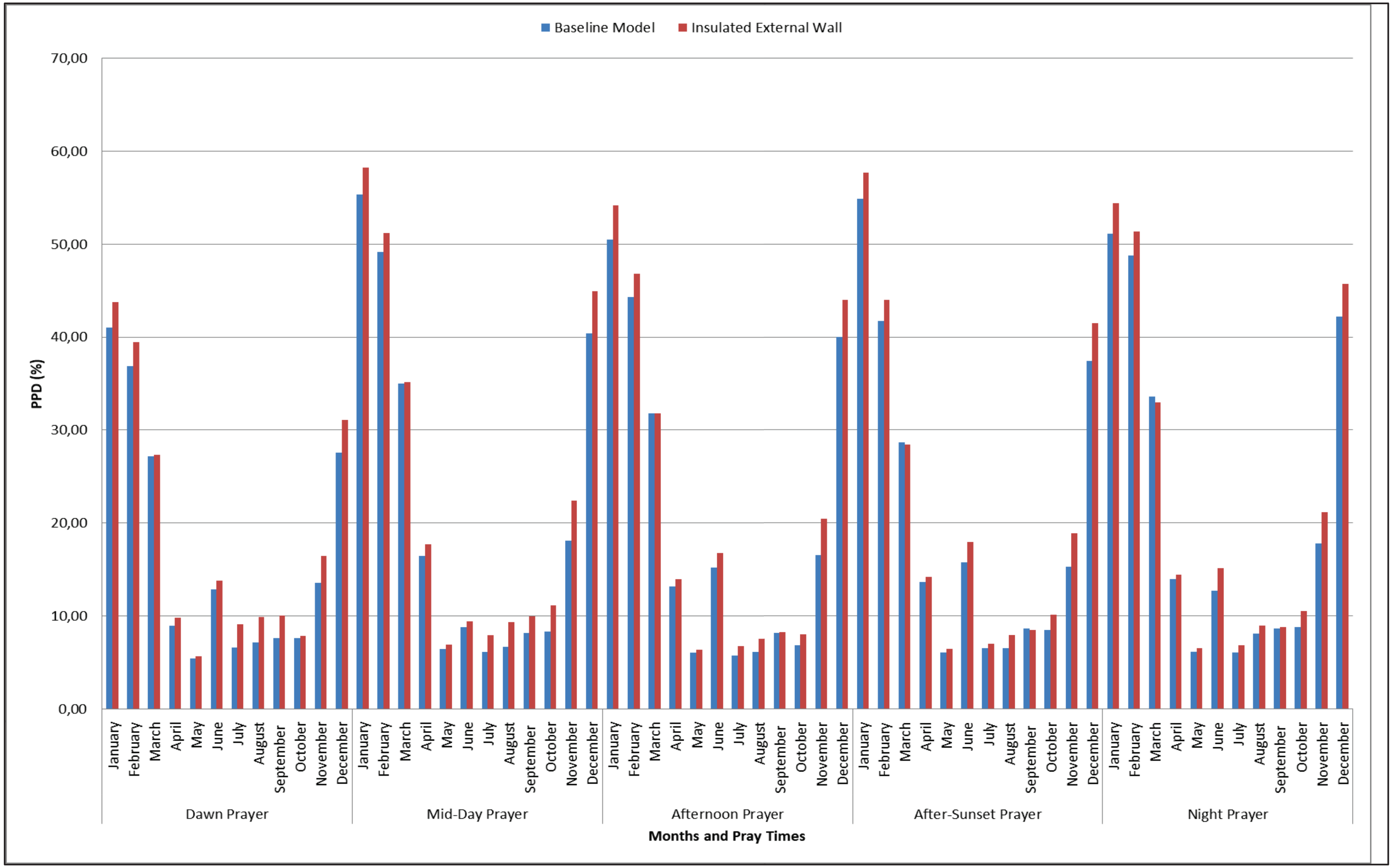


Figure 5.24. Comparison of PPDs between wall insulation and baseline model

5.4.2.2. Active Retrofitting Strategies

Active retrofitting strategies proposed in the Thesis are adding underfloor heating system, electric radiator and split type air-conditioner which consume energy. Proposed systems are operated in two different schedule: intermittent (given Table 5.6) and continuous (5:00-20:00). The heating season is considered as January, February, March, April, November and December where PPD level reached to 50%. Set point temperature during the heating season fixed as 22°C

Table 5.6. Operating schedules

Operating schedule		
Heating type	**Intermittent**	**Continuous**
Underfloor heating	Average 6 hours shown in details at Table 5.7	05:00-20:00
Electric radiator	5 hours a day (1 hour before pray time)	
Split type air-conditioner	5 hours a day (30 minutes before pray times and 30 minutes during pray times)	

5.4.2.2.1. Underfloor Heating System

Since mosques have high ceilings, large domes and volumes, significant temperature stratification is observed. Because the prayers stand up and sit during prayers, floor heating would be the best solution to obtain better thermal comfort in mosques (Bughrara et al., 2017). Electric heating mats which are installed under the carpeting are easy and proper way for intermittently occupied buildings with a quick heating response. On the other hand, DesignBuilder software has no such heating system in its library. Therefore, “heating elements that comprise water fed tubular systems embedded within the floor construction” is chosen (DesignBuilder, 2017). Application of this underfloor heating system requires an insulation layer to the ground. Operating hours of the system are given in Table 5.7. The layer thicknesses and overall heat transfer coefficient of the floor are presented in Table 5.8.

Underfloor heating system for continuous operation is compared with the baseline model in Fig. 5.25. It can be observed that PPD levels decreased to 5.9% (av.).

Maximum PPD is observed in October for dawn prayer while minimum PPD is encountered in December for night prayer.

Table 5.7. Intermittent operating schedules of underfloor heating

		Operating hours																							
	Hours	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Months	**January**						X	X						X		X	X		X	X					
	February						X	X						X		X	X		X	X	X				
	March						X	X						X			X		X	X	X				
	April																								
	May																								
	June																								
	July																								
	August																								
	September																								
	October					X	X						X			X			X	X					
	November						X						X			X		X		X					
	December						X						X			X		X		X					

Table 5.8. The properties of the floor

Material	**Thickness (cm)**	**U value (W/m²K)**
Cast concrete	10	0.130
PUR	20	
Floor screed	7	
Timber flooring	2	
Carpet	0.5	

Fig. 5.26 exhibits underfloor heating with intermittent operation, continuous operation and intermittent operation+wall insulation along with baseline model. With intermittent operation, maximum and minimum PPD levels are observed in February for afternoon prayer and in December for dawn prayer, respectively. Apart from February afternoon prayer, PPD values are quite similar (<15%) compared to the continuous heating strategy. Intermittent operation+wall insulation gives maximum PPD as 22.8% in January for mid-day prayer and minimum PPD as 5.37% in March for night prayer.

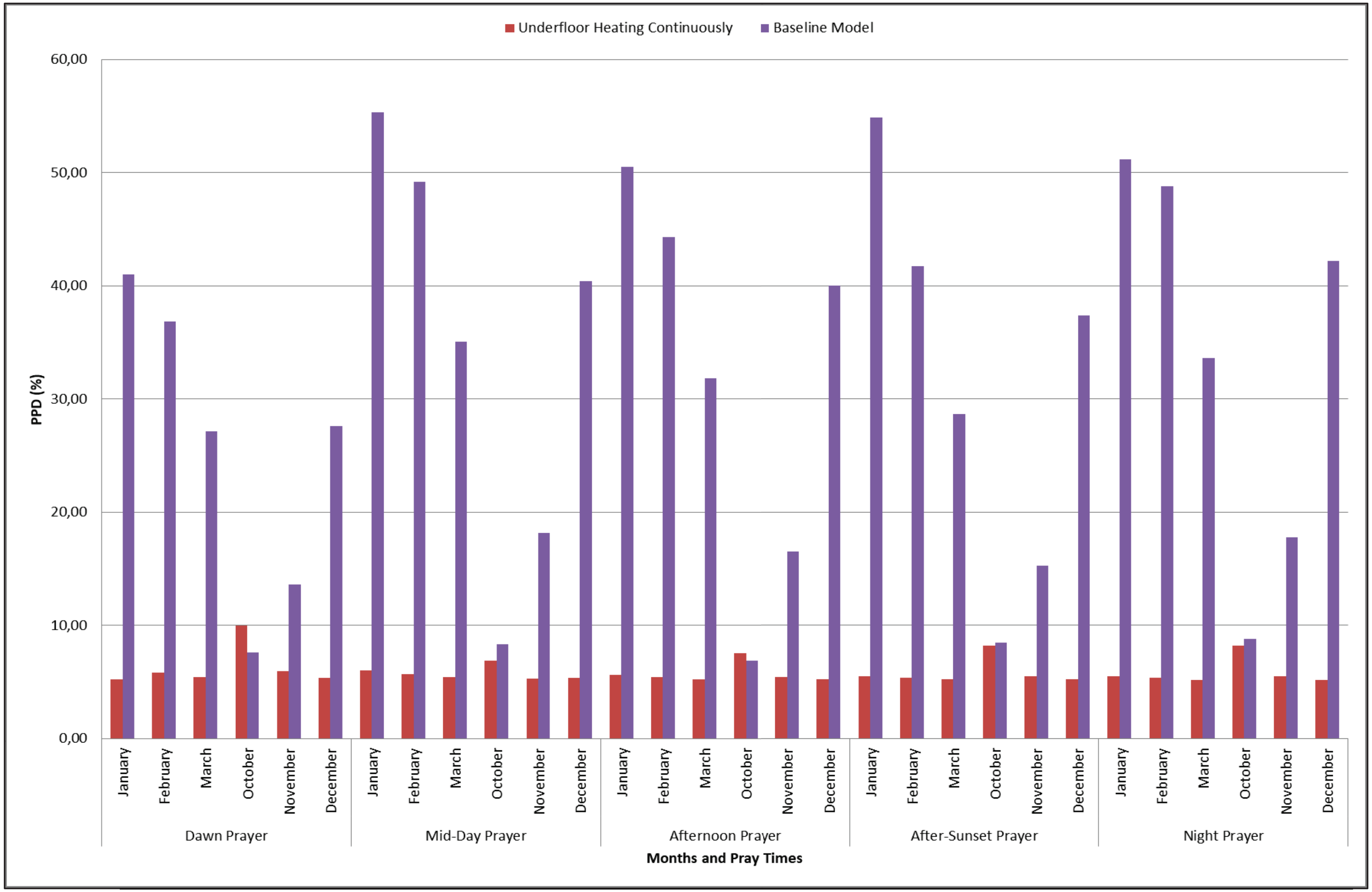


Figure 5.25. Comparison of PPDs between underfloor heating continuously and baseline model

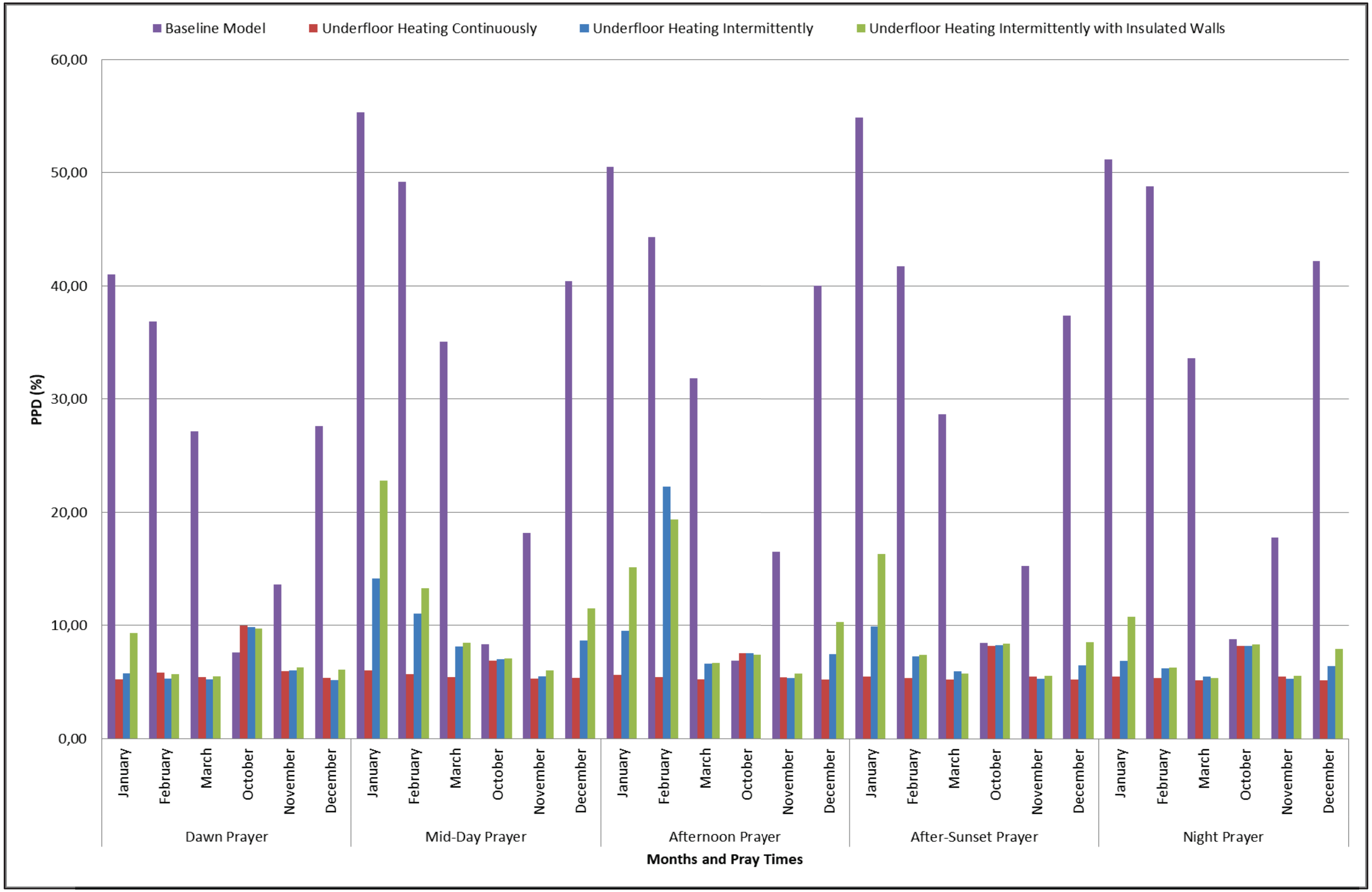


Figure 5.26. Comparison PPDs of underfloor heating for operating hours and insulation

5.4.2.2.2. Electric Radiator

DesignBuilder calculates convective and radiant heat transfer from the source to the environment in electric radiator model. Electric radiator is easy to install and not harmful to the structure of the building.

Thermal comfort analysis of the system resulted as 95% of the occupants are satisfied with the thermal conditions of the mosque with continuous operation as shown in Fig. 5.27. The Figure shows that maximum PPD value is observed as 7.25% in October for dawn prayer while minimum PPD value is 5.15% in March for night prayer.

Fig. 5.28 gives PPD values for electric radiators with intermittent, continuous operation and intermittent operation+wall insulation, and baseline model. With intermittent operation, maximum and minimum PPD values are seen as 22.1% in February and as 5.22% in November for both for after-sunset prayer, respectively. Apart from February after-sunset prayer, PPD values are quite similar (<15%) compared to the continuous heating strategy. With intermittent+wall insulation, maximum PPD is 16% in February for after sun-set prayer and minimum PPD is 5.3% in November for night prayer. Apart from February after-sunset prayer, all calculated PPD values are below 15%.

5.4.2.2.3. Split Type Air-conditioner

Advantages of split type air-conditioners are fast feedback time, instant relief for the occupants and easy installation.

The PPD values for heating with split type air-conditioner system with continuous operation is presented in Fig. 5.29 and compared with baseline model. The PPD level with continuous heating for all months is around 5%.

In Fig. 5.30, intermittent operation+wall insulation were also added to the options in Fig. 5.29. With intermittent operation, maximum PPD level is observed 23% in January for after-noon prayer. On the other hand, minimum PPD level is encountered in November as 5.27% for dawn prayer. The PPD level is above 15% in December for mid-day, in January for after-noon and night prayer, in February for afternoon and after-sunset prayer. Rest of the prayer times during the year, the PPD levels are below 15%.

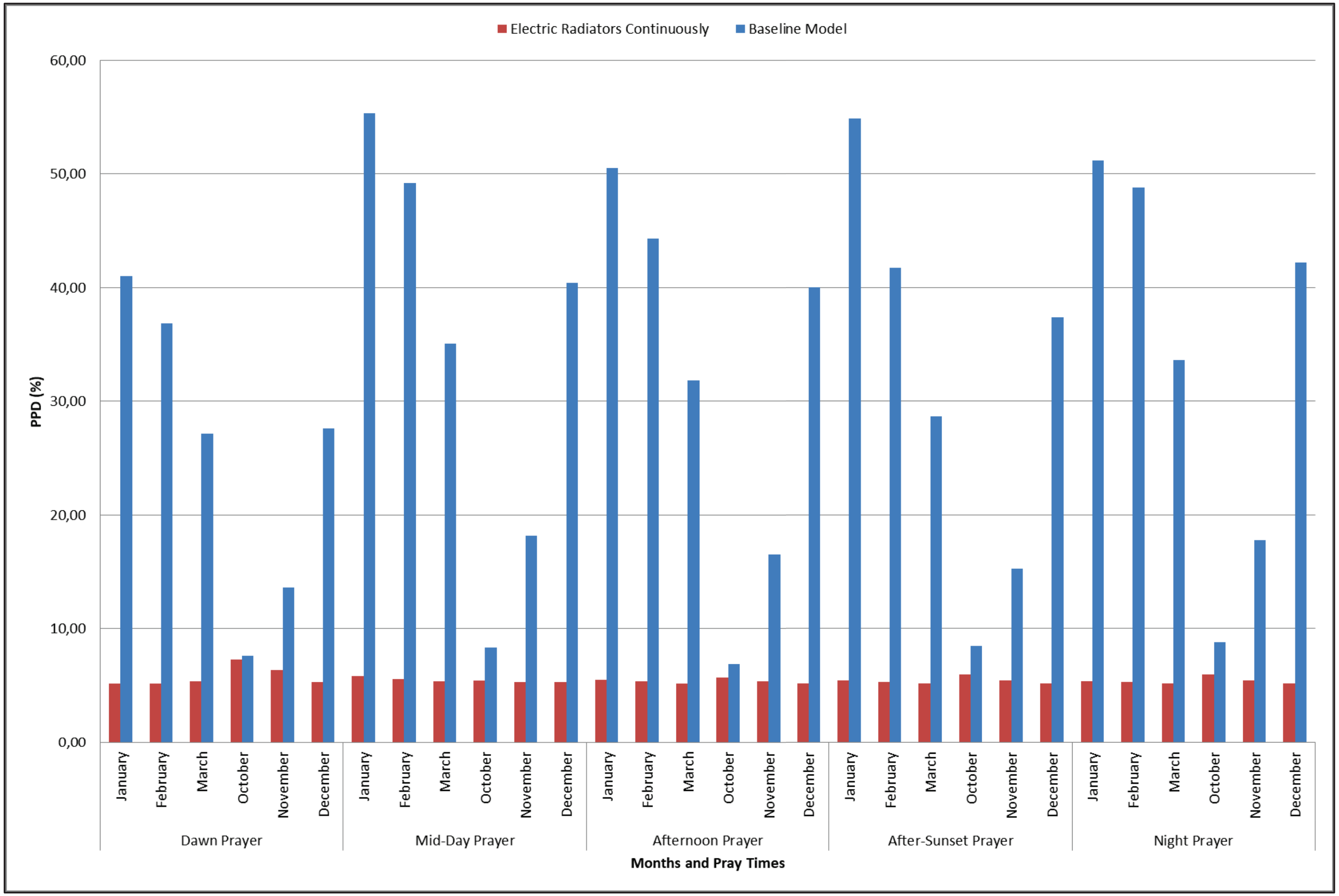


Figure 5.27. Comparison of PPDs between electric radiator heating continuously and baseline model

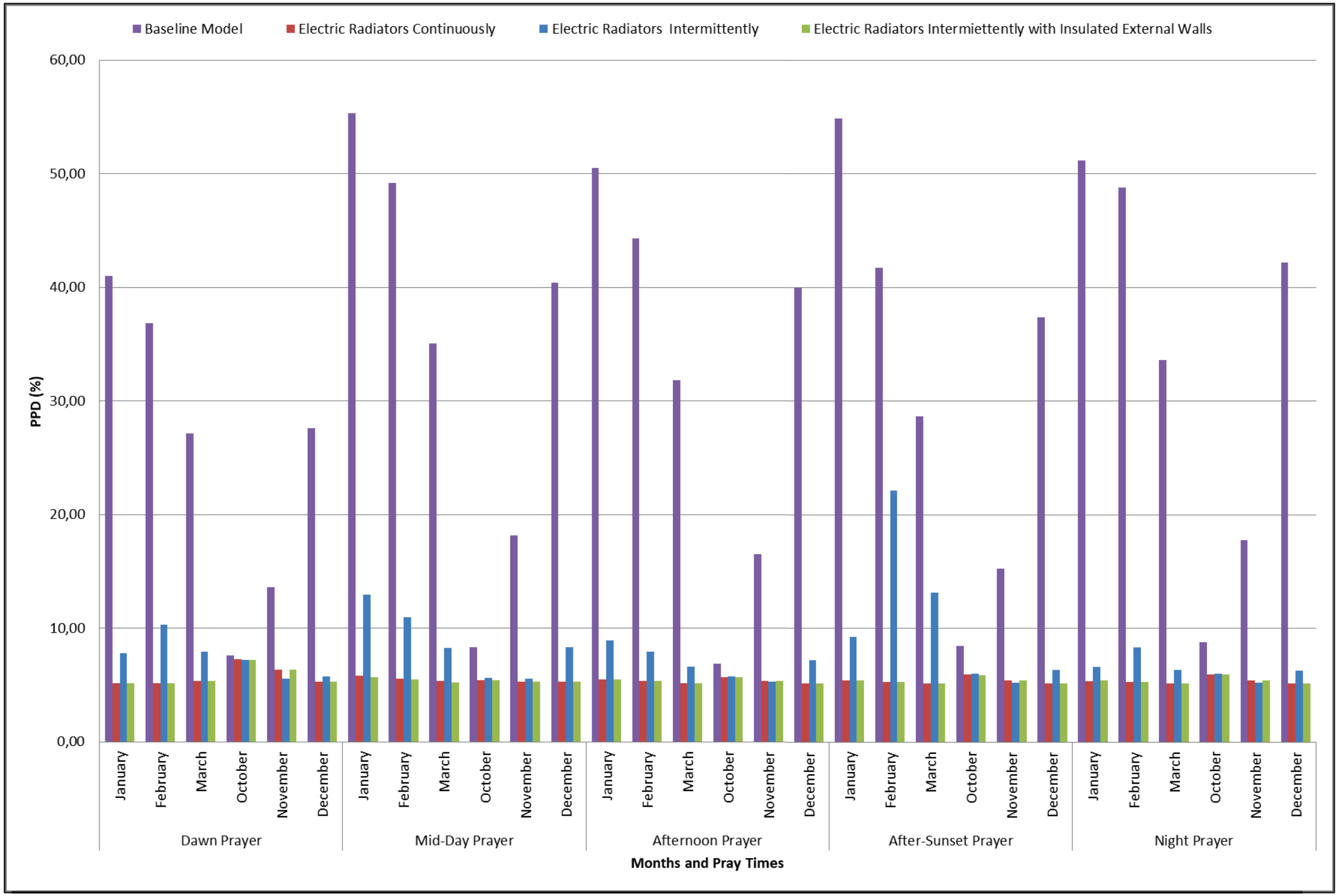


Figure 5.28. Comparison PPDs of electric radiator heating for operating hours and insulation

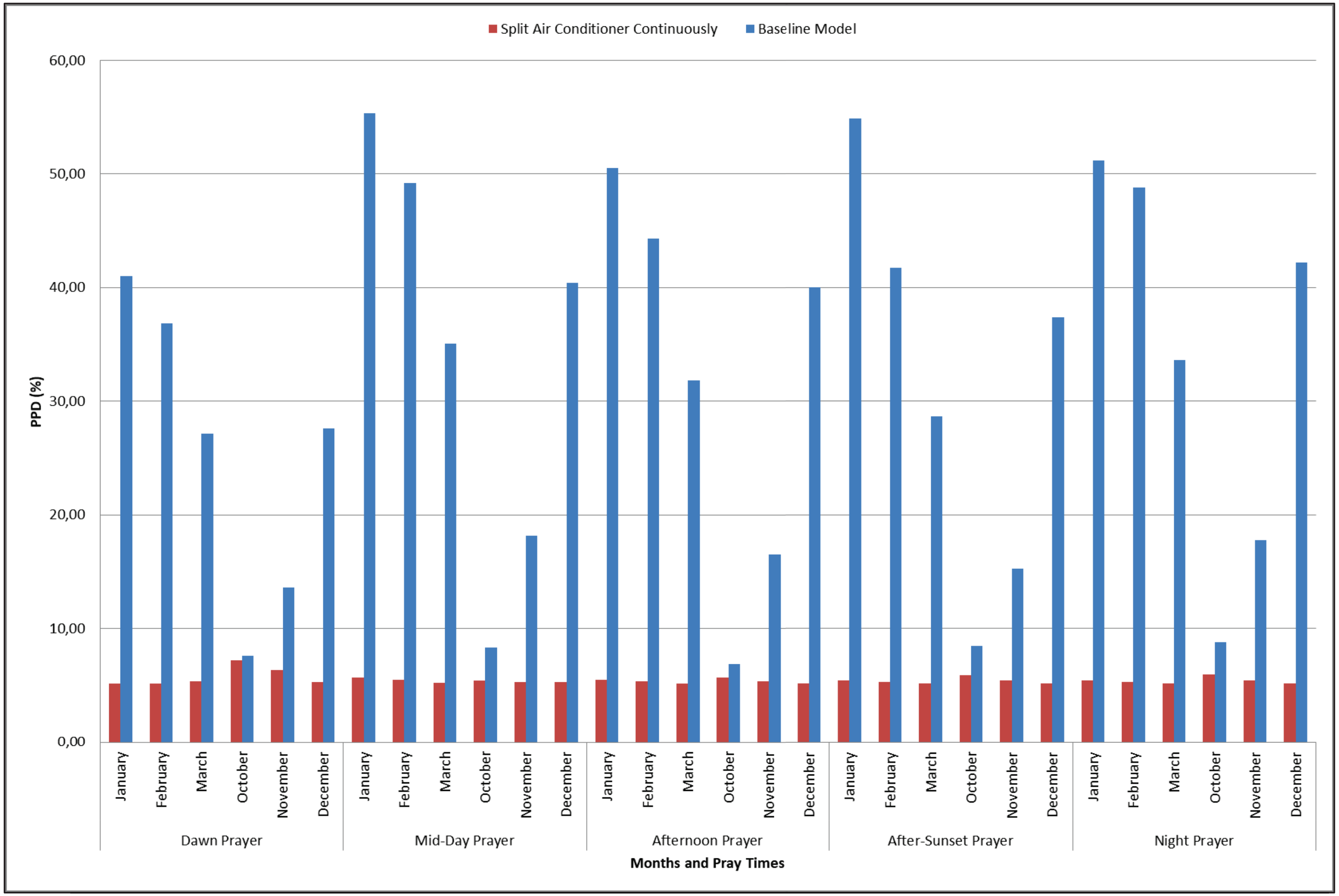


Figure 5.29. Comparison of PPDs between split air conditioner heating continuously and baseline model

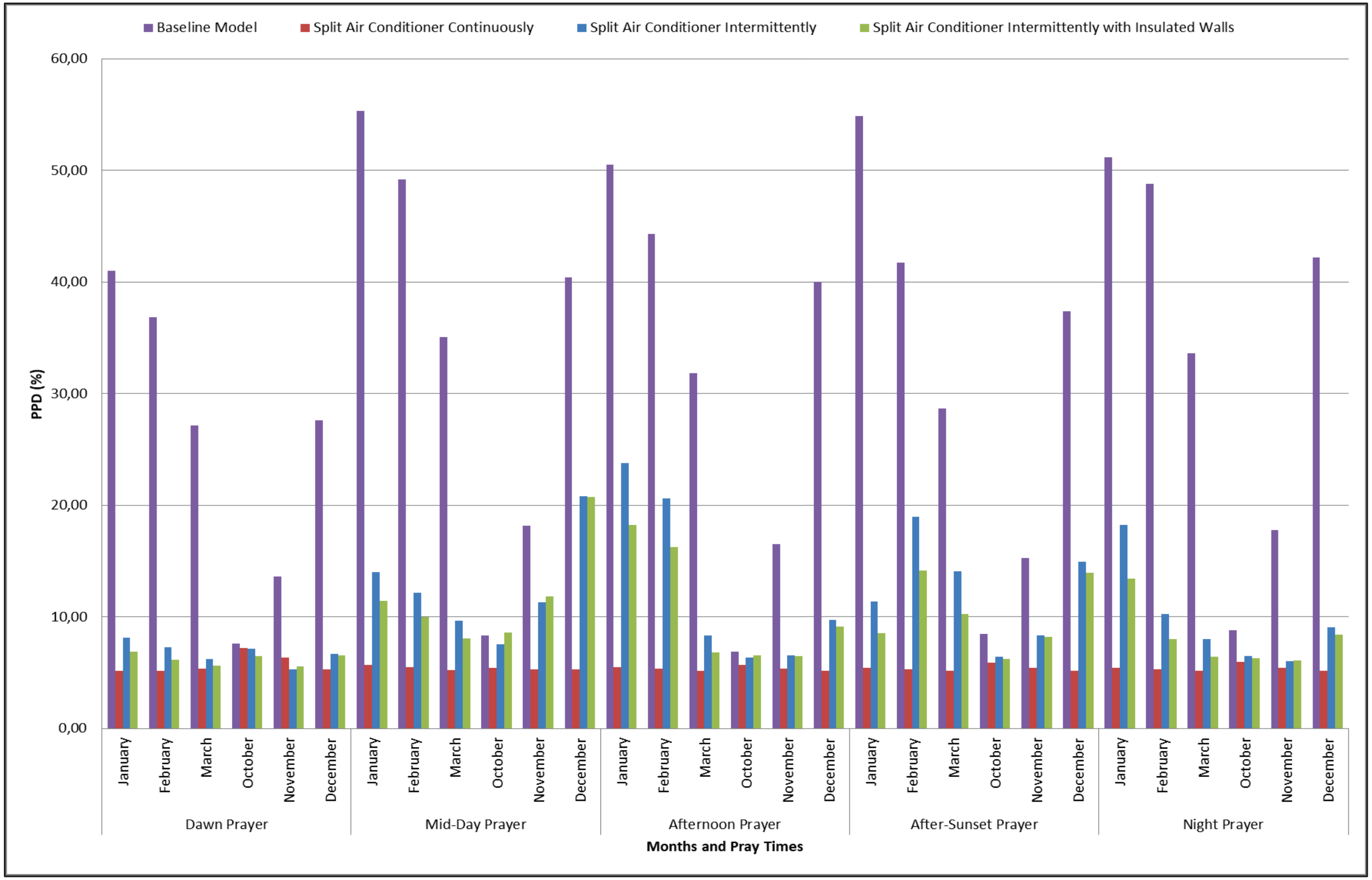


Figure 5.30. Comparison PPDs of split air conditioner heating for operating hours and insulation

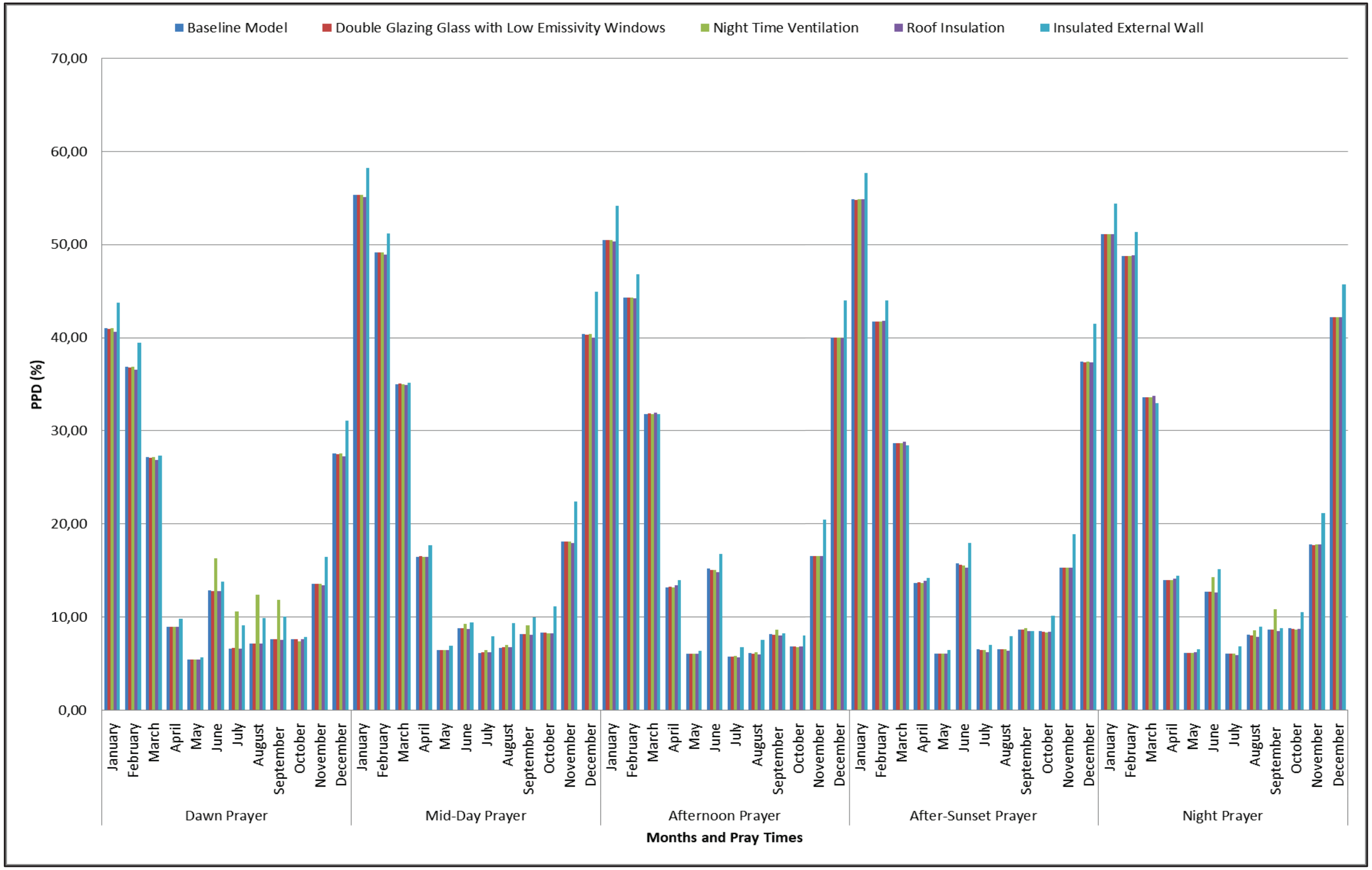


Figure 5.31. Comparison PPDs of passive design strategies

With intermittent opearation+wall insulation, maximum PPD level is observed as 20.7% in December for mid-day prayer while minimum PPD level is 5.6% in November for dawn prayer. The PPD is above 15% only in December for mid-day, January and February for after-noon prayers.

5.4.3 Comparison of Retrofitting Strategies

According to Fig. 5.31, changing windows with double glazing and low emissivity glass, night time ventilation and roof insulation have no or negligible effect on thermal comfort. Insulation of the walls has negative effect on thermal comfort if there is no heating system. If a heating system is installed, insulation could cause a decrease in energy consumption while maintaining thermal comfort. Energy saving rates for electric radiator, split type air-conditioner and underfloor heating systems are 18.4%, 11.8%, 23.2%, respectively (Fig. 5.32).

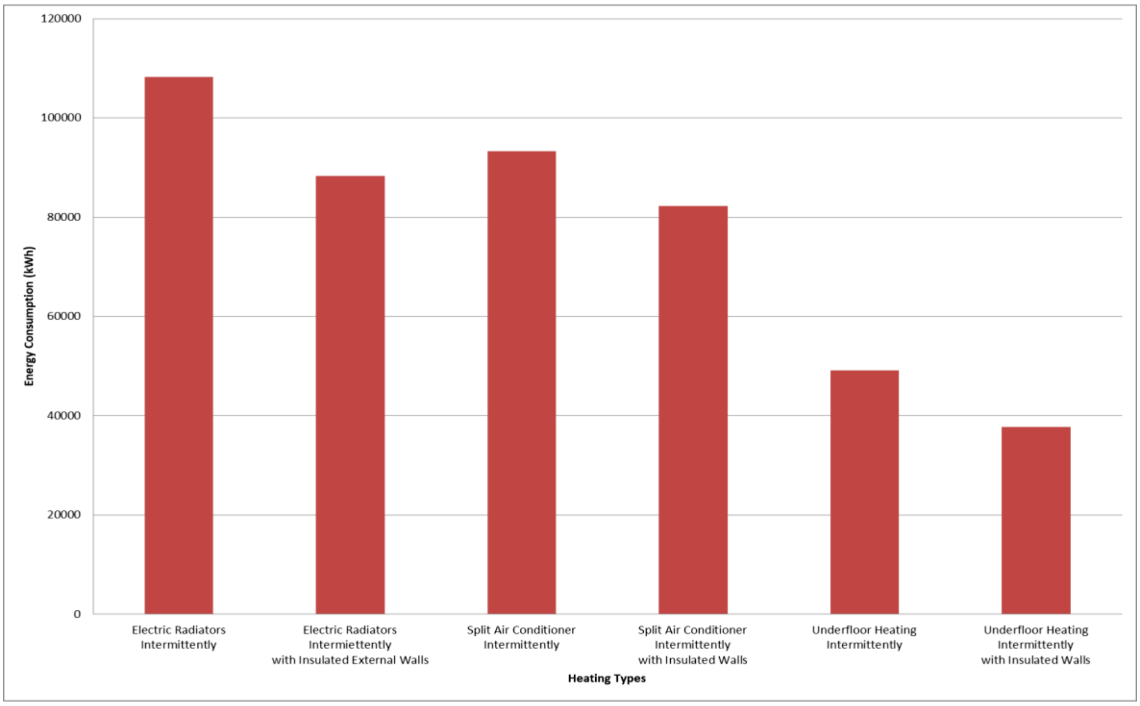


Figure 5.32. Comparison of energy consumption for wall insulation

PPD levels of active retrofitting strategies and baseline model are shown in Fig. 5.33 for winter (January, February and December) and autumn (September, October and November). PPD levels of active retrofitting strategies decreased from 45% to below

15% for winter which is considered as “acceptable” by EN ISO 7730. Even though PPD level of baseline model is below 15% for the autumn, active retrofitting strategies enhanced thermal comfort.

Comparison of annual energy consumption of active retrofitting strategies for winter and autumn season are shown Fig. 5.34. Significant reduction in annual energy consumption of Ulu Mosque could be obtained while maintaining thermal comfort when operating schedule of the heating system is properly designed and intermittently operated. A decrease in annually energy consumption of approximately 46.9% for electric radiator, 56.6% for split type air-conditioner and 26.9% for underfloor heating system are obtained compared to the continuous operating schedule.

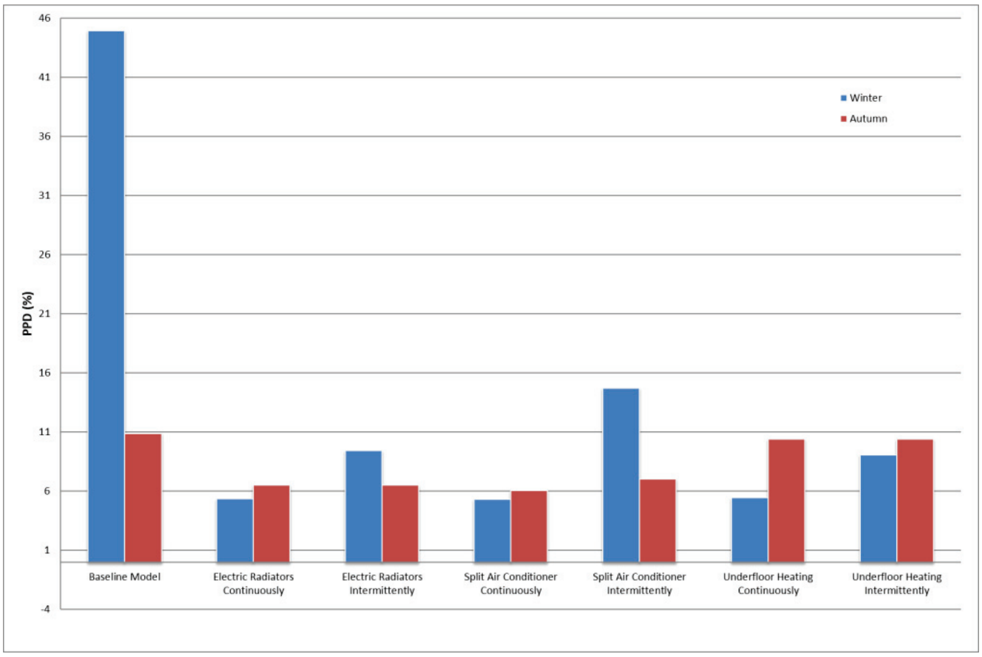


Figure 5.33. Comparison of PPDs for winter and autumn

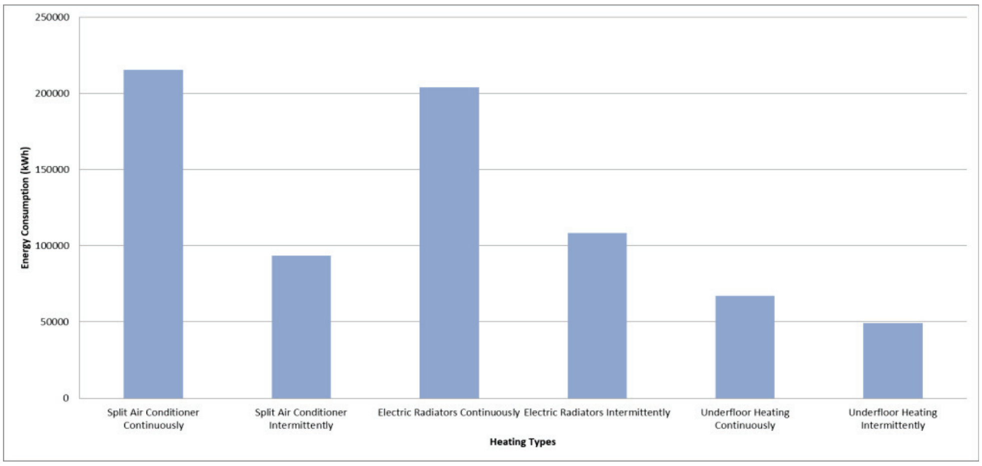


Figure 5.34. Comparison of annual energy consumption of active retrofitting scenarios

Table 5.9. PPD values and energy consumptions data for all scenarios (heating season)

	Prayer Times	Months	Baseline Model	Double Glazing Glass with Low Emissivity Windows	Night Time Ventilation	Roof Insulation	Insulated External Wall	Electric Radiators Continuously	Electric Radiators Intermittently	Electric Radiators Intermittently with Insulated External Walls	Split Air Conditioner Continuously	Split Air Conditioner Intermittently	Split Air Conditioner Intermittently with Insulated Walls	Underfloor Heating Continuously	Underfloor Heating Intermittently	Underfloor Heating Intermittently with Insulated Walls
PPD (%)	Dawn Prayer	Jan.	41.0	40.9	41.0	40.6	43.8	5.2	7.8	7.9	5.2	8.1	6.9	5.2	5.8	9.3
		Feb.	36.9	36.8	36.9	36.5	39.5	5.2	10.3	8.4	5.2	7.3	6.1	5.8	5.3	5.7
		Mar.	27.2	27.1	27.2	26.9	27.3	5.4	7.9	6.7	5.4	6.2	5.6	5.4	5.2	5.5
		Oct.	7.6	7.6	7.4	7.6	7.9	7.3	7.2	6.5	7.2	7.1	6.5	10.0	9.8	9.7
		Nov.	13.6	13.6	13.6	13.4	16.5	6.4	5.6	5.7	6.3	5.3	5.6	6.0	6.0	6.3
		Dec.	27.6	27.5	27.6	27.3	31.1	5.3	5.7	6.3	5.3	6.7	6.6	5.4	5.2	6.1
	Mid-Day Prayer	Jan.	55.3	55.3	55.3	55.1	58.2	5.8	12.9	13.3	5.7	14.0	11.4	6.0	14.2	22.8
		Feb.	49.2	49.2	49.2	48.9	51.2	5.6	11.0	10.8	5.5	12.2	10.0	5.7	11.1	13.3
		Mar.	35.0	35.0	35.0	34.9	35.2	5.3	8.2	8.0	5.2	9.7	8.1	5.4	8.2	8.5
		Oct.	8.3	8.3	8.3	8.3	11.1	5.4	5.6	5.6	5.4	7.5	8.6	6.9	7.0	7.0
		Nov.	18.1	18.1	18.1	17.9	22.4	5.3	5.5	5.7	5.3	11.3	11.8	5.3	5.5	6.0
		Dec.	40.4	40.3	40.4	40.0	45.0	5.3	8.3	8.9	5.3	20.8	20.7	5.3	8.6	11.5
	Afternoon Prayer	Jan.	50.5	50.5	50.5	50.3	54.1	5.5	8.9	8.1	5.5	23.8	18.2	5.6	9.5	15.1
		Feb.	44.3	44.3	44.3	44.2	46.8	5.4	8.0	7.0	5.4	20.6	16.2	5.4	22.3	19.3
		Mar.	31.8	31.8	31.8	31.9	31.8	5.2	6.6	6.1	5.2	8.3	6.8	5.2	6.6	6.6
		Oct.	6.9	6.9	6.8	6.9	8.0	5.7	5.7	5.5	5.7	6.4	6.5	7.5	7.5	7.4
		Nov.	16.5	16.5	16.5	16.5	20.4	5.4	5.3	5.4	5.4	6.5	6.5	5.4	5.3	5.7
		Dec.	40.0	40.0	40.0	39.9	44.0	5.2	7.2	7.8	5.2	9.7	9.1	5.2	7.5	10.3
	After-Sunset Prayer	Jan.	54.9	54.8	54.9	54.8	57.6	5.4	9.2	8.7	5.4	11.4	8.5	5.5	9.9	16.3
		Feb.	41.7	41.7	41.7	41.8	44.0	5.3	22.1	16.0	5.3	19.0	14.1	5.3	7.3	7.4
		Mar.	28.7	28.7	28.7	28.8	28.4	5.2	13.1	10.1	5.2	14.1	10.2	5.2	6.0	5.8
		Oct.	8.5	8.4	8.3	8.4	10.1	5.9	6.0	5.7	5.9	6.4	6.2	8.2	8.2	8.4
		Nov.	15.3	15.3	15.3	15.3	18.9	5.4	5.2	5.3	5.4	8.3	8.2	5.5	5.3	5.6
		Dec.	37.4	37.3	37.4	37.3	41.5	5.2	6.3	6.6	5.2	14.9	13.9	5.2	6.5	8.5
	Night Prayer	Jan.	51.1	51.1	51.1	51.1	54.4	5.4	6.6	6.0	5.4	18.3	13.4	5.5	6.9	10.8
		Feb.	48.8	48.8	48.8	48.8	51.3	5.3	8.3	7.6	5.3	10.3	8.0	5.3	6.2	6.3
		Mar.	33.6	33.6	33.6	33.7	33.0	5.2	6.3	5.9	5.1	8.0	6.4	5.2	5.5	5.4
		Oct.	8.8	8.8	8.6	8.7	10.5	6.0	6.0	5.7	5.9	6.5	6.3	8.2	8.2	8.4
		Nov.	17.8	17.8	17.8	17.8	21.2	5.4	5.2	5.3	5.4	6.0	6.1	5.5	5.3	5.5
		Dec.	42.2	42.2	42.2	42.2	45.7	5.2	6.2	6.2	5.2	9.1	8.4	5.2	6.4	7.9
Annual Energy Consumption (kWh)			-	-	-	-	-	203791	108206	88332	215127	93316	82295	67286	49174	37760

The PPD values and energy consumption data for all scenarios (heating season) and for all prayer times are summarised in Table 5.9.

5.5. Risk Assessment of Retrofitting Strategies

In this section, thirteen retrofitting scenarios were evaluated with respect to four measures which are heritage value protection, thermal comfort, energy consumption and energy cost according to EN 16883 as shown in Table 5.10.

Table 5.10. Risk assessment according to EN 16883 (2017)

Retrofit Impact Assessment																				
Type of Retrofit	Heritage Value Protection					Thermal Comfort					Energy Consumption					Energy Cost				
Windows with Double Glazing with Low Emissivity Glass		yellow						white					white					white		
Night Time Ventilation			white					white					white					white		
Roof Insulation		yellow						white					white					white		
Insulated External Wall	red						yellow						white					white		
Electric Radiators Continuously			white							green	red					red				
Electric Radiators Intermittently			white							green		yellow				red				
Electric Radiators Intermittently with Insulated External Walls	red									green		yellow				red				
Split Air Conditioner Continuously		yellow								green	red					red				
Split Air Conditioner Intermittently		yellow								green		yellow				red				
Split Air Conditioner Intermittently with Insulated Walls	red									green		yellow				red				
Underfloor Heating Continuously		yellow								green	red						yellow			
Underfloor Heating Intermittently		yellow								green		yellow					yellow			
Underfloor Heating Intermittently with Insulated Walls	red									green		yellow					yellow			

Thermal comfort assessment of retrofit scenarios which conducted in Section 5.4. is transferred to Table 5.10. Based on heritage value protection measure, window change and roof insulation are accepted as have low effect on building envelope and cultural heritage. External wall insulation could lead to the loss of historical appearance and indicates high risk on the heritage value and historical building character. Electric radiators can be placed away from sensitive surfaces or objects in order not to cause damage as particle deposition. Nighttime ventilation have no any harmful effect on cultural heritage (EN 15759-1, 2011). Even though particle deposition on surfaces may be inconspicuous with underfloor heating, the impact on the floor is considerable. Therefore, it is evaluated risky (EN 15759-1, 2011).

Annual energy consumption of heating strategies presented in Fig. 5.35. Split type air-conditioner has the highest energy consumption while underfloor heating consumes lowest. If air-conditioner system is used with wall insulation and operated intermittently, energy consumption decreases dramatically from 215.127 kWh to 82.295 kWh. Whereas If electric radiator is used with wall insulation and operated intermittently, energy consumption decreases from 203.191 kWh to 88.332 kWh.

All in all, intermittent operating strategy is decreased energy consumption 47%, 57% and 27% for split type air-conditioner system, electric radiators and underfloor heating system, respectively. Even though, insulation of the walls decreases energy consumption by 12%, 18% and 27% for split type air-conditioner system, electric radiators and underfloor heating system, it can not be applied because of the high risk on cultural heritage.

When thermal comfort, heritage value protection, energy consumption and cost are evaluated together, electric radiator heating with intermittent schedule is favourable. Underfloor heating system has positive effects on thermal comfort and energy consumption. But it can only applicable if electrical mats are used under the carpeting without any physical intervention to the cultural heritage value of the building.

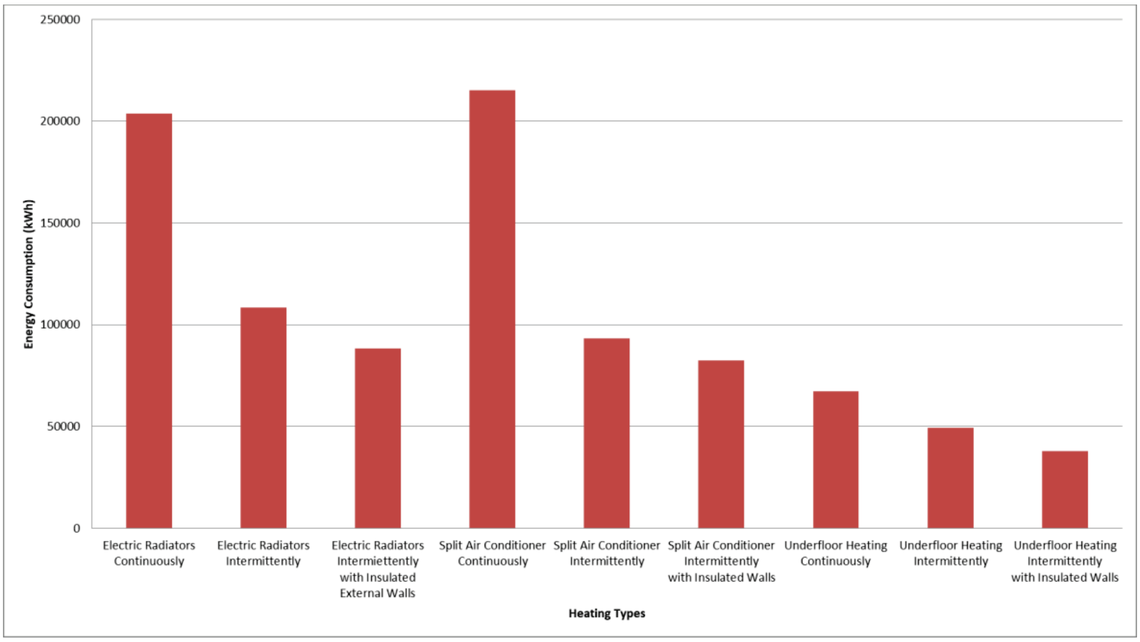


Figure 5.35. Comparison of energy consumption data

CHAPTER 6

CONCLUSIONS

Thermal comfort analysis during prayer times was conducted at naturally ventilated historical Ulu Mosque which is located in Manisa, Turkey. On-site T and RH measurements were taken indoor and outdoor for almost two years. The mosque is also modelled by DesignBuilder software and the model was calibrated according to ASHRAE Guideline 14. Results of the thermal comfort evaluation gave some dissatisfactions at certain periods. Therefore, retrofitting scenarios were proposed to be able to improve thermal comfort level of the mosque. Thirteen retrofitting scenarios were simulated by the model and results were discussed. Besides, all scenarios were evaluated according to EN 16883 owing to analyze the risks in terms of cultural heritage.

Passive retrofitting scenarios which are changing windows with double glazing and low emissivity glass, nighttime ventilation and roof insulation have no or negligible effect on thermal comfort. Insulation of wall has negatively affected the thermal comfort if there is no heating system. If a heating system is installed, insulation could decrease energy consumption while thermal comfort is maintained.

On the other hand, active retrofitting strategies which are underfloor heating system, heating with electric radiator and split type air-conditioner improved thermal comfort both in continuous and intermittent operation regimes. When intermittent operation is applied, all the retrofitting strategies had significant reduction in annual energy consumption while maintaining thermal comfort comparing to continuous operation. The results are also compatible with the literature (Al-Homoud et al., 2009; Budaiwi and Abdou, 2013; Azmi and Kandar, 2019).

Furthermore, the retrofitting scenarios must be carefully selected not to compromise the cultural value of historical buildings. Therefore, the number of scenarios could be applied to the mosque is limited. Electric radiator heating with intermittent operating schedule looks like the best option to protect cultural heritage, while it provides thermal comfort with lower energy consumption.

In addition, thermal comfort ought to be evaluated in mosques differ from other building types in terms of occupancy period during a day because of their unique function and intermittent operating schedule. Therefore, thermal comfort is analyzed at five times a day with various numbers of worshippers at different times during the year according to the motion of the moon. Thus, thermal comfort results are for the actual usage time of the mosque throughout the year.

Furthermore, software like DesignBuilder allows different scenarios to be used in the selection of strategies to be applied in historical buildings. The implementation of any of these strategies should be consistent with the heritage value of the building and risk assessments should be done according to EN 16883 for systematic approach.

Lastly, owing to the fact that thermal comfort is a situation where each person reacts differently to the same environmental condition, a further survey with questionnaire can be applied by using Fanger's thermal comfort model to understand thermal comfort better.

REFERENCES

Akman M., Güner A. & Aksoy H. (1986). The history and properties of khorasan mortar and concrete. *11th International Turkish-Islamic Science and Technology History Congress*, ITU.

Al-Homoud M., Abdou A. & Budaiwi I. (2009). Assessment of monitored energy use and thermal comfort conditions in mosques in hot-humid climates. *Energy and Buildings,* 41, 607–614.

ASHRAE. (2013). ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy. *ASHRAE Standards Committee*.

ASHRAE. (2002). ASHRAE Guideline 14: Measurement of Energy and Demand Savings. *ASHRAE Standards Committee*.

Atmaca A.B. & Gedik G.Z. (2019). Evaluation of mosques in terms of thermal comfort and energy consumption in a temperate-humid climate. *Energy & Buildings,* 195, 195–204.

Auliciems A. & Szokolay SV. (1997). *Thermal Comfort*, *(2nd Ed.)*, PLEA.

Autocad LT 2008. (2017, May 01). Retrieved from https://www.autodesk.com/products/autocad/overview.

Azmi, N. & Kandar M. (2019). Factors contributing in the design of environmentally sustainable mosques. *Journal of Building Engineering* 23, 27–37.

Budaiwi I. & Abdou A. (2013). HVAC system operational strategies for reduced energy consumption in buildings with intermittent occupancy: The case of mosques. *Energy Conversion and Management.* 73, 37–50.

Bughrara K. (2016). Adaptive thermal comfort analysis of historical mosque: The case study of Salepçioğlu Mosque, MSc thesis, IZTECH, İzmir, Turkey.

Bughrara K., Arsan Z. & Akkurt G. (2017). Applying underfloor heating system for improvement of thermal comfort in historic mosques: the case study of Salepçioğlu Mosque, İzmir, Turkey. *Energy Procedia* 133, 290-299.

DesignBuilder. (2017, May 22). “DesignBuilder-Building Simulation Software. Retrieved from the web page http://designbuilder.co.uk/helpv6.0/.

EN 15759-1:2011 Conservation of cultural property - Indoor climate - Part 1: Guidelines for heating churches, chapels and other places of worship, CEN, Switzerland.

EN 16883:2017 Conservation of cultural heritage – Guidelines for improving the energy performance of historic buildings. Brussels, Belgium.

EN ISO 7730:2005 Ergonomics of the thermal environment. Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria, CEN, Switzerland.

Fanger P. & Toftum J. (2002). Extension of the PMV model to non-air-conditioned buildings in Warm Climates. *Energy and Buildings.* 34,533-536.

Fanger, P. (1970). *Thermal Comfort: Analysis and applications in environmental engineering*. Mc.Graw-Hill.

Google Maps. (2017, May 22). "Ulu Cami" Retrieved from https://www.google.com/maps/place/Ulu+Cami/@38.608151,27.4280001,612m/data=!3m2!1e3!4b1!4m5!3m4!1s0x14b99c405894324f:0x7b6af1a4fdd1b382!8m2!3d38.608151!4d27.4301888.

Homebuilding. (2019, May 11). "External Wall Insulation" Retrieved from https://www.homebuilding.co.uk/external-wall-insulation/.

Houghton, F.C. & Yaglou, C.P. (1923). Determining lines of equal comfort. Journal of the American Society of Heating and Ventilating Engineers Trans. 29,163-176 and 361-384.

Iztech. (2015). İzmir Institute of Technology Department of Architectural Restoration Relievo Drawings, Urla, İzmir.

Jaafar R., Khalilb E. & Abou-Deif T. (2017). Numerical Investigations of Indoor Air Quality inside Al-Haram Mosque in Makkah. *Procedia Engineering.* 205, 4179–4186.

Mekan 360. (2017, June 05). "Ulu Cami" Retrieved from http://www.mekan360.com/sanaltur_ulu-camii-manisa_1568.html.

Murgula V. & Pukhkal V. (2015). Saving the Architectural Appearance of the Historical Buildings due to Heat Insulation of their External Walls. *Procedia Engineering.* 117, 891 – 899.

Onset Data Logger. (2017, May 22). Retrieved from https://www.onsetcomp.com/products/data-loggers/u12-012.

Panchyk K. (1984). Solar Interiors: Energy-Efficient Spaces Designed for Comfort, Van Nostrand Reinhold Company Inc., USA.

Semprini G., Galli C. & Farina S. (2017). Reuse of an ancient church: thermal aspect for integrated solutions Energy Procedia 133, 327-335.

Szokolay SV. (1985). Advances in Solar Energy, *Thermal Comfort and Passive Design, Advances in Solar Energy. (2nd Ed.)*, Springer, Boston, 257-296

TC Ministry of Culture and Tourism. (2017, June 02). Retrieved from http://www.manisakulturturizm.gov.tr/TR,73021/ulu-camii-ve--kulliyesi-manisa-merkez.html.

Turcanu F.E., Verdes M. & Serbanoiui. (2016). Churches Heating: The Optimum Balance Between Cost Management and Thermal Comfort. *Procedia Technology*. 22, 821-828.

Wang J., Wang Z., De Dear R., Maohui L., Ghahramani A. & Borongde L. (2018). The uncertainty of subjective thermal comfort measurement. *Energy & Buildings.* 181, 38–49.

Webb, A. (2017). Energy retrofits in historic and traditional buildings: A review of problems and methods. *Renewable and Sustainable Energy Reviews.* 77, 748–759.

Widström, T. (2012). Enhanced Energy Efficiency and Preservation of Historic Buildings: Methods and Tools for Modeling. *KTH Architecture and the built environment*. ISBN 978-91-7501-488-3.

Wu P., Hsieh C. & Hsua M. (2014). Using heritage risk maps as an approach to estimating the threat to materials of traditional buildings in Tainan (Taiwan). *Journal of Cultural Heritage*. 15, 441–447.

Yang Y., Li B., Liu H., Tan M. & Yao R. (2015). A study of adaptive thermal comfort in a well-controlled climate chamber. *Applied Thermal Engineering.* 76, 283-291.

Zomorodian Z., Tahsildoost M. & Hafezi M. (2016). Thermal comfort in educational buildings: A review article. *Renewable and Sustainable Energy Reviews.* 59, 895–906.