Energy & Buildings 252 (2021) 111441

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Thermal comfort analysis of historical mosques. Case study: The Ulu mosque, Manisa, Turkey

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ARTICLE INFO

Article history:
Received 26 April 2021
Revised 26 August 2021
Accepted 6 September 2021
Available online 9 September 2021

ABSTRACT

Mosques are sanctuary places for Muslims where they can perform their religious activities and also can communicate with each other. On the other hand, historical mosques may contain artworks which have cultural heritage values. These mosques originally have not any Heating, Ventilating and Air-Conditioning systems. For this reason, obtaining thermal comfort becomes a significant issue. In this study, a systematic approach on monitoring and evaluating thermal comfort of historical mosques were developed. As a case study, The Ulu Mosque, Manisa/Turkey was monitored from 2015 to 2018, and thermal comfort evaluation of the mosque was conducted during prayer times based on the method provided by ISO 7730. A dynamic Building Energy Performance Software, DesignBuilder, was used to model the mosque, and the model was calibrated by using hourly indoor temperature data. The calibrated model was then used to evaluate existing conditions of the mosque and develop retrofitting scenarios in order to increase thermal comfort of prayers. Thirteen different scenarios were proposed to improve thermal comfort of prayers during worship periods. The results were evaluated according to EN 16883 for conservation of cultural heritage of the mosque. Electrical radiator heating with intermittent operating schedules was obtained as the best scenario to protect cultural heritage via artworks, while decreasing disssatisfaction level of the prayers from 45% to 10% in winter months. Additionally, intermittent operation saved 46.9% of energy compared to continuous operating schedule.

1. Introduction

Historical buildings are originally non-air conditioned buildings which also have complex geometry due to their domed ceilings, round towers and different wall thicknesses. Generally, the walls are un-insulated, moreover, no mechanical ventilation system exists due to the lack of technology at the times those were built [1–2]. Besides, their structures may be damaged by natural climatic effects such as rain, wind, temperature and moisture during the centuries [3]. Restoration work is needed time to time to reverse damage and/or protect buildings against deterioration that could make them inaccessible or unrecognizable in the future. Intervention strategies for the restoration of historical buildings should preserve the historical value of the building while improving thermal comfort of visitors or occupants.

Religious buildings such as churches and mosques are mostly historical buildings. The mosques are the places of worship and only being visited during specific periods and prayer times are different during the year according to the motion of the moon. *Imam* is the leader of the prayers and stands through the *qibla*; the direction of the prayers towards to *Kaabe* in Mecca. A *mihrab* is a wall niche which indicates the direction of the *qibla*. Islamic prayer times change each month due to the difference of sunrise and sunset times for each day. Daily prayers are; dawn (*Fajr*): before sunrise, midday (*Dhuhr*): after the sun passes its highest; afternoon (*Ajr*): the late part of the afternoon; after sunset (*Maghrib*): just after sunset and midnight (*İsha*): between sunset and midnight. Furthermore, Friday prayer (*Jumu'ah*) replaces midday prayer once a week. During the holy month of *Ramadan*, special prayers called *Taraweeh* are conducted after every evening's midnight prayer. Therefore, mosques are religious buildings with five times a day and intermittent occupancy periods.

Thermal comfort is conventionally assessed with Fanger's Predicted Mean Vote (PMV) and Percentage of Predicted Dissatisfied (PPD) method [4]. PMV is a function of air temperature, mean radiant temperature, relative humidity, air velocity, and the personal variables of clothing value and metabolic rate. On the other hand,

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https://doi.org/10.1016/j.enbuild.2021.111441
0378-7788/

Nomenclature

A	Average of the measured values
CV (RMSE)	Coefficient of variant of root mean square error
I	Thermal resistance
M	Metabolic rate
MBE	Mean Bias Error
n	Number of observations
o	Measured value
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied (%)
RH	Relative humidity (%)
RMSE	Root-mean-square-error
t	Temperature (^{o}C)
s	Simulated value
v	Velocity (m/s)
2D	2 dimensional
3D	3 dimensional

Subscripts

a	Air
c	Convection
cl	Clothing
r	Relative

PPD depicts a quantitative prediction of the percentage of thermally dissatisfied people in the environment. 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 [5–14]. Although each type of buildings has its own occupancy and operational schedule, the mosques are very similar to other religious buildings which have intermittent occupation since the occupation period changes throughout the year [6]. In the literature, limited simulation studies on thermal comfort of mosques can be found [7–10]. For instance, Bughrara et al. [7] conducted a study to improve thermal comfort by various active and passive systems in a naturally ventilated historical mosque via a dynamic building energy simulation tool. The measurements were used to calibrate the model of the mosque. The model results indicated that underfloor heating system was the best alternative to enhance thermal comfort level in the mosque. Budaiwi and Abdou [8] investigated the impact of operational zoning and oversized HVAC systems on thermal comfort in mosques with intermittent operation. In the study, zoning was required due to the different occupancy rates for each prayer time. The study contained 132 mosques which were classified into six categories in terms of the mosque's floor type, capacity, aspect ratio, etc. The study 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.

On the other hand, empirical studies on thermal comfort in religous buildings can be found in [5,11–14]. For instance, Atmaca and Gedik [5] investigated indoor thermal comfort levels of two mosques based on international standards. The PMV and PPD values were predicted from measurements to compare and monitor thermal comfort level in the mosques which have the same natural and 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 have better thermal comfort level compared to the mosque with traditional building envelope and natural ventilation . Karyono et al. [11] investigated thermal comfort in a naturally ventilated cathedral and compared the comfort temperatures with naturally ventilated market and museum. The authors indicated that higher comfort temperature is found in cathedrals than other buildings due to the lower metabolic rate of occupants in cathedral. Vella et al. [12] used adaptive thermal comfort model in naturally ventilated churches in Malta. Indoor and outdoor air temperatures were measured in five different churches with varying characteristics, quantify and thermal behaviours. The authors concluded that hourly temperatures during occupancy period were lower than the adaptive thermal comfort limits in winter.

Apart from providing thermal comfort for the prayers, preserving cultural heritage of the historical mosques should be also taken into consideration. However, any inattentive intervation may arise unexpected results. On the other hand, construction materials, thermal mass, moisture cushioning, location, general form and exterior wall openings highly affect hygrothermal performance of historical mosques. Design of historical building may lead to low and high-pressure areas which create natural ventilation. In addition, occupants of historical buildings may change indoor climatic conditions with interventions such as opening/closing windows and doors when they feel hot/cold. Therefore, the biggest challenge on improving thermal conditions of historical buildings is to preserve cultural heritage. Each retrofit intervention should not only aim to obtain thermal comfort but also not to be harmful on the heritage value of the building. EN 16,883 "Conservation of cultural heritage" standard [15], 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*".

Although vast amount of studies encountered in the literature on thermal comfort of residential buildings, offices, classrooms and schools; there are limited studies concentrated on thermal comfort of historical mosques which are mostly located on hot-humid climates while thermal comfort analysis for temperate climates are quite rare. Because of the intermittent occupation, changing occupancy rate and prayer time for each worship, mosques are unique places where a dynamic thermal comfort and energy consumption analysis is required. To the best of authors' knowledge, there is no study on specifically concentrated on thermal comfort analysis for changing prayer times. The aim of this study is threefold: investigating thermal comfort of prayers on only during prayer times for one year in a historical mosque located in temperate climate; assessment of energy consumption of the mosque and performing risk assessment study which aims to preserve cultural heritage values of mosque.

2. Metarials and methods

The methodology of conducting thermal comfort evaluation of a historical mosque consists of three main phases: detailed data collection, development of a dynamic building energy model and analysis of retrofitting strategies to improve thermal comfort without detoriating heritage value of the building. 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 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 [16], can be used to evaluate indoor climate of the mosque and, to develop and analysis of retrofitting proposals. Third phase discusses retrofitting strategies and simulation of retroffitting 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. 1 gives the flow diagram of the methodology.

2.1. Case study

The Ulu Mosque was selected as a case study to analyse the thermal comfort of prayers. The mosque is a part of the Ulu Mosque Complex, which is located on the northern skirts of Spil Mountain in Manisa-Turkey, was built in 1366 [17]. The location of the Complex is given in Fig. 2. 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. 3).

A plan view of the mosque is given in Fig. 4. The prayer hall is naturally ventilated by windows located on entrance wall (twelve windows), west wall (five windows) and east wall (one window). There is no window on the qibla wall of the building. The entrance door and two windows next to this door are kept open for natural ventilation. Rest of the windows are fixed and cannot be opened.

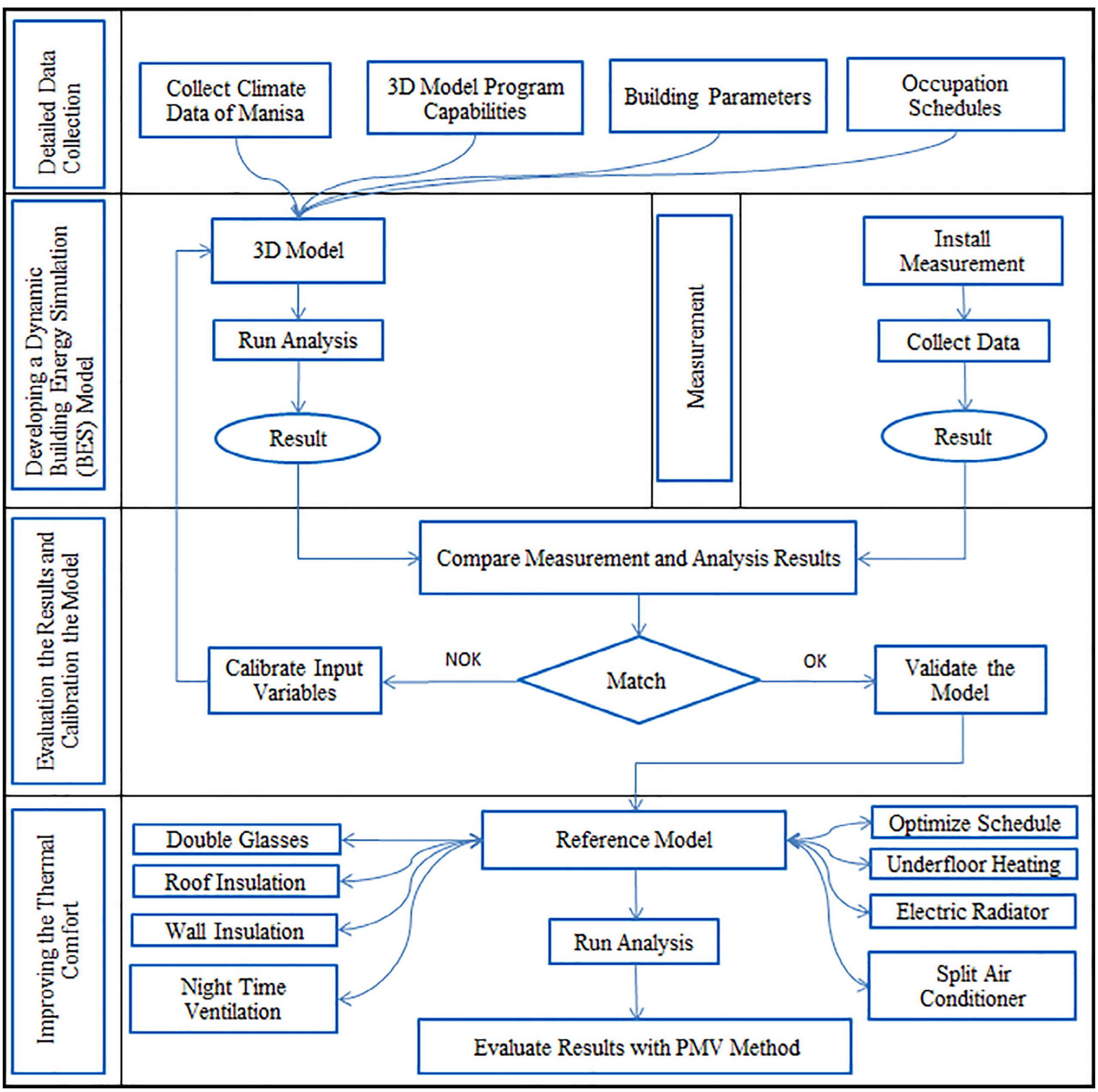

Fig. 1. Flow diagram of the methodology.

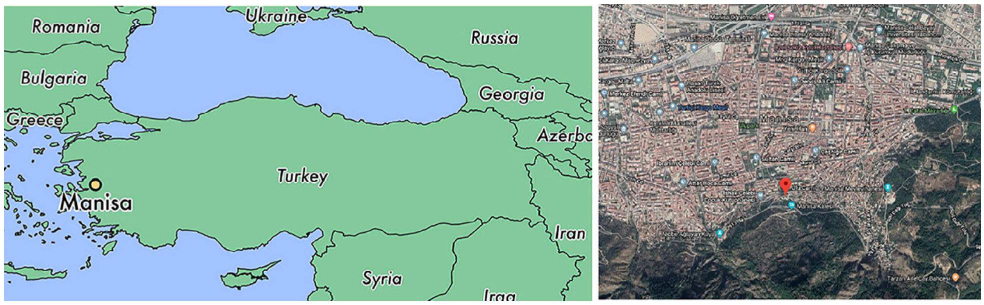

Fig. 2. Location of the Ulu Mosque complex-Manisa-Turkey.

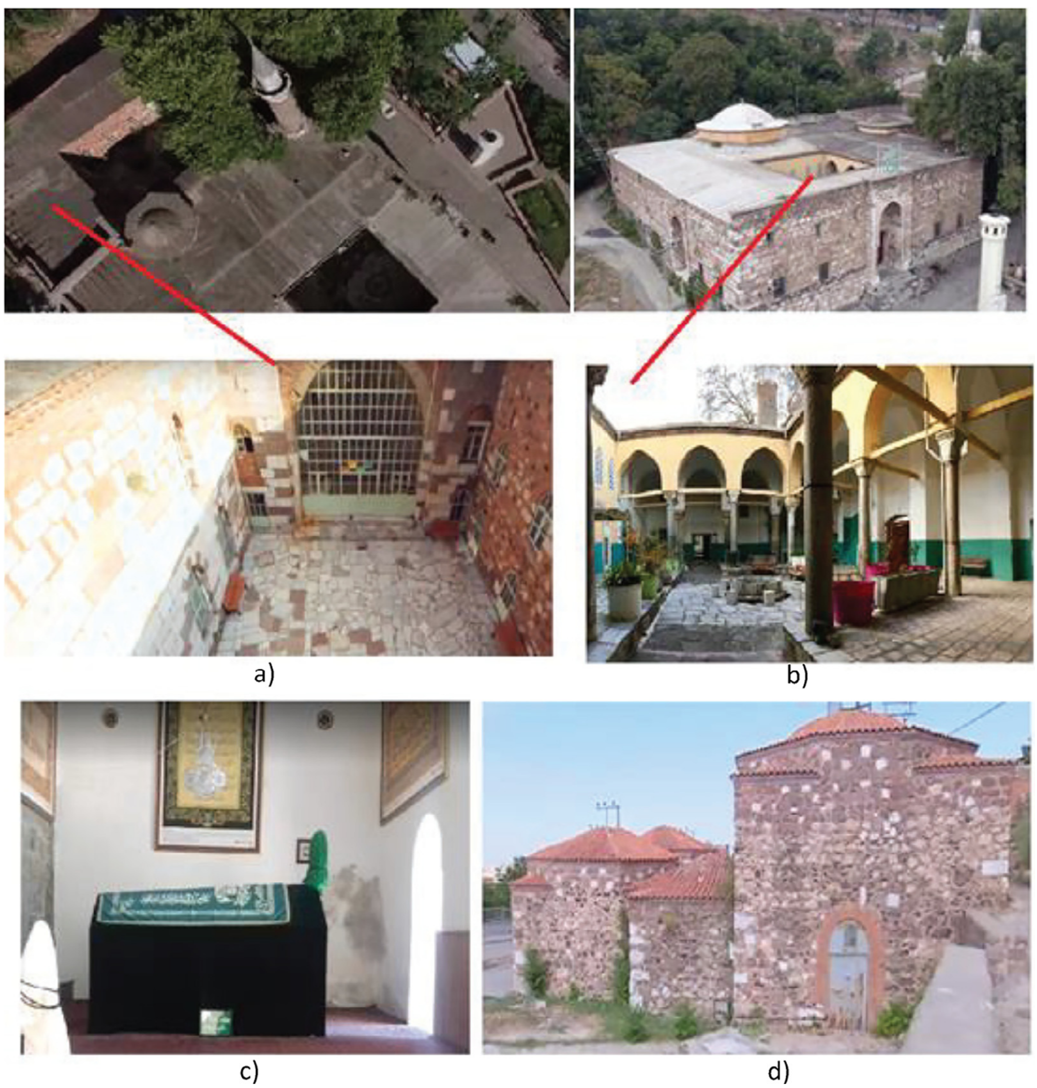

Fig. 3. The Ulu Mosque Complex a) Fethiye Madrasah, b) Courtyard, c) Tomb, d) Çukur Hamam.

2.2. Data collection

Data collection process includes collecting existing data of the mosque, and indoor and outdoor data measurement campaign. Existing data, including structural characteristics of the building, thermal properties of building materials, heating/cooling system, ventilation strategies, and number of occupants and occupation time, were collected from architectural and restoration projects, reports, books, surveys and personal communications with staff of the mosque. The materials of building components, wall thicknesses, thermo-physical properties were obtained from restoration project if it is available [17]. If not, assumptions were made based on walk-through inspections, then the assumed parameters were validated by calibration results. Table 1 shows the overall heat transfer coefficients, thicknesses and position of each building component.

Islamic prayer times change each month due to the difference of sunrise and sunset times for each day (Table 2). The occupancy

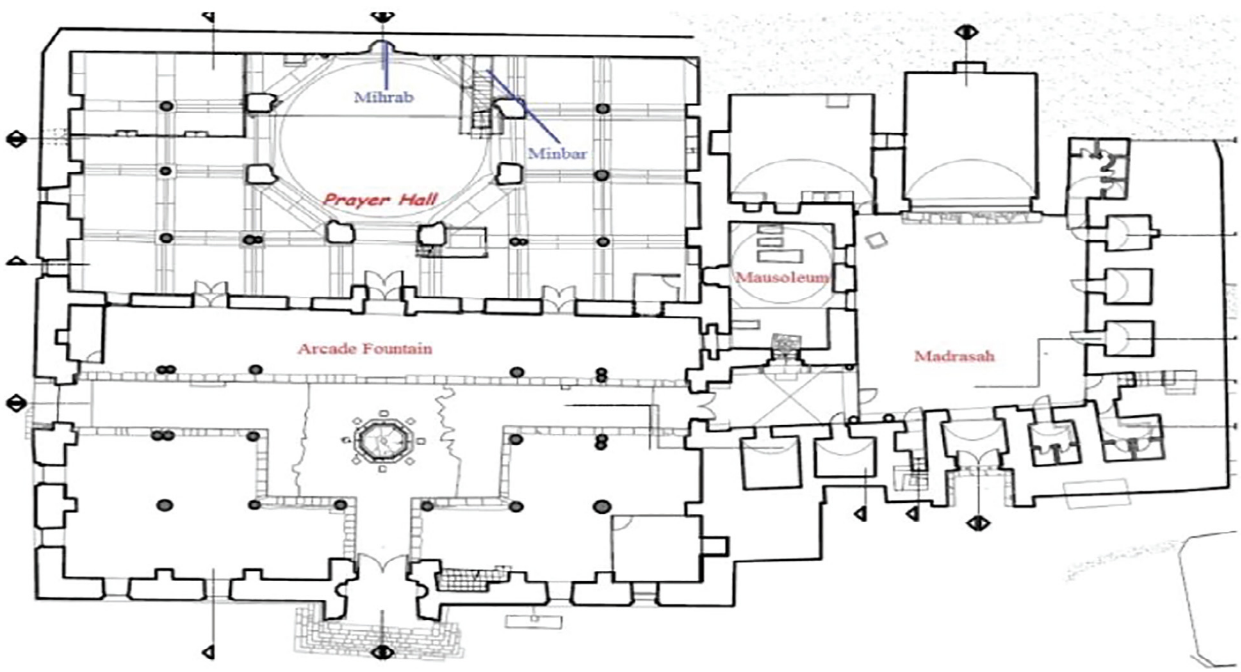

Fig. 4. Plan of the Ulu Mosque.

Table 1
Thermo-physical properties, thicknesses, positions and layers of building components.

Building components	Overall heat transfer coefficient (U) (W/m^{2}K)	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

Table 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

rates in the mosque were determined by observing the number of participation in five prayer times and Friday time, and obtained via interviewing with the Imam. Occupancy rate was 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 was assumed as 100%.

In addition, long-term measurements of indoor and outdoor climatic data (temperature and relative humidity) were conducted by dataloggers. Five dataloggers were installed in the prayer hall while one datalogger is located outside to the courtyard (Fig. 5). Temperature (T) and relative humidity (RH) data were recorded every 10 min between April 4th, 2016 - March 11th, 2018. The dataloggers were positioned at different heights to protect them from any human interaction (Table 3). Furthermore, since mosques are open to public for 24 h, the sensor locations are chosen high enough to prevent vandalism of theft.

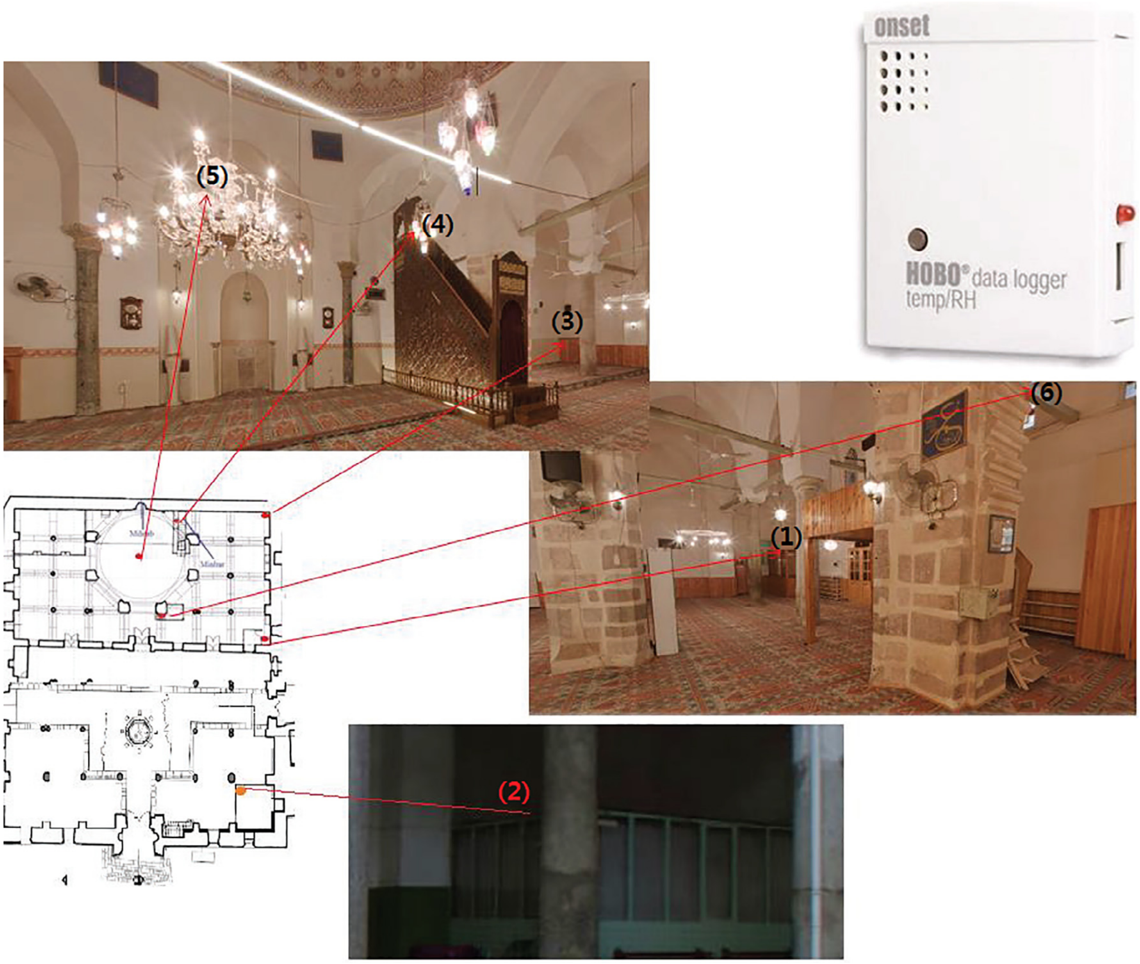

Fig. 5. Locations of dataloggers.

Table 3
Heights of dataloggers.

Datalogger locations	Height (cm)
Above imam* room (1)	230
Next to muezzin** place (6)	440
Right corner of qibla*** wall (3)	130
Mimber**** (4)	410
Chandelier (5)	245
Outside (2)	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 the imam in a mosque.

2.3. Development of a dynamic building energy simulation (BES) model

Architectural drawings of the Ulu Mosque were obtained from the Department of Architectural Restoration of Izmir Institute of Technology. Using input data and drawings, the mosque was modelled by DesignBuilder software [18] including surrounding buildings and trees to evaluate the shading effects and it is called "baseline model". Three inter-connected inner zones (prayer hall) and one outer zone (courtyard) were created by the model. The materials of the walls, windows, doors and domes were selected from the database of the software. The building was positioned as mihrap was directed to Qibla with 171° as the actual building direction. The model was then calibrated by measured T data of a datalogger, which is located on the chandelier, according to the ASHRAE Guideline 14 [16]. The Ulu Mosque was modeled and the model was calibrated to determine thermal comfort conditions at the baseline. The proposed retrofit interventions to improve thermal comfort are simulated by this model. DesignBuilder v.5.0.3.007 (2017) software was chosen for BES modeling because of the integration with Energy Plus which enables to complete the simulation within the DesignBuilder interface [18]. By this way, results were displayed and analyzed effectively in different intervals.

The architectural drawing of the mosque was transferred to the software by AutoCAD LT 2008 (2017) [19]. Two-dimensional "dwg." data was scaled and transformed into"dxf." to draw model into DesignBuilder with higher accuracy.

Afterward, the two-dimensional file was called up with DesignBuilder software. Height and thickness values were uploaded to the software and the mosque was modeled in three dimensions with building materials, construction technology, number of users, occupancy schedule, window and door components. Giving the fact that the thicknesses of the walls were different, they were fixed by keeping the volume as constant as possible for modelling. Absolutely, historical buildings such as Ulu Mosque are generally characterized by a complex geometry which include complicated shapes of openings such as windows and doors. Square and rectangular shapes of openings can be easily modelled with the DesignBuilder [18]. To this aim, openings with complex shape were split in several smaller pieces with simplified shape such as discussed in detail in [20]. In baseline model, doors and windows were modelled as open during prayer times in summer season. Otherwise, they were modelled as closed.

The developed model was then calibrated by measured T data of datalogger which is located on the chandelier in order to match the behavior of the model and the building. First, indoor and outdoor temperature were measured for the desired time interval. Secondly, the measured T data were integrated with the weather data. Then, the building was modelled and the simulation was run. Simulated results were compared with measured values. In the ASHRAE Guideline 14, 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 [16]. If the simulation results are within the limits which are specified in the ASHRAE Guideline 14, the model is assumed as calibrated. If not, the parameters of the BES model causing the discrepancy are identified and are tuned until the simulation results are within the error limits. 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 were used to obtain error range between simulated and measured data, and calculated by Eqns 1, 2 and 3 [16].

$$\mathrm{MBE} = \frac{\sum_{i=1}^{n}|s_i - o_i|}{n}$$

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

$$\mathrm{CV(RMSE)} = \frac{RMSE}{A}$$

where A means the average of measured values and n is the number of observation while s_i and o_i represent simulated and observed values of i^{th} data, respectively.

2.4. Thermal comfort analysis

Following the calibration period, PMV /PPD method was used to determine thermal comfort of the prayers according to ASHRAE Guideline 14 [16]. Indoor environment conditions were investigated to understand if the conditions meet the recommended threshold values specified in EN ISO 7730 [21] for the occupants. Clothing insulation were calculated using clo values from [21] and metabolic rate were taken from [21] and given for each season in Table 4.

If thermal comfort was not achieved at the base case, various retroffitting strategies were proposed and simulated to improve the thermal comfort of prayers. It is worth to note that all retrofitting strategies were proposed considering historical value of the building.

2.5. Retrofitting strategies

The main aim of proposing retrofitting scenarios was to improve thermal comfort of the prayers in the mosque. The developed scenarios were classified as passive and active retrofitting scenarios. The aim of passive retrofitting scenarios is to achieve thermal comfort without consuming any energy source such as electricity or natural gas [22]. Examples of passive strategies are changing single-glazing windows with double-glazing and low emissivity glass, night-time ventilation, roof and wall insulation while. In the study, four passive retrofitting strategies, namely, windows with double/low emissivity glazing, night-time ventilation, roof insulation, and wall insulation were developed (Table 5).

Low-emissivity glass had 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 insulation to reduce heat transfer from the warm pane to the cold pane. It is worth to remind that, in baseline model, doors and windows were modelled as open during prayer times only in summer season. Otherwise, they were modelled as closed. On the other hand, nighttime ventilation strategy was used in summer season by opening all windows from 09:00p.m. to 06:00 a.m. from May to October.

Active retrofitting strategies proposed in the study were implementing underfloor heating system, electric radiator and split type air-conditioner. Proposed systems were operated in two different schedules: intermittent (Table 6) and continuous (5:00–20:00).

Heating season was considered as January, February, March, April, November and December where PPD level reached to 50%. Set point temperature in the mosque during heating season was fixed as 22 °C. The active and passive scenarios were simulated using calibrated model, then PMV and PPD values were obtained for each case.

It is worth to note that, for split-type air-conditioner, the cooling and heating were selected as electricity from grid in the fuel section. Heating and cooling capacities are given to the BES program (COP of 2.2). Then, operation schedule is added. For intermittent operation schedule, the split-type air conditioner is operated for 5 h a day (1 h before prayer time).

The DesignBuilder software has no such underfloor heating system in its library. Therefore, "heating elements that comprise water fed tubular systems embedded within the floor construction" is chosen for the study. In addition, application of the

Table 4
Clothing insulation and metabolic rate for prayer.

Mid-day prayer, afternoon prayer, after-sunset prayer, night prayer				Dawn-prayer			
Seasons	Month	Total clothing insulation* (clo)	Metabolic rate** (W/m²)	Seasons	Month	Total clothing insulation* (clo)	Metabolic rate** (W/m²)
Summer	June July August	0.49	70	Summer	June July August	0.49	70
Spring and Autumn	April May September October	1.03	70	Spring and Autumn	April May September October	1.28	70
Fall	November December January February March	1.28	70	Fall	November December January February March	1.48	70

Table 5
Physical properties of baseline model and retrofitting scenarios.

Windows with double/low emissivity glazing			Night-time ventilation	Roof insulation			Wall insulation		
Physical Properties	**Baseline Model**	**Retrofitting**		Physical Properties	**Baseline Model**	**Retrofitting**	Physical Properties	**Baseline Model**	**Retrofitting**
Glazing type	Clear single	Double	By opening the windows from 09:00 p.m. to 06:00 a.m. from May to October.	Material Name	-	The khorasan mortar	Material Name	-	Wood fiber board and wool
Thickness (mm)	6	3		Thicknesses (mm)	-	25	Thicknesses (mm)	-	180
SHGC (Solar Heat Gain Coefficient)	0.819	0.697		U value (W/m^2K)	-	1.963	U value (W/m^2K)	-	0.27
Direct solar transmission	0.775	0.633							
Light transmission	0.881	0.771							
Gap	-	13 mm air							
U value (W/m^2K)	5.778	2.253							

Table 6
Operating schedules of active retrofitting scenarios.

Operating schedule		
Heating type	Intermittent	Continuous
Underfloor heating	Average 6 h shown in details at Table 8	05:00–20:00
Electric radiator	5 h a day (1 h before prayer time)	
Split type air-conditioner	5 h a day (30 min before prayer times and 30 min during prayer times)	

underfloor heating system requires an insulation layer to the ground (with a U value of 0.130). For underfloor heated system, the floor constructions are modelled as an internal source in the BES program. Thus, the floors are converted to the heated floors. Finally, the qualification of the underfloor heated system are given to the program as a local HVAC system template. For intermittent operation schedule, the underfloor heating system is operated for 6 h a day. It is worth to remind that for continuous operation, both system was operated from 05:00–20:00 (Table 6).

Besides thermal comfort analysis, the effect of retrofit interventions on heritage value of the mosque was also evaluated to find the most appropriate solutions for the components of building's envelope based on EN 16,883 "Conservation of cultural heritage - Guidelines for improving the energy performance of historic buildings" [15]. Finally, the results were compared with the baseline model concerning four measures: heritage value protection, thermal comfort, energy consumption and energy cost.

3. Results and Dıscussıons

Fig. 6 shows the BES model of the Ulu Mosque developed by DesignBuilder v.5.0.3.007 (2017) software. As a first step, the baseline model was developed in DesignBuilder by using input data and architectural drawings. It is worth to note that the mosque was modeled with surrounding buildings and trees to evaluate the shading effects. Then, the BES model was calibrated according to ASHRAE Guideline 14 [16]. Afterwards, using the calibrated model, thermal comfort analysis and retrofit scenarios were developed

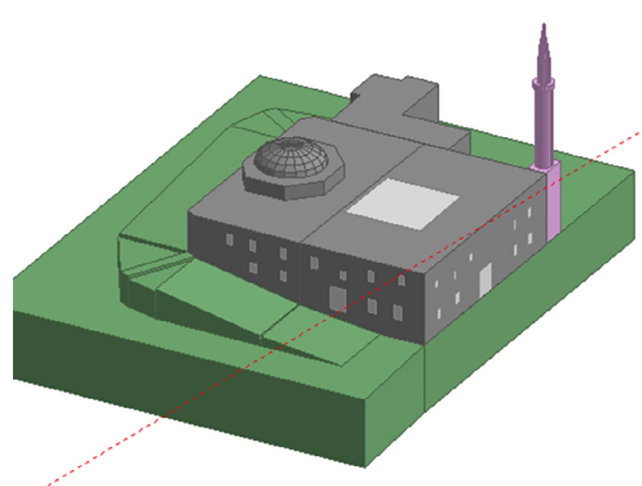

Fig. 6. BES model of the Ulu Mosque.

and simulated. Simulation results were evaluated based on thermal comfort, energy consumption and risk on cultural heritage.

3.1. Measurements

A measurement campaign was conducted between April 4th, 2016 and March 11th, 2018 with six dataloggers. Thermal condition of the mosque was highly influenced by the outdoor weather conditions since there was no heating/cooling system in the mosque. Therefore, collection of outdoor T and RH data were as significant as indoor data.

3.1.1. Outdoor measurements

Fig. 7 exhibits hourly outdoor T and RH data during measurement period (almost 2 years). Outdoor T range was encountered as 1.1–38.6 °C with an average of 20 °C while RH varied between 15% and 100% with an average of 60.8%.

3.1.2. Indoor measurements

The daily T data collected by five dataloggers in the prayer hall are given in Fig. 8. It is worth to say that the temperature at muezzin place is generally lower than other locations. The RH values are recorded as lowest with an average of 14% in right corner of qible wall. On the other hand, the highest average RH values are at above imam room with a 26% RH.

3.2. Dynamic building energy simulation (BES) model results

Hourly measurements were used in the calibration and calculated error values for each zone are given in Table 7. In ASHRAE Guideline 14, the upper limits for MBE and CV(RMSE) in hourly calibration process are defined as ± 10% and 30%, respectively [16]. The results depicted that all MBE and CV(RMSE) values were within the limits. Fig. 9 depicts measured and simulated T values of prayer hall as an example.

The BES model is calibrated with measured T data of a datalogger which is located on the chandelier. Sensor location is a critical factor for achieving better results in the calibration of the BES model. It is worth to remind that the sensor locations in this study are chosen high enough to prevent human interaction and vandalism of theft. Therefore, in order to highlight how the sensor locations affect the vertical temperature difference, the comparison of the hourly temperatures between the chandelier (+2.45 m) and ground level (+0.4 m) dataloggers is represented in Fig. 10. According to the ASHRAE 55 [23], vertical air temperature difference between at head level and the air temperature at ankle level should not exceed 3 °C. In the figure, the dashed black line shows the vertical temperature difference limit from the ground level according to the ASHRAE 55 [23]. The figure indicates that vertical temperature difference between the chandelier and ground level never exceeds 3 °C, thus, the measurement can be used for the calibration.

3.3. Thermal comfort results of the baseline model

Once the calibration was completed, energy consumption of the mosque and thermal comfort indices of the prayers were obtained with the help of DesignBuilder software. Then, the data were separated with respect to the prayer times. It is worth to remind that mean monthly PMV and PPD values were taken from DesignBuilder, were calculated according to ISO 7730 [21]. Based on the calculation of PMV values on prayer times, occupants of the mosque generally felt cool in winter and almost neutral in summer. In summer season, the PMV value was found between −0.57 and 0.33 (Fig. 11).

The PPD values are exhibited in Fig. 12, indicates that the prayers were not satisfied during the winter season. The highest dissatisfaction level was encountered as 55.3% in January during mid-day prayer. From December to March, the lowest PPD was obtained during dawn prayer times compared to the other prayer times in the same month since prayers preferred thick clothes. Although PPD started to decrease in March, the results were still outside the threshold limits. However, PPD values were in acceptable range between April and October. In addition, May had lowest PPD as 5.4% during dawn prayer times. Occupants felt comfortable between May and October since PPD was below 15% on these months.

3.4. Thermal comfort results of retrofitting strategies

According to the baseline model results, prayers were not sufficient with their thermal environment in winter. Thus, various retrofitting scenarios were developed in order to increase thermal comfort of prayers during winter.

3.4.1. Passive retrofitting strategies

The PPD levels of all passive retrofit scenarios for winter months were presented in Fig. 13.

Implementing the double-glazed windows with low emissivity glass to the mosque, PPD decreases by 0.5% compared to baseline model (Fig. 13). Night-time ventilation was a cost-effective approach by opening the windows at night time to cool inside the mosque during summer when the outdoor temperature was lower than indoor temperature. The results showed that night-time ventilation helped to decrease T around 1 °C while increasing RH by 4%. On the other hand, night-time ventilation increased PPD around 5% which results discomfort for prayers in early morning hours during dawn prayer in summer. Night-time ventilation had no effect to the other prayer times.

An insulation material for the dome and roof of the prayer hall was presented to decrease heat transfer and increase indoor T for the cold season. The khorasan mortar with a 2.5 cm thickness was used as insulation material and an overall heat transfer coefficient was obtained as 1.963 W/m^2K [24].The results show that PPD level was decreased barely around 0.5–1% by adding khorasan mortar to the mosque.

External wall insulation was applied to the walls to increase thermal comfort in winter season. Wood fiber board (9 cm) and wool (9 cm) insulation were applied on the stone walls of the prayer hall. Then, a hemp-lime render was applied as two 10 mm coats which could be colored [24]. With insulation, overall heat transfer coefficient of the walls was decreased to 0.273 W/m^2K. Wall insulation affected thermal comfort of prayers via increasing PPD level approximately 3% in winter while maximum increase was encountered as 3.45% in December during night prayers. The PPD had minor decrease only in March during afternoon, after sun-set and night prayers as 0.06, 0.15 and 0.19%, respectively. It seems like without any heating system, wall insulation had no benefit for the Ulu Mosque. The reason could the high thermal mass of the Ulu Mosque, therefore, wall insulation had poor thermal stability, additionally, insulation acts as a thermal barrier if there is no heating system. The insulation could change the indoor temperature more quickly due to the poor thermal stability for a naturally ventilated building. Therefore, for this study, wall insulation could be a cause of fluctuation on indoor temperature. If a heating system is installed, insulation could cause a decrease in energy consumption while maintaining thermal comfort.

Possible contributions of wall insulation with a heating/cooling system will be evaluated in active retrofit strategies.

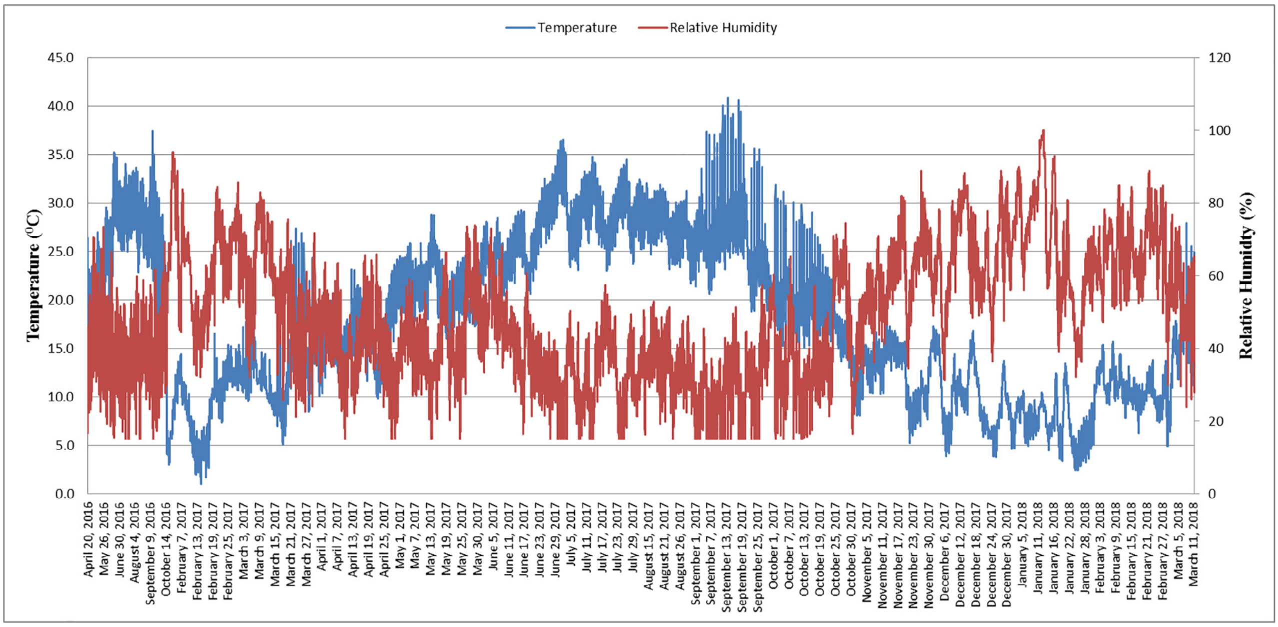

Fig. 7. Hourly outdoor T and RH measurements results.

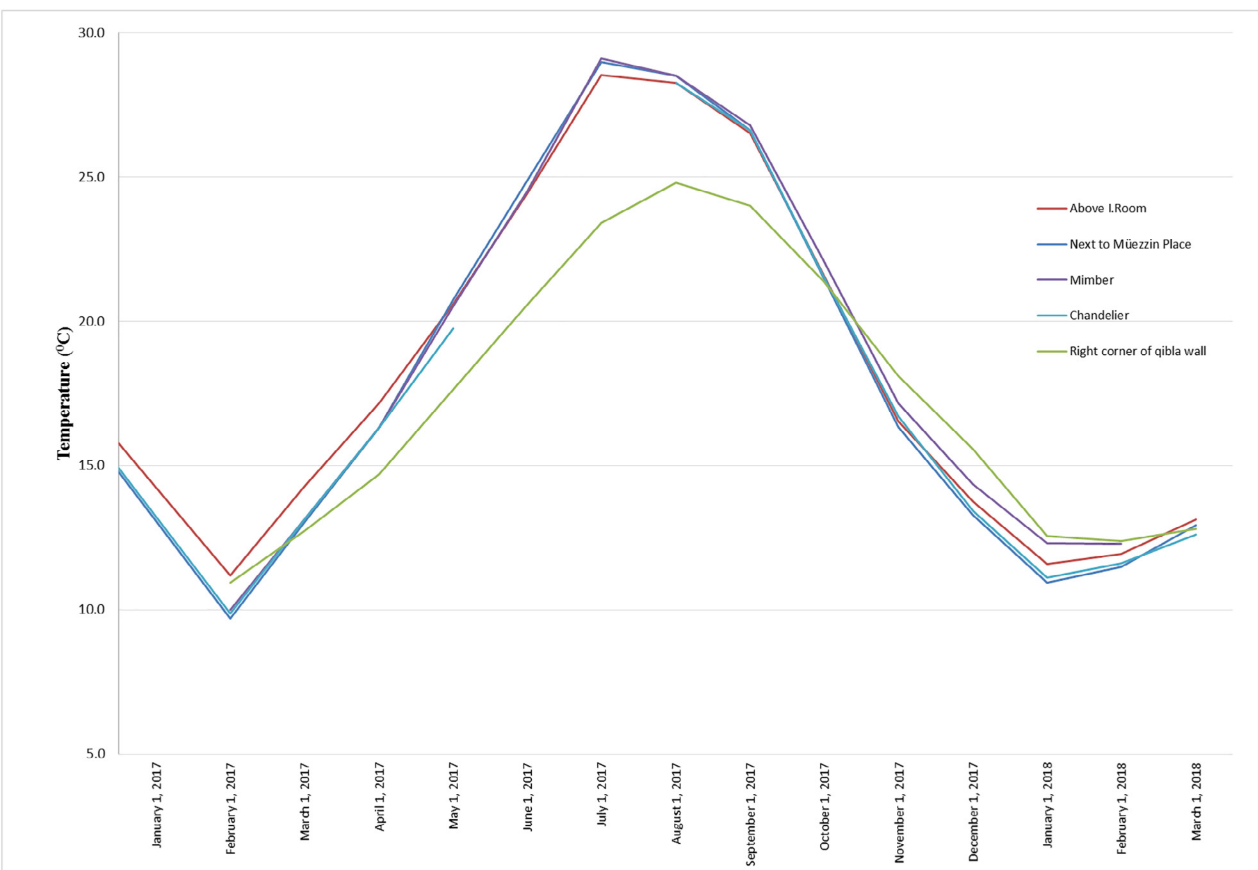

Fig. 8. Comparison of daily indoor T data.

3.4.2. Active retrofitting strategies

Figs. 14, 15 and 16 depict comparison of PPD levels for active retrofitting strategies, separately.

It is worth to remind that mosques have high ceilings, large domes and volumes. Since the prayers stand up and sit during prayers without shoes, floor heating would be the best solution to obtain better thermal comfort in mosques [7]. Intermittent operating hours of the system were given in Table 8.

In addition to intermittent operating schedule, underfloor heating system for continuous operation was also applied to the

Table 7
Calculated error values for the BES model.

Months	MBE (%)	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 [16]	**±10**	**30**

mosque. For continous operation, it can be observed that PPD levels decreased to 5.9% while maximum PPD level was observed in October during dawn prayer. On the other hand, minimum PPD level was found in December during night prayer.

With intermittent operation, maximum and minimum PPD levels were observed in February during afternoon prayer and in December during dawn prayer, respectively (Fig. 16). Apart from February's afternoon prayer, PPD values were quite similar (<15%) compared to the continuous heating strategy. Intermittent operation addition to the wall insulation gives maximum PPD level as 22.8% in January during mid-day prayer and minimum PPD level as 5.37% in March during night prayer.

Convective and radiant heat transfer from the source to the environment in electric radiator model was simulated by the model. Portable electric radiators were found as easy to install and not harmful to the structure of the building.

Thermal comfort analysis of the system showed that 95% of the occupants were satisfied with the thermal conditions of the mosque with continuous operation. Maximum PPD value was observed as 7.25% in October during dawn prayer while minimum PPD value was 5.15% in March during night prayer for continous operation schedule (Fig. 14). With intermittent operation, maximum and minimum PPD values were seen as 22.1% in February and as 5.22% in November for after-sunset prayer, respectively. Apart from February after-sunset prayer, PPD values were quite similar (<15%) compared to the continuous heating strategy. With intermittent heating and wall insulation together, maximum PPD was 16% in February during after sun-set prayer and minimum PPD was 5.3% in November during night prayer. Apart from February after-sunset prayer, all calculated PPD values were below 15%.

The PPD values for heating with split type air-conditioner were compared with baseline model. The PPD level with continuous heating for all months was around 5%. In Fig. 13, intermittent operation with wall insulation were also added to the options. With intermittent operation, maximum PPD level was observed as 23% in January during afternoon prayer. On the other hand, minimum PPD level was encountered in November as 5.27% during dawn prayer. The PPD level was above 15% in December during mid-day, in January during afternoon and night prayers, in February during afternoon and after-sunset prayer. Rest of the prayer times during the year, the PPD levels were below 15%. With intermittent opearation + wall insulation, maximum PPD level was observed as 20.7% in December during mid-day prayer while minimum PPD level was 5.6% in November during dawn prayer. The PPD level was above 15% only in December during mid-day, January and February during afternoon prayers. Advantages of split type air-conditioners were found as fast feedback time, instant relief for the occupants and easy installation.

3.4.3. Comparison of retrofitting strategies

According to Fig. 13, changing windows with double glazing and low emissivity glass, night-time ventilation and roof insulation had no effect on thermal comfort. Insulation of the walls had negative effect on thermal comfort if there was no heating system. If a heating system was installed, insulation could cause a decrease in energy consumption while maintaining thermal comfort. When insulation is added to walls, the energy saving rates for portable electric radiator, split type air-conditioner and underfloor heating systems were 18.4%, 11.8% and 23.2%, respectively as represented in Fig. 17.

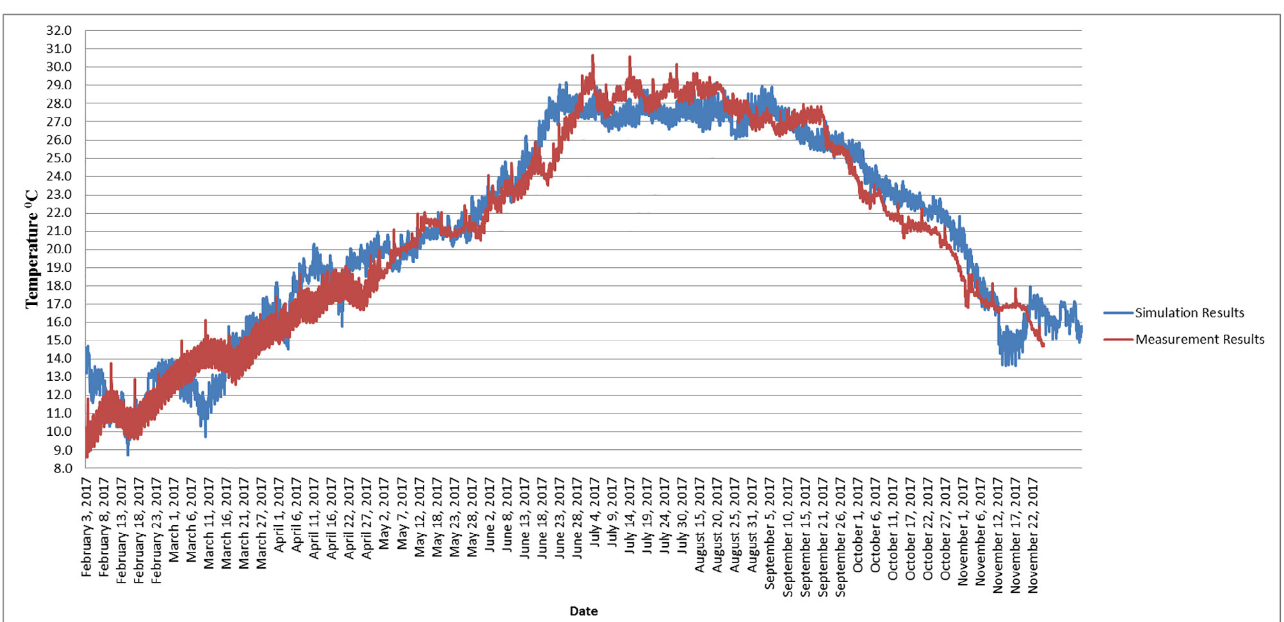

Fig. 9. Hourly measured and simulated T data of prayer hall.

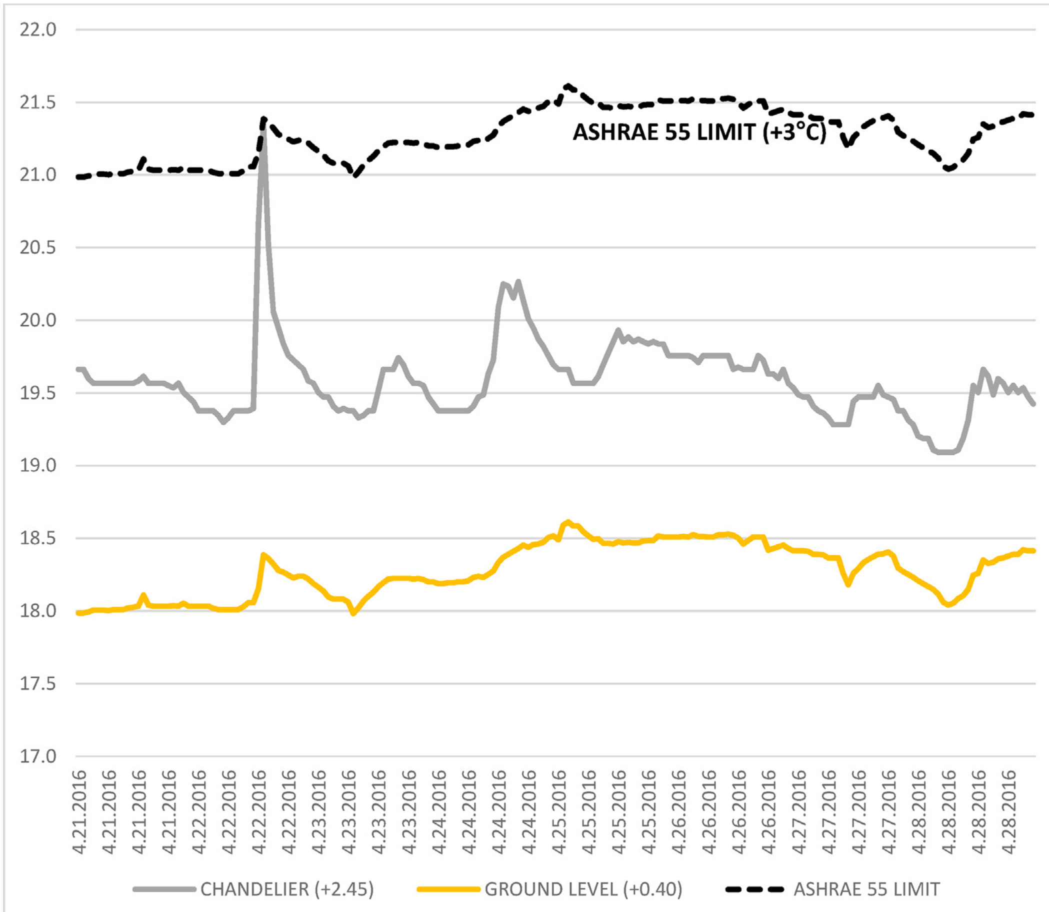

Fig. 10. Comparison of hourly temperatures measured by the chandelier and ground level dataloggers.

The PPD levels of active retrofitting strategies and baseline model were shown in Fig. 18 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 was considered as "acceptable" by ISO 7730 [21]. Even though PPD level of baseline model was below 15% for the autumn, active retrofitting strategies enhanced thermal comfort.

Comparison of annual energy consumption of active retrofitting strategies for winter and autumn seasons were shown Fig. 19. Significant reduction in annual energy consumption of the Ulu Mosque could be obtained while maintaining thermal comfort when intermittently operated heating system was properly designed. Compared to the continuous operating schedule, intermittent operation decreases annual energy consumption as approximately 46.9% for portable electric radiator, 56.6% for split type air-conditioner and 26.9% for underfloor heating system.

3.5. Risk assessment of retrofitting strategies

A risk analysis was conducted for the Ulu Mosque including thirteen retrofitting strategies. Retrofitting scenarios were evaluated via four measures, namely, heritage value protection, thermal comfort, energy consumption and energy cost according to EN 16,883 [15] as shown in Table 9.

Thermal comfort assessment of retrofit scenarios was transferred to Table 9. Based on heritage value protection measure, window change and roof insulation were accepted as having 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. Portable electric radiators could be placed away from sensitive surfaces or objects not to cause damage as particle deposition. Nighttime ventilation had no any harmful effect on cultural heritage [25]. Even though particle deposition on surfaces may be inconspicuous with underfloor heating, the impact on the floor was considerable. Therefore, it was evaluated as risky [25].

Annual energy consumption of heating strategies were presented in Fig. 20. Split type air-conditioner had the highest energy consumption while underfloor heating consumes lowest. If air-conditioner system was operated with wall insulation retrofitting and intermittent heating schedule, energy consumption decreased dramatically from 215.1 kWh to 82.2 kWh. Whereas the electric radiator was used with wall insulation and operated intermittently, energy consumption decreased from 203.1 kWh to 88.3 kWh.

All in all, intermittent operating strategy was 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 decreased energy consumption by 12% for split type air-conditioner system, 18% for electric radiators and 27%, for underfloor heating system, it could not be applied due to the high risk on cultural heritage.

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

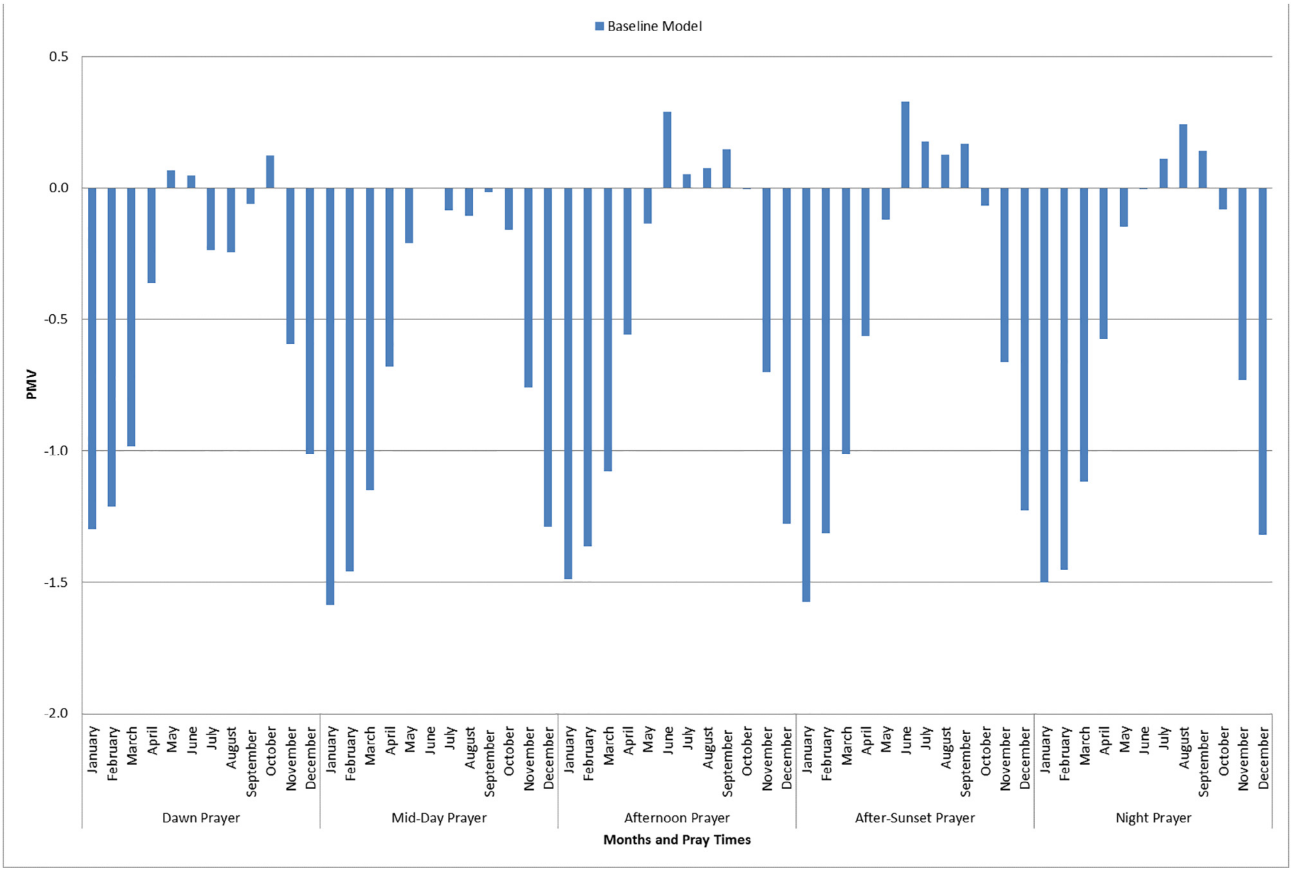

Fig. 11. Mean monthly PMV values obtained from baseline model.

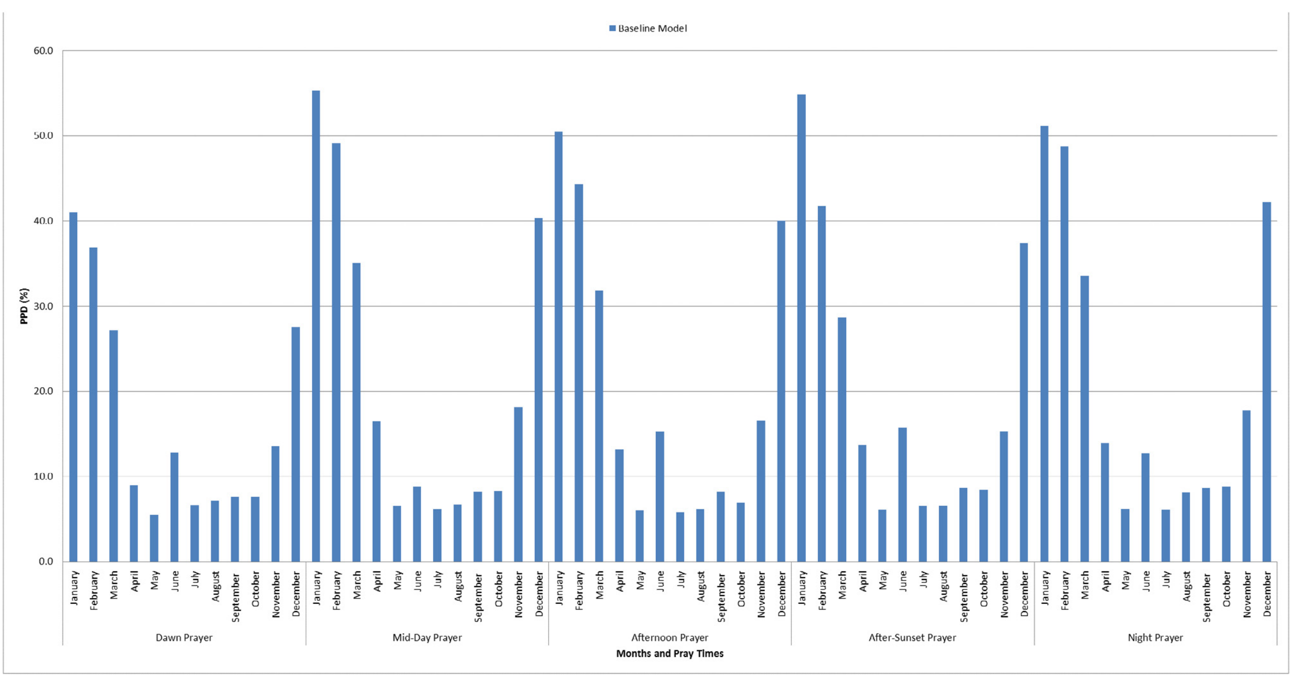

Fig. 12. Mean monthly PPD levels of prayers.

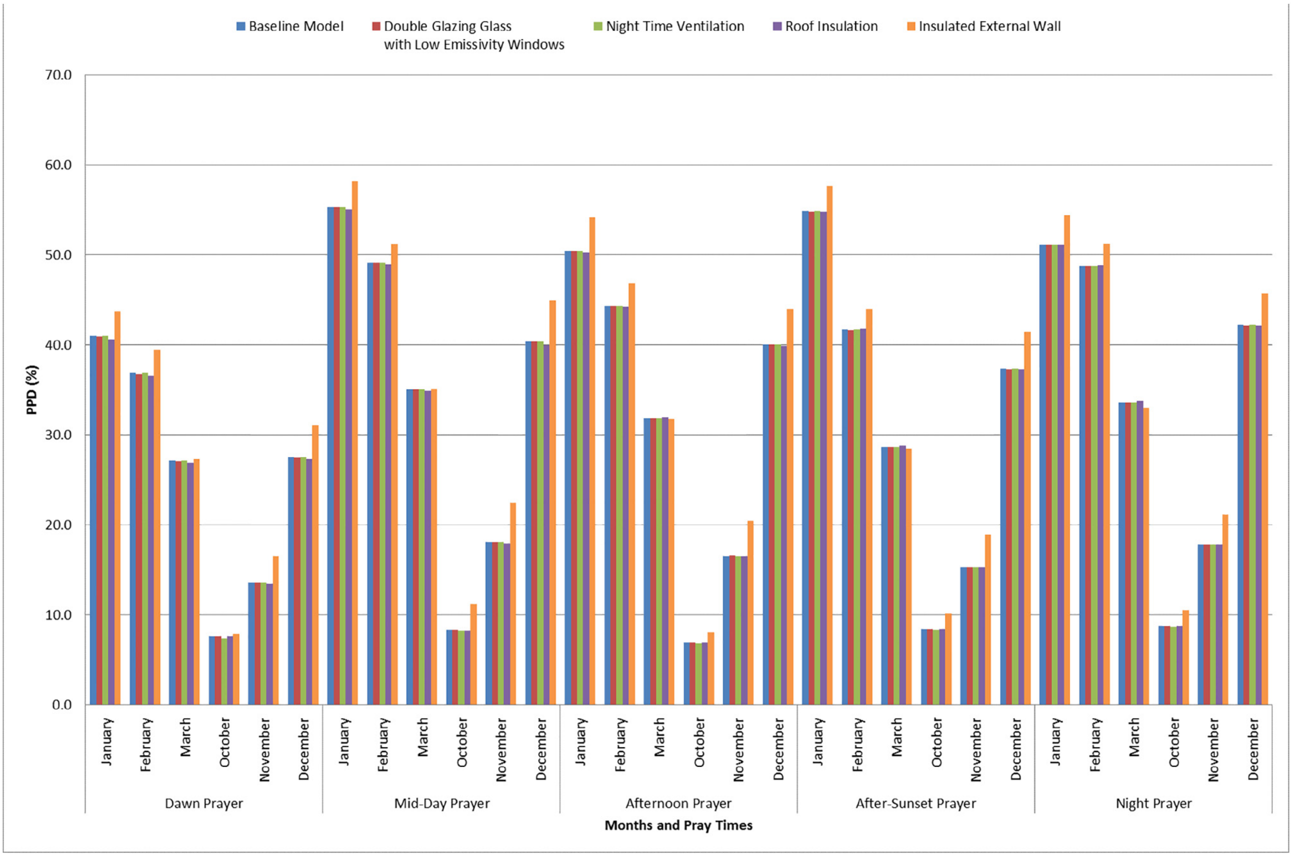

Fig. 13. Comparison of passive retrofitting strategies with baseline model for winter.

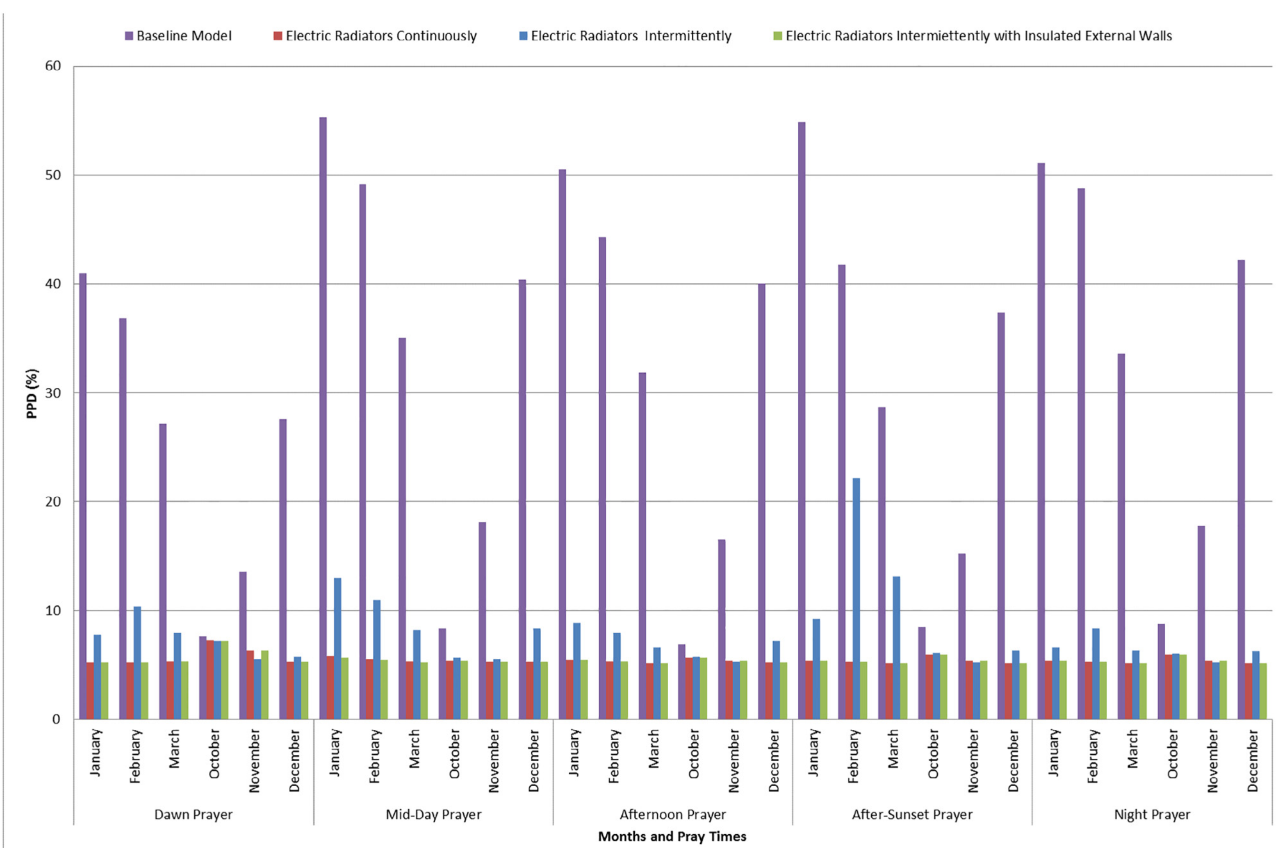

Fig. 14. Comparison of PPD levels for active retrofit scenarios (Part A).

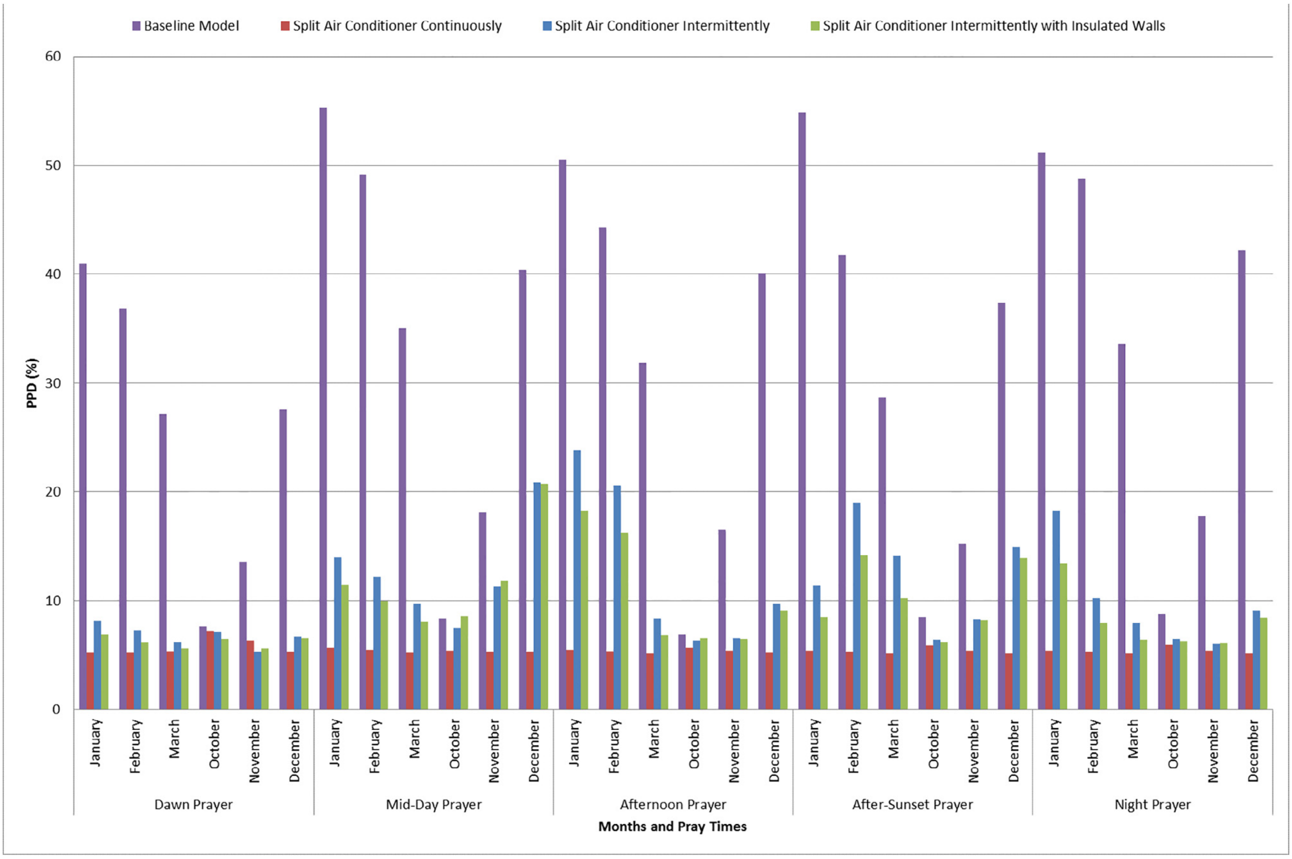

Fig. 15. Comparison of PPD levels for active retrofit scenarios (Part B).

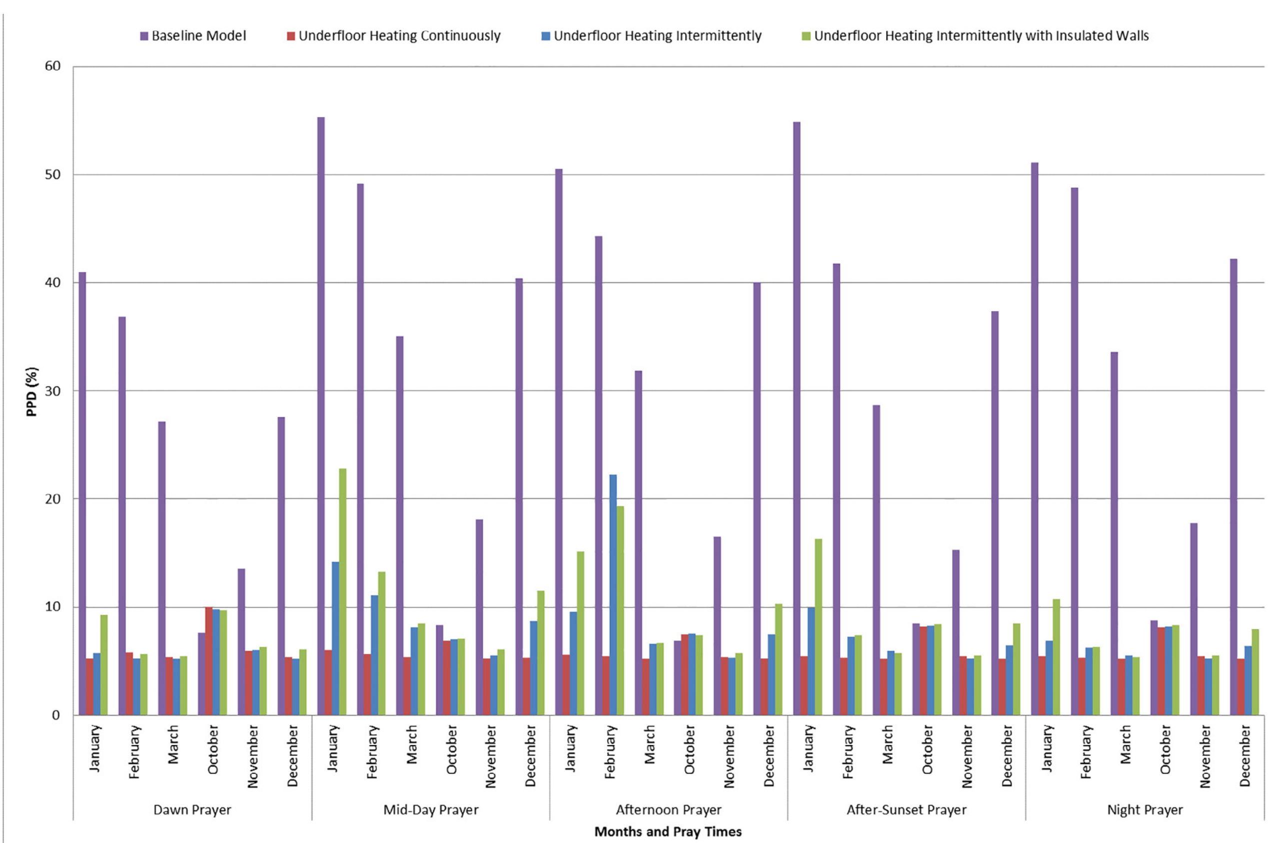

Fig. 16. Comparison of PPD levels for active retrofit scenarios (Part C).

Table 8
Intermittent operating schedules of underfloor HEATİNG.

	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					

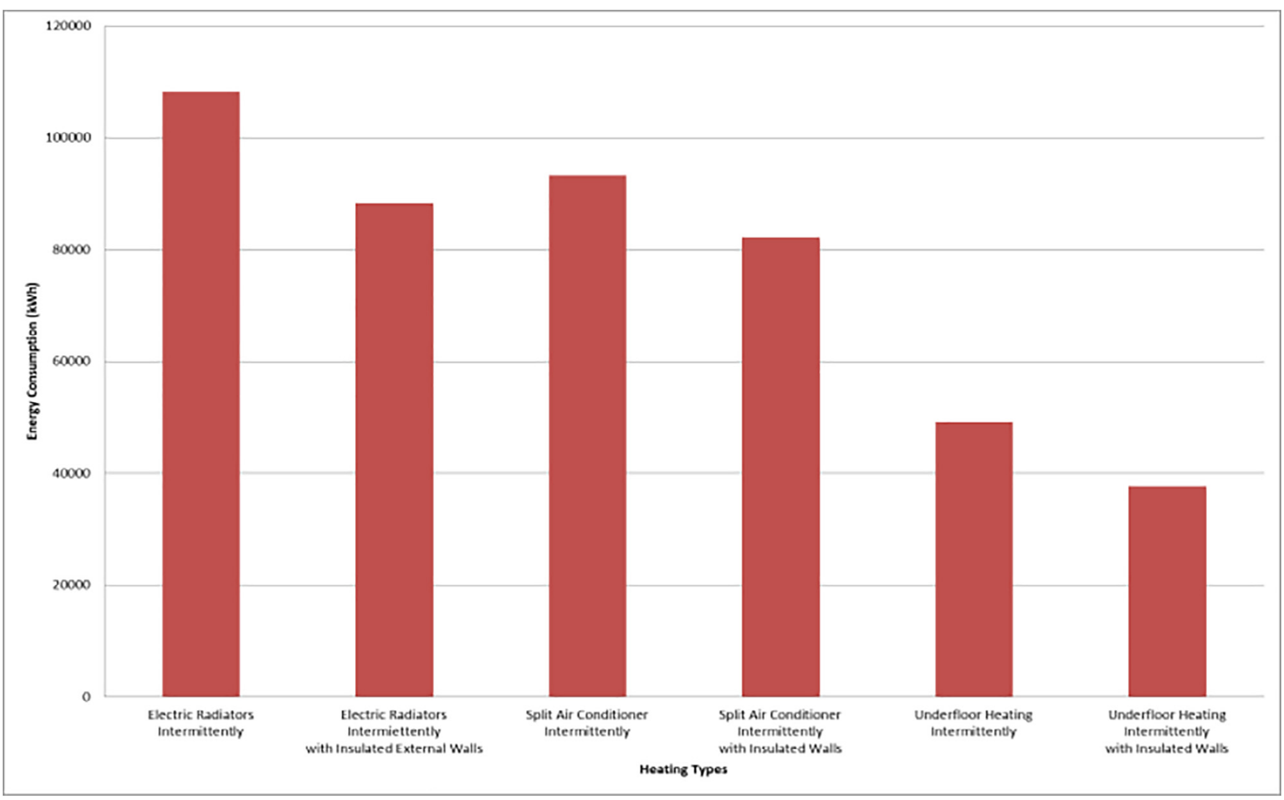

Fig. 17. Comparison of energy consumption for active retrofitting scenarios and additional insulation.

4. Conclusions

Thermal comfort analysis was conducted during prayer times at a historical and naturally ventilated mosque, the Ulu Mosque which is located in Manisa, Turkey. On-site indoor and outdoor T and RH measurements were taken for almost two years. The mosque was then modelled by DesignBuilder software and the model was calibrated according to ASHRAE Guideline 14. Baseline model results were concentrated on prayer times only and it showed that thermal comfort of the prayers were not satisfied at certain periods during prayer times. 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 the EN 16,883 to analyze the risks in terms of cultural heritage.

Passive retrofitting scenarios (changing windows with double glazing and low emissivity glass, nighttime ventilation and roof insulation) had no effect on thermal comfort. Wall insulation had negatively affected thermal comfort if there was no heating sys-

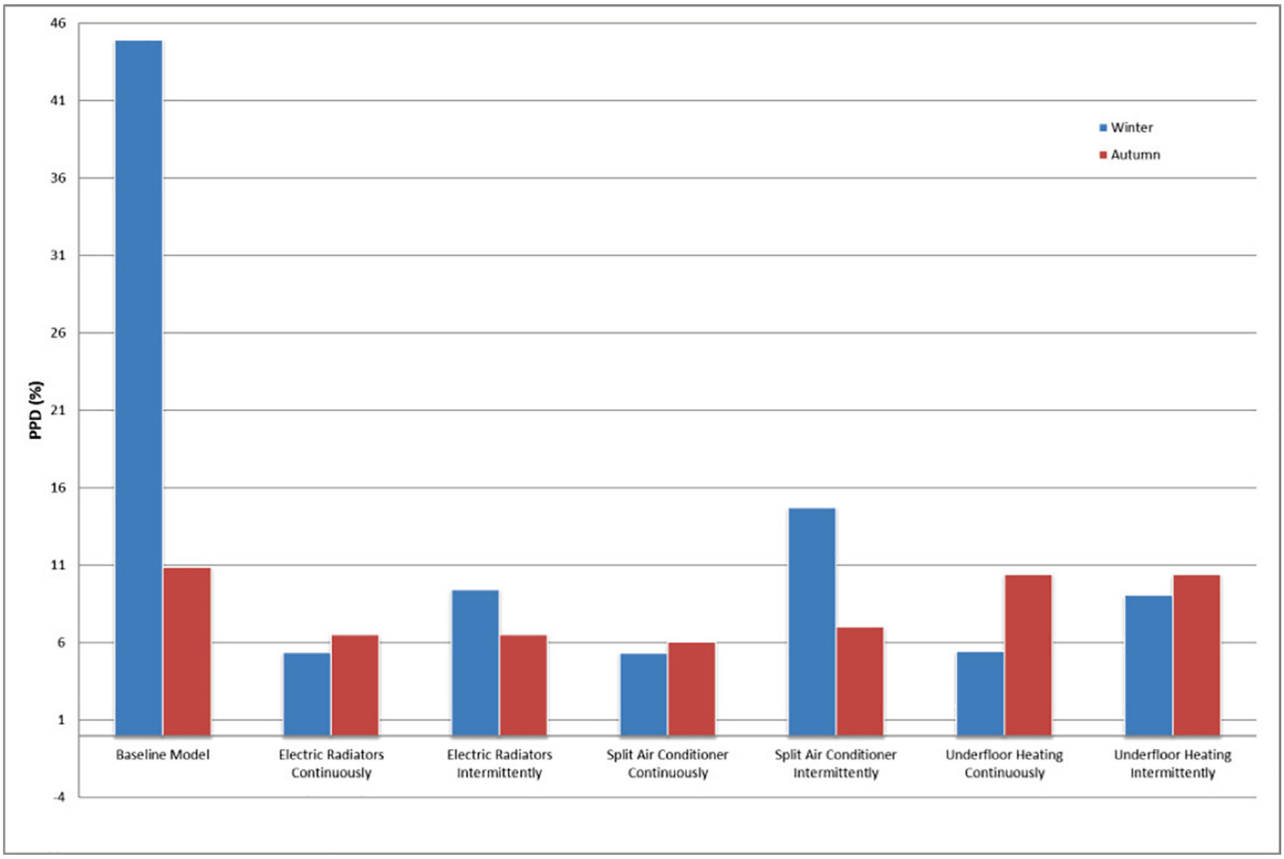

Fig. 18. Comparison of PPDs for winter and autumn.

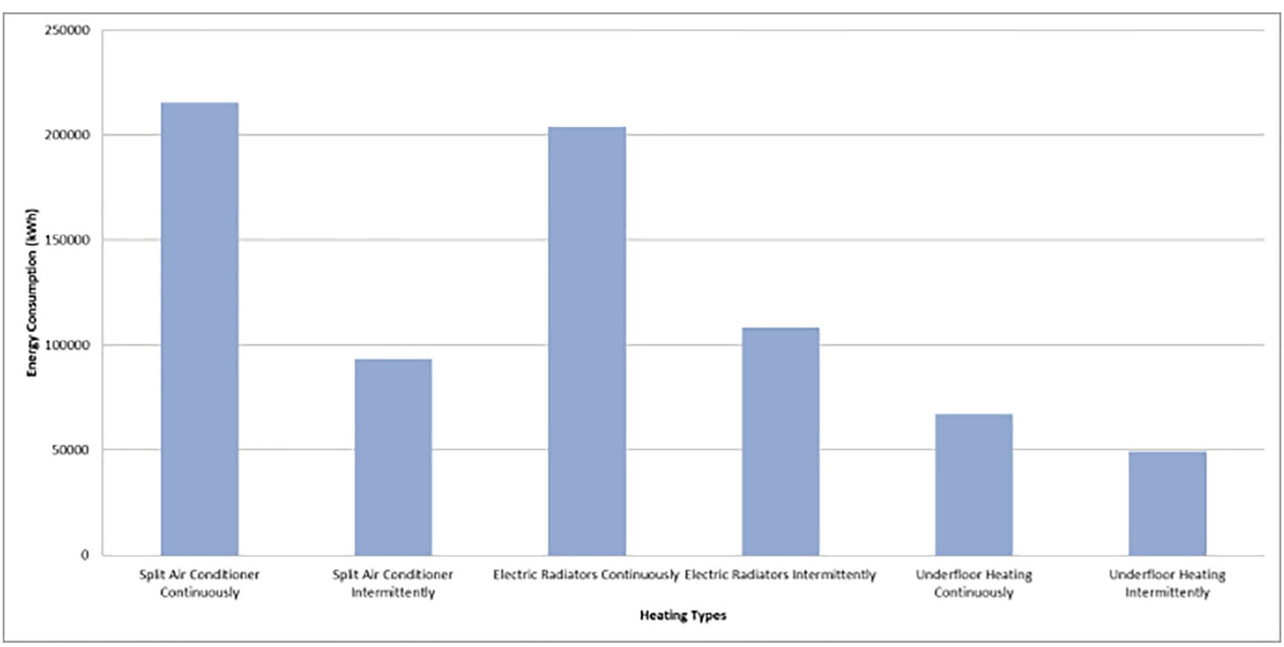

Fig. 19. Comparison of annual energy consumption of active retrofitting scenarios.

tem. If a heating system was installed, insulation could decrease energy consumption while thermal comfort is maintained. On the other hand, active retrofitting strategies (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 was applied, all the retrofitting strategies had significant reduction in annual energy consumption while maintaining thermal comfort comparing to continuous operation. These results were also compatible with the literature [8–9,14]. Furthermore, the retrofitting

Table 9
Risk assessment according to EN 16883 [15].

Type of Retrofit	Heritage Value Protection	Thermal Comfort	Energy Consumption	Energy Cost
Windows with Double Glazing with Low Emissivity Glass	Low Risk	Neutral	Neutral	Neutral
Night Time Ventilation	Neutral	Neutral	Neutral	Neutral
Roof Insulation	Low Risk	Neutral	Neutral	Neutral
Insulated External Wall	High Risk	Low Risk	Neutral	Neutral
Electric Radiators Continuously	Neutral	High Benefit	High Risk	High Risk
Electric Radiators Intermittently	Neutral	High Benefit	Low Risk	High Risk
Electric Radiators Intermittently with Insulated External Walls	High Risk	High Benefit	Low Risk	High Risk
Split Air Conditioner Continuously	Low Risk	High Benefit	High Risk	High Risk
Split Air Conditioner Intermittently	Low Risk	High Benefit	Low Risk	High Risk
Split Air Conditioner Intermittently with Insulated Walls	High Risk	High Benefit	Low Risk	High Risk
Underfloor Heating Continuously	Low Risk	High Benefit	High Risk	Low Risk
Underfloor Heating Intermittently	Low Risk	High Benefit	Low Risk	Low Risk
Underfloor Heating Intermittently with Insulated Walls	High Risk	High Benefit	Low Risk	Low Risk

Retrofit Impact Assessment*

***Assessment Scale**: High Risk | Low Risk | Neutral | Low Benefit | High Benefit

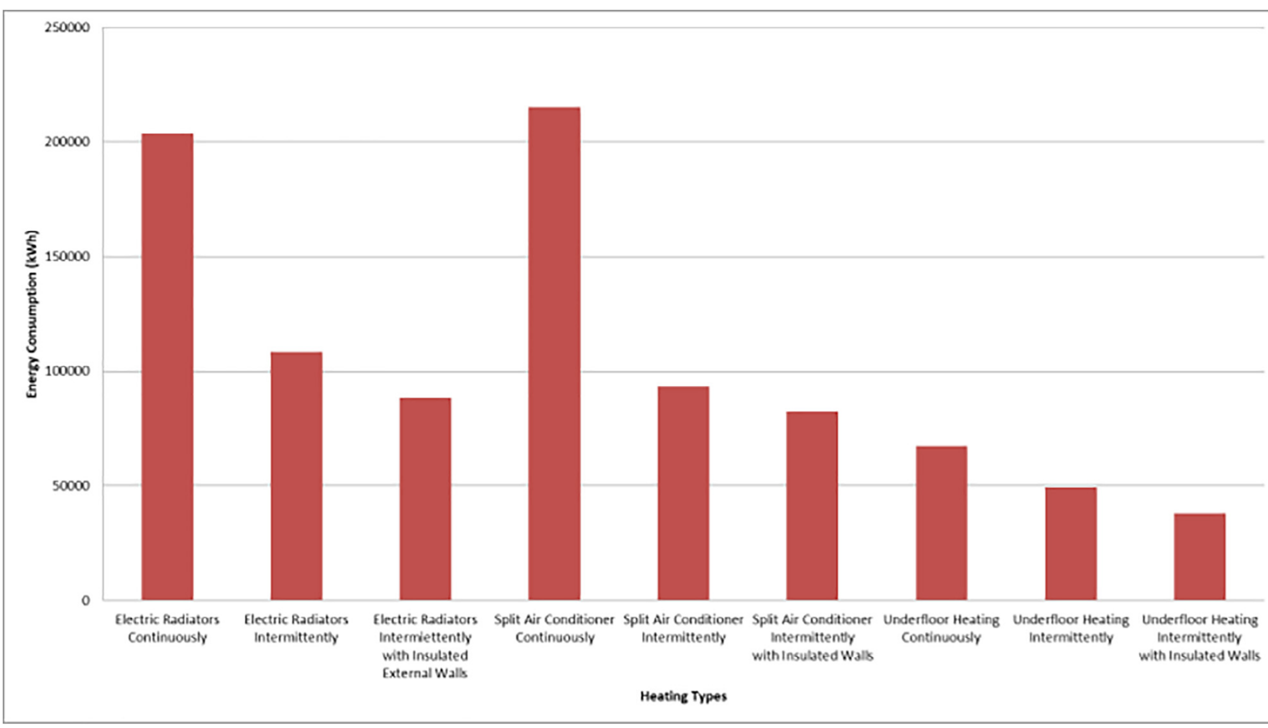

Fig. 20. Comparison of energy consumption data.

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 were limited. Electric radiator heating with intermittent operating schedule was found as the best option to protect cultural heritage, while providing thermal comfort with lower energy consumption.In addition, thermal comfort should 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 was analyzed five times a day with various numbers of worshippers at all prayer times during the year according to the motion of the moon. Furthermore, software like DesignBuilder allows different scenarios to be used in the selection of strategies to be applied in historical buildings. The implementation any of these strategies should be consistent with the heritage value of the building and risk assessments should be done according to the EN 16883 for systematic approach. 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 retrofitting scenario should be supported by laboratory tests. Lastly, owing to the fact that thermal comfort is a situation where each person reacts differently to the same environmental condition, a further thermal comfort survey should be conducted to the prayers to obtain their preferences and compare with the model.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would also like to thank The Directorate General of Foundations, Republic of Turkey for the permission to take measurements at Ulu Mosque. Additionally, many thanks should be given to Izmir Institute of Technology, Department of Architectural Restoration which opens its archives and enables to use measured drawings of the mosque.

References

[1] 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.
[2] A. Webb, Energy retrofits in historic and traditional buildings: A review of problems and methods, Renew. Sustain. Energy Rev. 77 (2017) 748–759.
[3] P. Wu, C. Hsieh, M. Hsua, Using heritage risk maps as an approach to estimating the threat to materials of traditional buildings in Tainan (Taiwan), J. Cult. Heritage 15 (2014) 441–447.
[4] P. Fanger, Thermal Comfort: Analysis and Applications In Environmental Engineering, Mc.Graw-Hill, 1970.
[5] A.B. Atmaca, G.Z. Gedik, Evaluation of mosques in terms of thermal comfort and energy consumption in a temperate-humid climate, Energy Build. 195 (2019) 195–204.
[6] R. Jaafar, E. Khalilb, T. Abou-Deif, Numerical investigations of indoor air quality inside Al-Haram Mosque in Makkah, Procedia Eng. 205 (2017) 4179–4186.
[7] K. Bughrara, Z. Arsan, G. Akkurt, Applying underfloor heating system for improvement of thermal comfort in historic mosques: the case study of Salepçioğlu Mosque, İzmir, Turkey, Energy Proc. 133 (2017) 290–299.
[8] I. Budaiwi, A. Abdou, HVAC system operational strategies for reduced energy consumption in buildings with intermittent occupancy: The case of mosques, Energy Convers. Manage. 73 (2013) 37–50.
[9] N. Al-Thamimi, A. Qahtan, O. Abuelzein, Rear zone for energy efficiency in large mosques in Saudi Arabia, Energy Build. 223 (2020) 110148.
[10] Sayitoglu Taş Ç. (2019). Thermal comfort analysis in historical mosques: Case study of Trabzon Çarşı Mosque, Master Thesis, Avrasya University The Graduate School of Natural and Applied Sciences Architecture and Built Environment Department, Trabzon, Turkey.
[11] T.H. Karyono, E. Sri, J.G. Sulistiawan, Y. Triswanti, Thermal Comfort Studies in Naturally Ventilated Buildings in Jakarta, Indonesia, Buildings 5 (2015) 917–932.
[12] R.C. Vella, F.J.R. Martinez, C. Yousif, D. Gatt, A study of thermal comfort in naturally ventilated churches in a Mediterranean climate, Energy Build. 213 (2020) 109843.
[13] M. Al-Homoud, A. Abdou, I. Budaiwi, Assessment of monitored energy use and thermal comfort conditions in mosques in hot-humid climates, Energy Build. 41 (2009) 607–614.
[14] N. Azmi, M. Kandar, Factors contributing in the design of environmentally sustainable mosques, J. Build. Eng. 23 (2019) 27–37.
[15] EN 16883:2017 Conservation of cultural heritage – Guidelines for improving the energy performance of historic buildings. Brussels, Belgium.
[16] ASHRAE, ASHRAE Guideline 14: Measurement of Energy and Demand Savings, ASHRAE Standards Committee, 2002.
[17] TC Ministry of Culture and Tourism, June 02) Retrieved from http://www.manisakulturturizm.gov.tr/TR,73021/ulu-camii-ve–kulliyesi-manisa-merkez.html, 2017.
[18] DesignBuilder version 6.1.3.008, (2017).
[19] AutoCad 2017 (2017), AutoDesk.
[20] G.G. Akkurt, N. Aste, J. Borderon, A. Buda, M. Calzolari, D. Chung, V. Costanzo, C. Del Pero, G. Evola, H.E. Huerto-Cardenas, F. Leonforte, A. Lo Faro, E. Lucchi, L. Marletta, F. Nocera, V. Prancchi, C. Turhan, Dynamic thermal and hygrometric simulation of historical buildings: Critical factors and possible solutions, Renew. Sustain. Energy Rev. 118 (2020) 109509.
[21] 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.
[22] K. Bughrara, Adaptive thermal comfort analysis of historical mosque: The case study of Salepçioğlu Mosque MSc thesis, IZTECH, İzmir, Turkey, 2016.
[23] ASHRAE Standard 55 (2020), Thermal Environmental Conditions for Human Occupancy, ASHRAE, Atlanta, Geo., USA.
[24] Homebuilding. (2019, May 11). ''External Wall Insulation'' Retrieved from https://www.homebuilding.co.uk/external-wall-insulation/.
[25] EN 15759-1:2011 Conservation of cultural property - Indoor climate - Part 1: Guidelines for heating churches, chapels and other places of worship, CEN, Switzerland.