Thermal Design Optimization of Mosques in Saudi Arabia

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ABSTRACT

Mosques comprise the heart of any Islamic community where people perform their daily and weekly prayers. Special importance is given to Mosques in Saudi Arabia being the site of the two Holly Mosques and where there is a large number of Mosques operating all over the country. Thermal comfort is a very important aspect of Mosques for performing prayers in tranquillity. Optimum thermal design and operation of Mosques is essential to acheive the required thermal comfort throughout the day. Mosques are chracterized by a unique function and operating schedule that are not typical to other types of buildings. Nevertheless, their thermal design and operation have not been studied carefully.

This paper describes the physical and operating characteristics typical for Mosques as well as the results of the thermal optimization of a medium size Mosque in the two hot-dry and hot-humid Saudi Arabian cities of Riyadh and Jeddah utilizing a direct search optimization technique that is coupled to an hourly energy simulation program. It also describes design guidelines for the optimum thermal performance of Mosques in these two cities in addition to other design and operating factors that need to be considered and/or investigated for Mosques in general.

Key Words: Energy conservation, optimization, thermal design, Mosques, Saudi Arabia

التصميم الحراري الأمثل للمساجد في المملكة العربية السعودية

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قسم الهندسة المعمارية

جامعة الملك فهد للبترول والمعادن
الظهران ٣١٢٦١

الخلاصة

يمثل المسجد القلب النابض لأي مجتمع إسلامي حيث يجتمع فيه الناس لأداء فرائضهم اليومية والاسبوعية . والمساجد في المملكة العربية السعودية تتميز بأهمية خاصة كمهبط للرسالة وقبلة للمسلمين حيث الحرمين الشريفين في مكة والمدينة بالإضافة إلى وجود عدد كبير من المساجد في مناطق المملكة المختلفة.

ويمثل الإرتياح الحراري عاملاً مهماً في المسجد حتى يؤدي الناس صلاتهم في راحة وخشوع ، وإن للتصميم الحراري للمسجد وطريقة تشغيله دوراً كبيراً في تحقيق البيئة الداخلية الملائمة للمصلين . وتنفرد المساجد بوظيفة وطريقة تشغيل يومية تميزها عن غيرها من المباني حيث يتم استخدام المساجد وتشغيل أجهزة التكييف فيها خمس مرات متقطعة على مدار اليوم استخداما لايتجاوز الساعة الواحدة في كل صلاة . ومع كل ذلك إلا أن التصميم الحراري للمساجد واستراتيجيات تشغيلها ومدى احتياجاتها من الطاقة لم تلق الدراسة الكافية من قبل المهندسين والباحثين.

يهدف هذا البحث الى التعريف بما يتميز به بناء وتشغيل المسجد وعرض لنتائج أمثلة التصميم الحراري لمسجد متوسط السعة في كل من مدينتي الرياض وجده وذلك عن طريق تطبيق نموذج رياضي بالحاسب الآلي . وينتهي البحث بتقديم توصيات عدة لتحسين الأداء الحراري في تصميم وتشغيل المساجد بالمملكة.

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This paper describes the physical and operating characteristics typical for Mosques as well as the results of the thermal optimization of a medium size Mosque in the two hot-dry and hot-humid Saudi Arabian cities of Riyadh and Jeddah utilizing a direct search optimization technique that is coupled to an hourly energy simulation program. It also describes design guidelines for the optimum thermal performance of Mosques in these two cities in addition to other design and operating factors that need to be considered and/or investigated for Mosques in general.

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INTRODUCTION

Mosques are characterized by having a unique operating schedule compared to other types of buildings. They are usually occupied five intermittent times a day all year round. People usually come to the mosque at different times, and therefore the maximum occupancy is expected to occur during the actual performance of prayer which lasts from about 15 to 20 minutes. After prayer they leave gradually as well. Exceptions to this are weekly Friday prayer and Taraweeh prayer during the nights of the month of Ramadan as well as during other special occasions such as lecturing and similar activities where people tend to stay longer in the Mosque.

Another unique operating characteristic of mosques is that prayer times change following changes in day and night hours over the year. This is different from one locality to another depending on the longitude. Therefore, analysis based on a specific time is not possible. However, this change in prayer times over the year is usually within an hour range especially for peak energy demand periods such as the noon (Duhr) and the afternoon (Asr) prayers. Within a given region of similar time zone, Mosques are operated at the same time. This would have a great impact on the demand for energy particularly at areas with high demand for air-conditioning which frequently coincides with peak energy demand periods.

All of these factors with the importance of thermal comfort for performing prayers in spiritual environment, make the design and operation of Mosques very important to all Muslims. Because they comprise an important sector of buildings in every Muslim community all over the world. However, the subject of research on the thermal design and energy analysis of Mosques, lacks the literature needed by designers, engineers, and operation and maintenance staff involved in this field.

The purpose of this paper is to introduce the subject of thermal design of Mosques. Also it focuses on the selection of the envelope parameters for an optimum thermal performance based on the objective function of minimizing Energy Utilization Index (EUI), Btu/sq. ft.yr (kWh/m^2.yr). A medium size Mosque operating schedule for two hot-dry and hot-humid Saudi Arabian cities is considered. The subject of HVAC operation and the evaluation of various operating strategies for Mosques and its impact on energy consumption and demand will be discussed in a near future paper.

TYPICAL CHARACTERISTICS OF MOSQUES

The typically common design and operation characteristics of Mosques in Saudi Arabia are summarized as follows:

Building	**Characteristic**
Shape	Typically rectangular open space with long axis facing the Holly Kaabah (Qiblah) in the city of Makkah. Typically heigh ceilings, 10-17 ft (3-5 m)
Construction	Usually medium to heavy construction with concrete blocks and reinforced concrete slabs with carpeted floors.
Zoning	Typically one single open space zone for small to medium daily prayer Mosques. Two zones for large Friday prayer Mosques small one for daily prayers and a large zone for Friday prayer.Third zone is for women which could be a partial second floor or a section in the back end of the main prayer area. An ablution (Whodow) area and storage are usually attached to the Mosque (normally unconditioned).
HVAC type	Varies from window type A/C units especially for small size Mosques, split DX units to central systems especially for large size (Friday) Mosques
Lighting	Task level is at the floor where people sit and read Quran. Fluorescent type lighting is common often combined with some incandescent lamps. Lighting levels vary with a typical value of 1.5 W/sq. ft (16.5 W/m^2). Daylighting can be greatly utilized during daytime prayers.
Internal loads	Mainly from people, then lighting. No equipment load.
Occupancy	8 ft^2/person (0.72 m^2/person, 1.2m by 0.6m).

Operating schedule	Typically five times daily intermittent occupancy with an average of one hour for each occupancy
Inside conditions	75 ^{o}F (24 ^{o}C) and 50% relative humidity.
Ventilation rate short	Large number of occupants especially during full operation (usually periods). This implies the need for reasonable ventilation rate without excessive sizing of the HVAC equipment.
Infiltration	The most difficult parameter to measure as usual. Frequent opening of doors and not very tight construction

The specific characteristics of the base case Mosque investigated in this study and described below are presented in Table 1 along with the optimization results.

THE PRESENT STUDY

The Mosque building considered for this study is a typical open space single zone medium size, 3300 sq. ft (300 m^2). It is rectangular in shape with 3:1 aspect ratio with 15 ft (4.5 m) ceiling height and the long axis facing Qiblah. The Mosque operates 7 days a week all year round with five intermittent operation a day with assumed maximum occupancy of 60% of the 400 people capacity of the Mosque (assuming an average occupancy area of 8 ft^2/person ,0.72 m^2/person) according to the occupancy profiles shown in Figures 1 and 2 for the cities of Riyadh and Jeddah, respectively. The Mosque is assumed to be used for daily prayers only. The HVAC system used is roof-top type with average ventilation rate of 15 cfm/person (7.5 L/s. person). Fluorescent lighting system is used with an average heat gain of 1.5 W/sq. ft (16.5 W/m^2).

Operating profile

The load profile considered in this analysis is based on a typical intermittent operation of the HVAC system according to Mosque use during the daily five prayers with two hours of operation during each prayer all over the year. A 5% of occupancy is assumed an hour earlier than the actual hour of use by the Muathin (the person who calls for prayer) and some few early comers. The profile of use is similar for both cities analyzed except that Jeddah prayer time is shifted one hour later than that for Riyadh as shown in Figures 1 and 2 for both cities. Summer prayer times were used as the basis where peak energy demand is expected and air-conditioning load dominates in many parts of Saudi Arabia. The lighting and ventilation profiles are assumed to coincide with the use profiles where all lights and HVAC system are assumed to be turned on with the first comer to the Mosque and turned off with the last person leaving the Mosque as observed in most Mosques in Saudi Arabia. Little seasonal variation in indoor conditions is assumed as people are usually fairly dressed for both seasons. The summer and winter thermostat setting of 75 ^{o}F and 74 ^{o}F (24 and 23 ^{o}C) according to the profiles shown in Figures 3 to 6 for both cities of Riyadh and Jeddah. The assessment of other HVAC operating strategies such as continuos versus intermittent operation or combination of the operation between two or more periods during the day as well as other alternatives are not considered in this paper but will be studied in future papers.

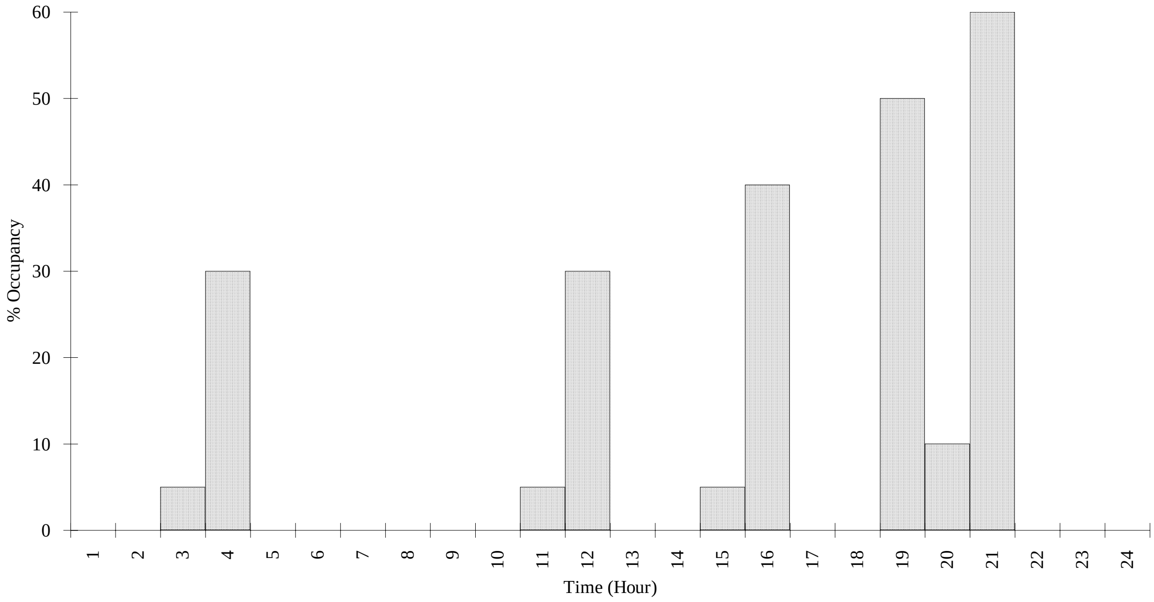

Figure 1. A Typical Operating Profile for a Mosque in Riyadh, Saudi Arabia

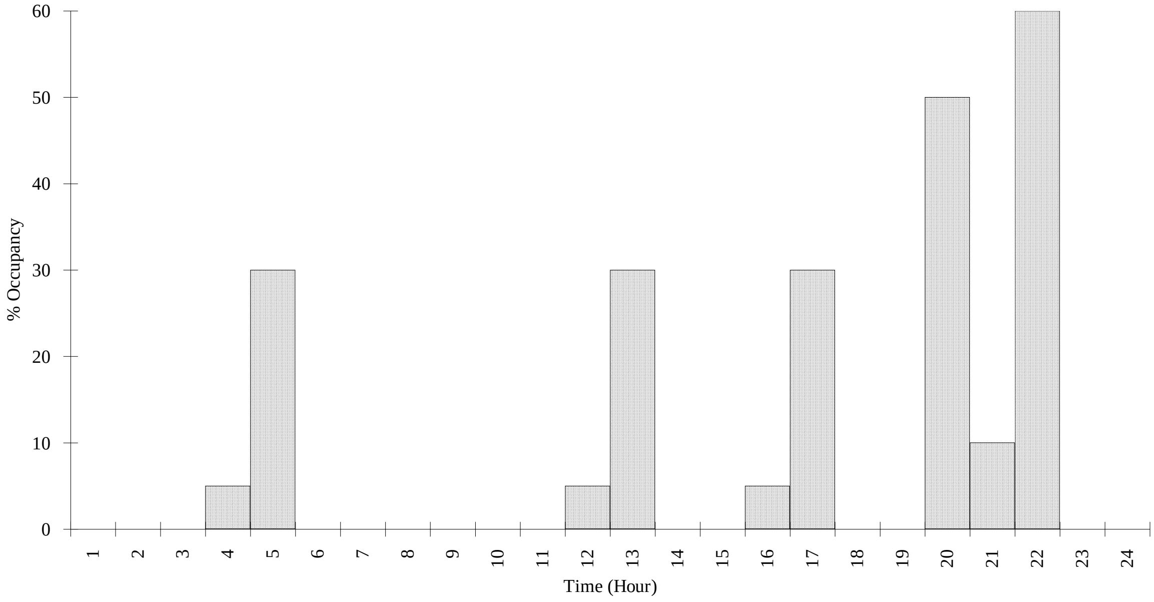

Figure 2. A Typical Operating Profile for a Mosque in Jeddah, Saudi Arabia

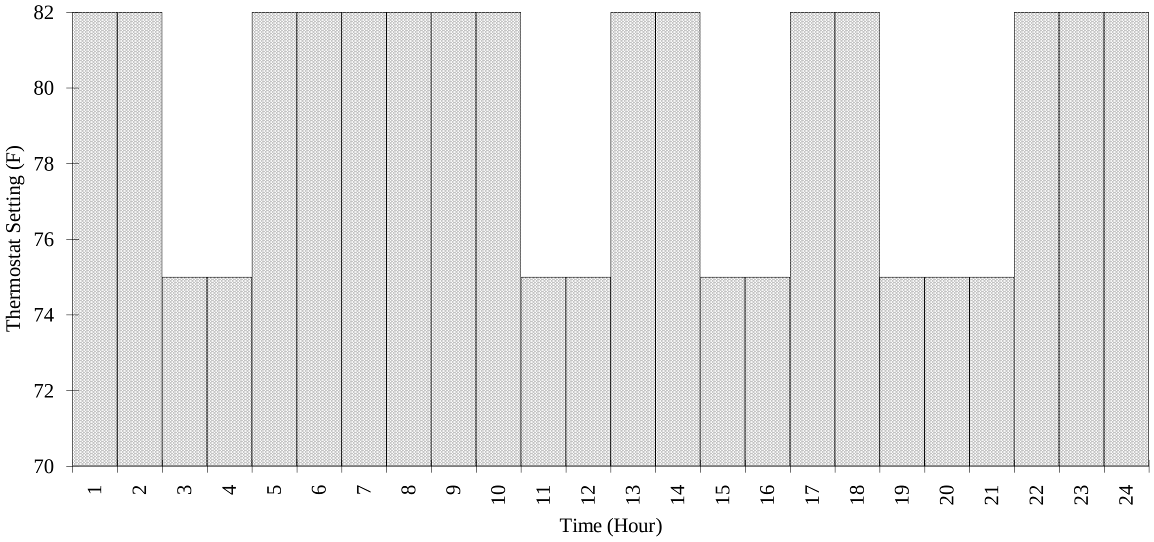

Figure 3. A Typical Summer Thermostat Setting Profile for a Mosque in Riyadh

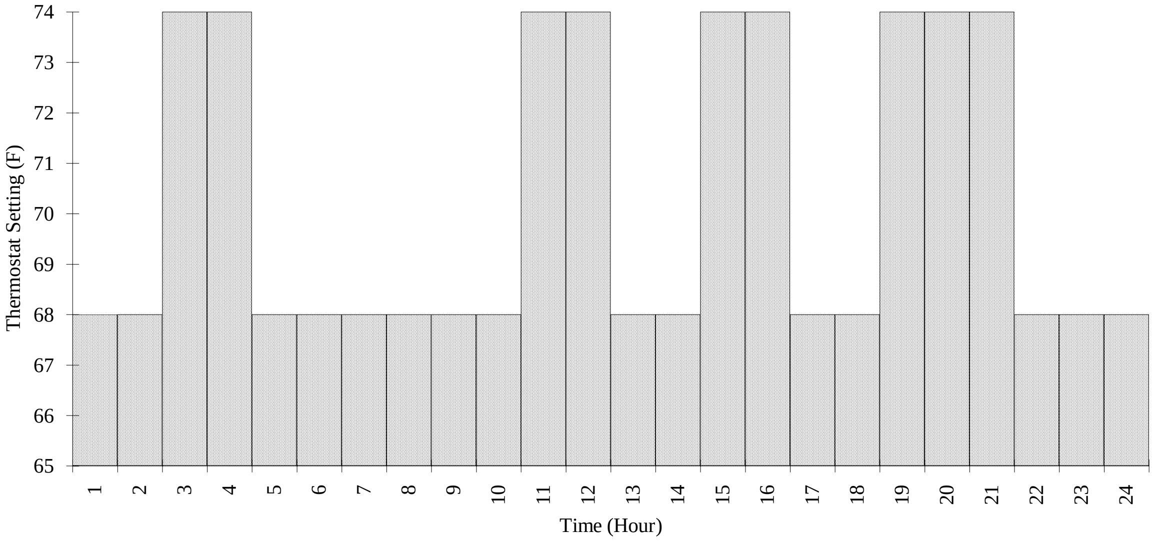

Figure 4. A Typical Winter Thermostat Setting Profile for a Mosque in Riyadh

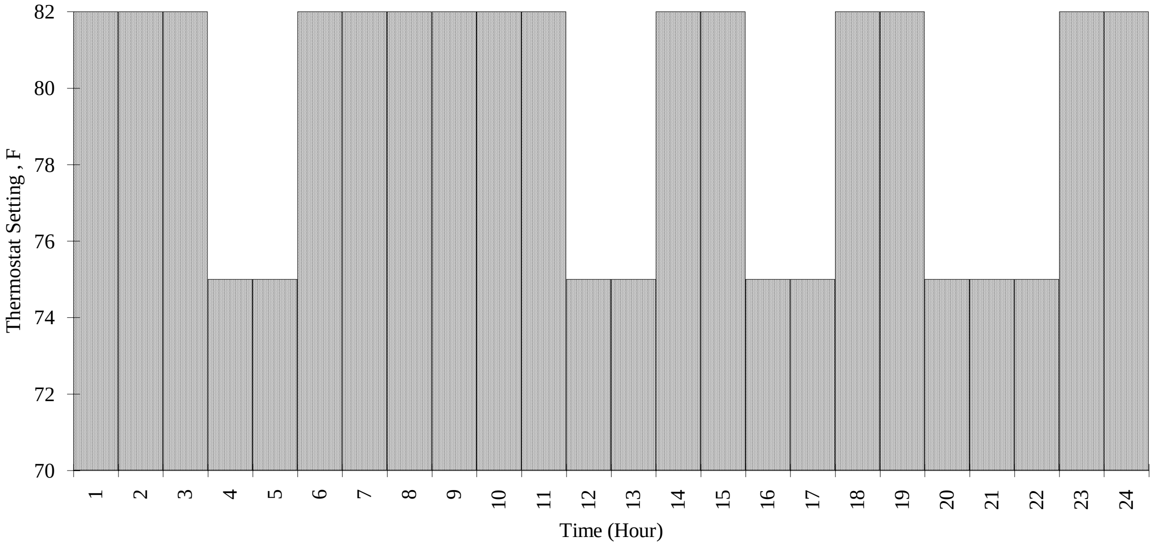

Figure 5. A Typical Summer Thermostat Setting Profile for a Mosque in Jeddah

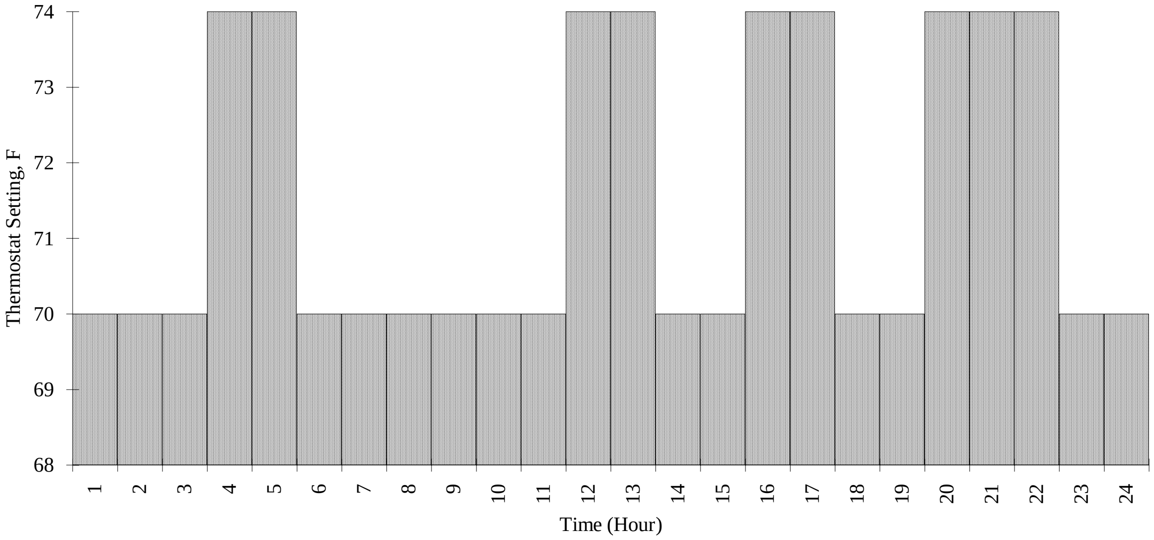

Figure 6. A Typical Winter Thermostat Setting Profile for a Mosque in Jeddah

Climates Analyzed

Every site is unique either in its physical constraints or in its micro climate and, therefore, it is difficult to specifically describe the micro climate for any region in the world. However,the available published weather data usually provide reasonable representations for regions with similar climate characteristics which can be modified to fit the specific site.

For detailed energy analysis of a certain building, local weather data has to be used. However, for the purpose of early design decisions, information obtained from studies on typical buildings can be utilized in studying thermal behavior at sites with similar climates.

For the purpose of this research, the weather data for the two Saudi Arabian cities of Riyadh and Jeddah were analyzed representing the two most harsh areas of hot-arid and hot-humid climates of the country, respectively.

Riyadh

Riyadh [24^{o} 42' 40 N. latitude, 46^{o} 44' 18 E. longitude, and 2000 ft. (611 m) above sea level] represents the central regions' hot-dry climate of the Kingdom. It is characterized by extremely hot and dry summers with very large diurnal temperature ranges and moderately cold winters. Skies are clear most of the year and the main concern for a designer is summer overheating.

Jeddah

Jeddah [21^{o} 40' 42 N. latitude, 39^{o} 8' 54 E. longitude, and 56 ft. (17 m) above sea level] represents the western coastal hot-humid climate of the Kingdom characterized by long hot and humid summers with very small diurnal temperature ranges. Winters, on the other hand, are short and mild which makes hot and humid summer conditions the main concern for building designers.

The two cities were selected because they represent the most critical two climatic zones demanding summer air-conditioning in the Kingdom. Also to address building designers and those concerned with thermal design optimization trends at these regions.

THE OPTINMIZATION MODEL

Detailed energy calculations apply hour-by-hour energy simulation. Many programs exist to simulate the energy consumption in a building and its sub-systems for every hour of an average weather year. They offer detailed analysis of a buildings' energy use accounting for all factors such as building schedule, occupancy as well as building mass. They also offer life-cycle cost analysis with different output options depending on the individual program.[1,4,5]

The drawbacks of simulation, however, are that it requires a prior knowledge of the solution which is not usually available to building designers in the early stages of the design process. Also, evaluating the effect of changing any of the design variables can only be achieved by trial and error, a method that is inconvenient and lacks the interaction between design variables that are of great importance for an integral evaluation of the thermal behavior of buildings.

In optimization the best solution is sought that satisfies objectives from among a field of feasible solutions under the restriction of certain constraints. Optimization utilizes mathematical techniques to systematically model and analyze certain quantitative measures to get the best course of action possible for a decision problem.

Optimization does not require prior knowledge of the solution to the problem as is the case in simulation. However, optimization models have the disadvantage of difficult and sometimes impractical formulation of the problem into a mathematical model, especially ill-defined problems such as those encountered in architectural design.

The optimization model (ENEROPT) implemented in this study utilizes a direct search optimization technique coupled with the ENERCALC hourly simulation model [1] to optimize as many as 14 design variables subject to upper and lower constraints imposed by the designer with the objective of minimizing the building annual energy consumption [2,3].

DISCUSSION OF THE RESULTS

The ENEROPT optimization model was utilized for the optimization of thirteen design variables for the described Mosque in the two selected cities with the objective of minimizing the annual Source Energy Utilization Index (MBtu/sq. ft. yr.). Values at the base case with the initial values of the design variables were used as the bases for comparison of thermal performance improvement in each optimization run. This common reference was used in order to investigate the importance of improving the selected design variables and their impact on the thermal performance of the corresponding building as the climate varies.

Analysis of the optimization results for the described Mosque in the two selected climates shows that building thermal design optimization can provide designers with very useful information on the decision making process. Results indicate that potential improvement in the thermal performance of Mosques can be achieved from the implementation of optimization techniques as demonstrated by the used model especially in the early phases of the design process.

The optimization results revealed significant reductions in the Mosque's EUI for both climates. Significant energy savings were achieved for such buildings with optimization. The magnitude of reduction in the Mosque's energy use for the optimum design from the starting base case reached 21 % and 18.8 % for Riyadh and Jeddah, respectively as shown in Figure 7 and illustrated in the optimization results of Table 1.

In addition to the potential energy savings, design optimization produced buildings with smaller peak heating and cooling loads as illustrated in Figure 8 (positive values represent cooling load while negative values represent heating load in the figure). The optimization results revealed as much as 12 % reduction in peak cooling loads for Riyadh and 15.4 % for Jeddah. This correspond to reduction in the required capacity of the HVAC system from 40.3 ton to 35.5 ton for Riyadh and from 35.1 to 29.7 ton for Jeddah as shown in Figure 9.

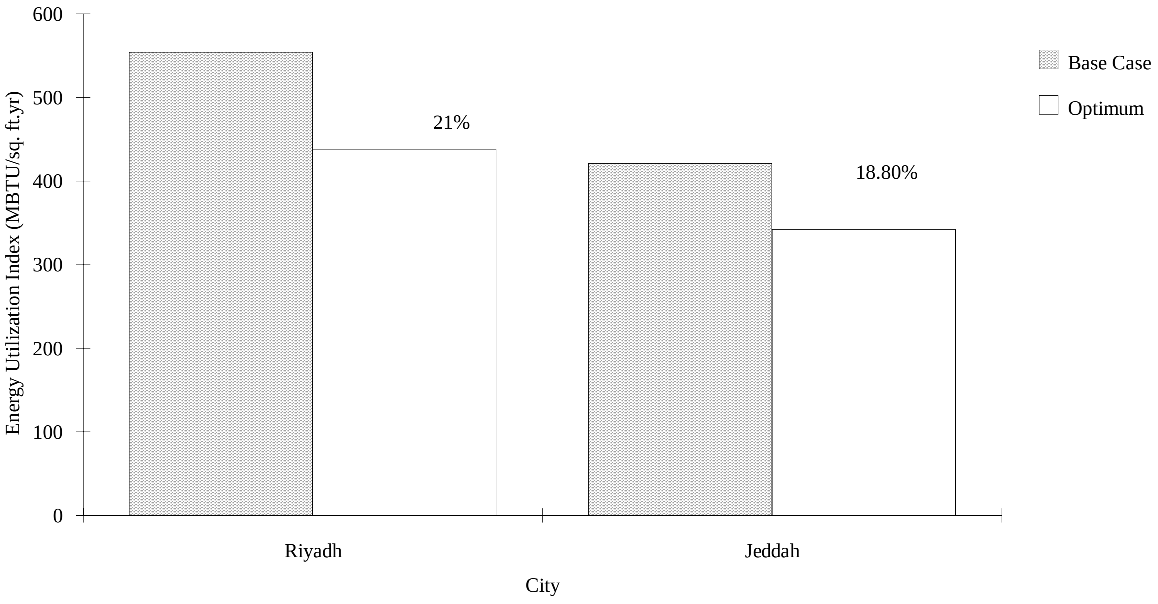

Figure 7. Mosque's optimum versus base case annual source energy utilization index for Riyadh and Jeddah, Saudi Arabia.

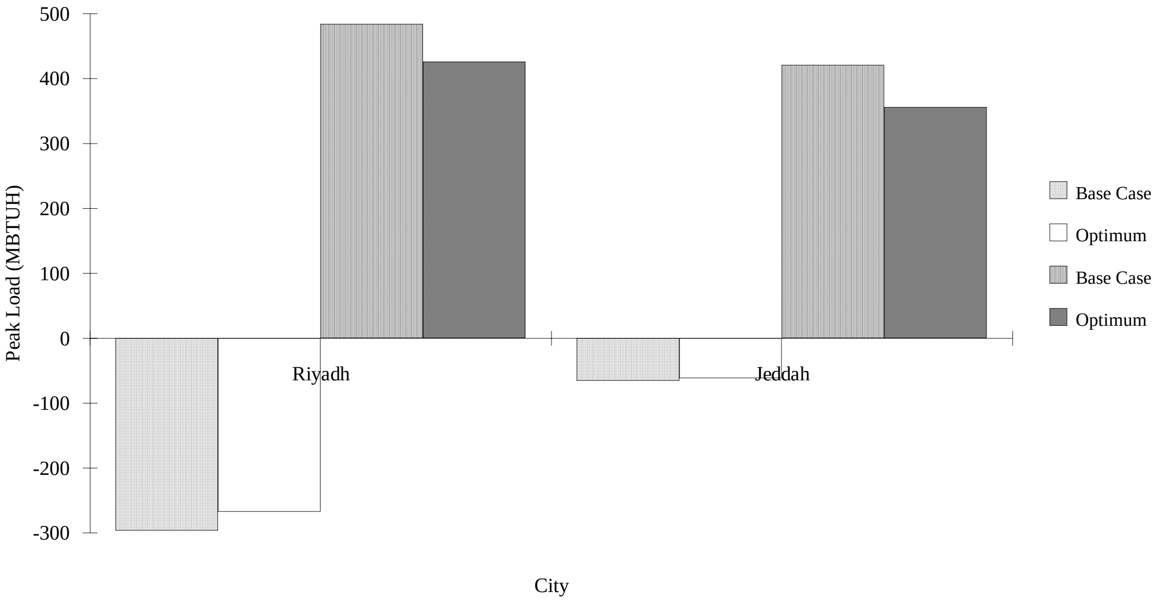

Figure 8 Mosque's heating and cooling peak loads evaluation.

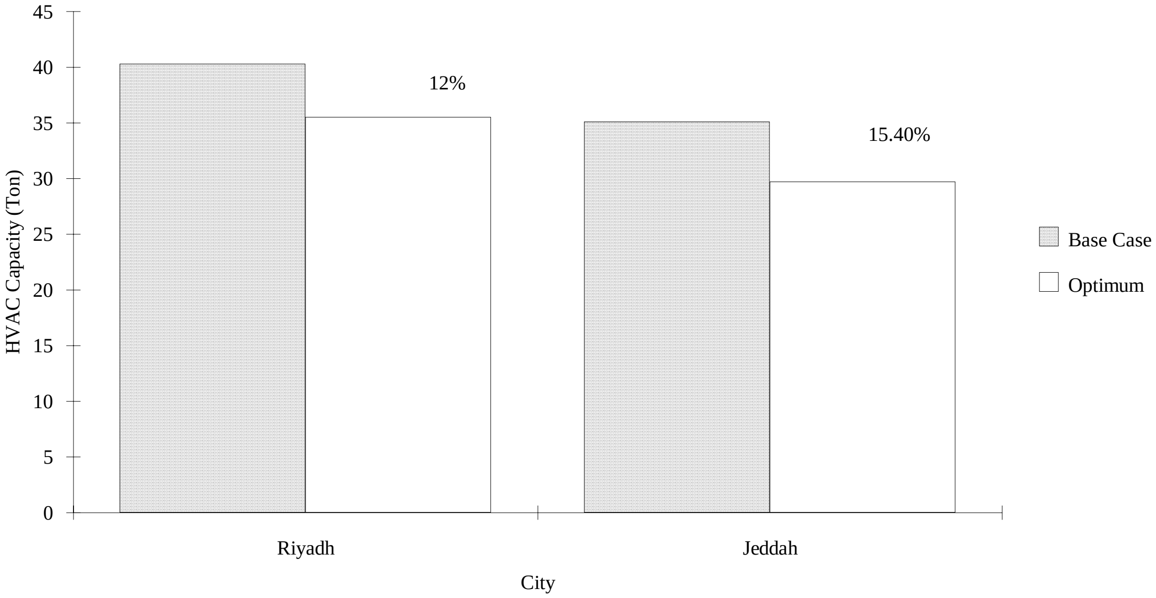

Figure 9 Optimum versus base case reduction in Mosque's HVAC capacity.

Design Parameters

One of the most important advantages of optimization is the interaction between the design variables. Therefore, it is important to have an overall look at all values of the optimum solution (not only at individual variables) as change in the value of one variable might affect the optimum values of other variables. Therefore, it is hard to conclude exact optimum values for any climatic region but rather general conclusions can be drawn on the trend of optimization for the selected variables as a function of climate. A summary of the optimum thermal design solutions for the analyzed Mosque in the two selected climates is illustrated in Table 1 along with the design values for the base case as well as the limiting constraints used in the analysis. Optimum thermal design trends are discuused below for each parametr.

Building Orientation and Form

The orientation of Mosques is determined by the Qiblah (direction with respect to the Holy Kaabah in the city of Makkah) where all Mosques are oriented to that direction. Therefore, the orientation is fixed with respect to Makkah rather than being a design variable. Mosques are usually formed elongated with the long axis facing Qiblah with a typical aspect ratio ranging from 2:1 to 3:1 for the purpose of having the largest number of people performing prayer in the first rows of a Mosque. This orientation is different from one area to another depending on its location with respect to Makkah. Therefore, Mosques in the regions east of Makkah are oriented towards west, and those to the west are oriented east and so on. However, variations occur in Makkah itself and around Kaabah where people pray toward Kaabah from all directions in a circular form.

In the present study, the Mosque in Jeddah is oriented with the long axis facing 21^{o} south-east toward Makkah while oriented 25^{o} due south of west for Riyadh.

Glazing

Glazing was optimized as a percentage of the gross wall area for each of the four exposures of the building. Without considerations for daylighting, a minimum glass area of 15% and a maximum of 99% of the wall area on each exposure was specified. The optimization trend was generally toward the specified minimum glass area some with flexibility to benefit from winter heat gains.

Other glazing variables included in the optimization were shading coefficient, U-value and emittance of the glazing system. In both climates, the optimization trend was to improve those variables. The optimum is generally to the lower boundary of the constraint on each of these variables. The shading coefficient is referred to in the optimization model as a single property of the glass and represents the value for the window system as a whole. Lower values for the glass emittance were called for in both climates. However, the significance of such fenestration properties increased as the amount of glass used at the optimum design increased. This interaction among the variables is important and valuable for proper selection of glazing materials.

Wall and Roof Construction

Optimization trends were toward lower U-values of both the walls and the roof for the selected locations to decrease conduction losses. Roof absorptance was kept constant at 0.75, while wall absorptance was optimized toward the specified minimum value.

Infiltration

Optimum rates were to the lower end of the specified constraint boundary for both cities. This indicates the importance of sealing all leaks in the building to minimize infiltration loads.

Other Parameters

Lighting is a major participant in both annual electrical consumption as well as generation of heat within the space causing more cooling load on the HVAC system. However, a fixed lighting load of 1.5 Watts/sq. ft. with no equipment load was used in the optimization of the Mosque, and for practicality, as the reality in most buildings, obvious benefits from daylighting were not considered.

The building operating schedule, as well as the type of HVAC system used, also have an impact on the values of the annual energy utilization. However, the objective of this optimization study was to investigate the improvement in the values of the Energy Utilization Index with respect to the climate as envelope parameters were optimized, as well as the general trend in the optimization results for each climate. Therefore, a single typical profile of use and a roof top unit HVAC system were used in the optimization.

In general, the operation of Mosques varies with location and time of the year as prayer times vary with the dominating load from occupants followed by lighting during the short occupied periods which are not controlled by the designer but rather an operational parameters. However, significant energy savings can still be achieved by implementing envelope optimization in the design of Mosques as demonstrated in the results of this research.

Design Guidelines

Based on the optimization results of this research, a number of recommended design guidelines for optimum thermal performance of Mosques and similar buildings in Riyadh and Jeddah are summarized as follows:

- Careful considerations should be given to the amount and distribution of glazing over the exposures of the building to balance summer and winter thermal tradeoffs. The southerly exposure is the most desirable glass exposure if proper shading is used to avoid excessive summer heat particularly in climates with cool winters such as that of Riyadh. West orientation, however, is generally the least desirable glass exposure.

- Glazing system shading coefficient is the first line of defense especially in such hot climates of Riyadh and Jeddah where summer gains are the major concern and glass shading treatment that would produce the lowest possible shading coefficient should be used. External shading intercepts the incoming intense sun rays before they are transmitted through the glass instead of afterwards resulting in lower heat gains through glass while allowing for view and daylighting and, therefore, is the best choice when possible.

- Use low U-values by the utilization of thermal insulation for both roof and walls in both climates of Riyadh and Jeddah. However, roof U-value is generally more critical than walls and should be given more consideration.

Table 1

Optimum Thermal Design Summary for a Typical Mosque in the Two Saudi Arabian Cities of Riyadh and Jeddah

Variable	Base Case	Constraints	Optimum Values	
	Initial		Riyadh	Jeddah
Wall U-value (Btu/hr. F. ft.^{2})	0.33	0.06 - 1.10	0.06	0.06
Absorptance	0.26	0.10 - 0.98	0.18	0.18
Time Lag (hr)	5.00	1.00 - 10.00	1.51	1.01
Roof U-value (Btu/hr. F. ft.^{2})	0.34	0.04 - 1.10	0.10	0.04
Glass U-value (Btu/hr. F. ft.^{2})	0.55	0.25 - 1.10	0.25	0.25
Shading Coeff	0.35	0.20 - 1.00	0.21	0.23
Emittance	0.20	0.20 - 0.98	0.25	0.23
% glass area: N	20.00	15.0 - 99.0	30.85	17.84
E	20.00	15.0 - 99.0	21.72	17.64
S	20.00	15.0 - 99.0	21.15	24.96
W	20.00	15.0 - 99.0	26.88	15.01
Infiltration rate (ach)	0.70	0.50 - 3.0	0.50	0.50
Internal mass (lb/ft.^{2})	75.00	50.0 - 150.0	88.20	93.1
Opt. SEUI (MBtu/sq.ft. yr.)	**--**	**--**	**438**	**342**
Base SEUI (MBtu/sq.ft. yr.)	--	--	554	421
% Reduction in SEUI	**--**	**--**	**21**	**18.8**
% Reduc. in HVAC Size	**--**	**--**	**12**	**15.4**

1 Btu/hr. F. ft.^{2}= 5.679 W/m^2. C.;
1 lb/ft.^{2} = 4.883 kg/m^2.

- Infiltration is the most difficult variable to measure and its losses are the most difficult to control. Due to frequent opening of doors in Mosques during occupied hours, consideration for infiltration control should be given enough attention. Therefore, minimum infiltration rate should be allowed and careful treatment of cracks and leaks around window and door frames should be implemented. Especial attention should be given to sealing leaks around window type a/c units openings which are common in Mosques and other buildings in Saudi Arabia in general.

- At times where outdoor air could be utilized for cooling especially at cool summer nights in hot-dry climates such as that of Riyadh, controlled ventilation should be considered.

- Use light colored surfaces to minimize heat absorbed into the building surfaces especially during the summer period for both hot climates of Riyadh and Jeddah.

- Obvious benefits from daylighting were not considered in this research. However, greater energy savings could have been obtained had daylighting been considered. Therefore, daylighting should always be considered seriously during daytime prayers in Mosques as well as in other buildings when proper.

Other operational parameters of Mosques such as lighting and HVAC operation are beyond the control of the designer. However, careful considerations should be given to the operation and management of such parameters as they have great impact on energy consumption and demand. Significant improvement in energy use can be achieved through proper control of lighting by the use of more efficient lamps, reduction in illumination levels, as well as utilizing daylighting during daytime prayers.

Other Design Considerations

There are other design and operating strategies that could be suitable to Mosques with their unique operation. These strategies were not investigated in the present study but should be considered in the design and operation of Mosques. These design considerations are summarized below:

- Fairly well dressed people during both summer and winter seasons. Therefore, middle range of the design temperature is favorable with little summer/winter variations.

- Zoning is important for comfort control and energy savings especially for Mosques with Friday, daily and women prayer areas. Each area should be designed to operate independently for use when needed only.

- Precooling of building mass several degrees below comfort level sometime (at least one hour) before occupancy will help to absorb portion of the peak heat load which would result in less demand and smaller equipment size.

- High ceilings of Mosques may cause stratification of heat above the occupied zone. Stratification is good for cooling and can be achieved by low elevation supply and return air where it does not mix with upper air. However, stratification is not good for heating and its effect can be reduced by using ceiling fans or low air distribution [6].
- Side wall supplies should have enough throw to satisfy the air distribution requirements (watch for noise).

CONCLUSIONS AND RECOMMENDATIONS

Optimization results showed that valuable design information on the selection and arrangement of various components of Mosque can be obtained in the early phases of the building design process by implementing optimization techniques as demonstrated in this analysis. Such information could aid building designers in their decision making process to achieve building design with optimum thermal performance.

Proper treatment of building envelope contributes to the improvement of the thermal performance of Mosques. Therefore, the use of optimization in the design of buildings and the selection of envelope components is highly recommended.

The optimization results indicate that Mosques design in the climates of Riyadh and Jeddah should be air tight, well insulated, with light colored surfaces and minimum area of shaded glass to avoid the dominant summer overheating. This revealed both lower energy use as well as lower peak heating and cooling loads. Therefore, operating as well as initial HVAC equipment costs can be reduced due to smaller system capacity required to provide comfort for the optimized buildings. Had systems and operating parameters been also optimized, more energy savings would have been obtained

The unique short and frequent intermittent operation of Mosques makes the operating strategy of the HVAC system very important to achieve the desired thermal comfort with minimum energy requirements. Therefore, different operating strategies as well as other design considerations as illustrated above need to be investigated further for Mosques for proper design and operation of this important type of buildings.

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