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Daylighting Analysis of Pedentive Dome's Mosque Design during Summer Solstice with Case Studies in Istanbul, Turkey

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ABSTRACT

In this study, the analysis is to measure lighting performance of single pedentive dome type in mosque design built during the Ottoman Empire in Istanbul, Turkey. The selected case studies are the Firuzaga and Orhan Gazi Mosque. This study investigates whether Turkish style's pedentive dome mosque design provides efficient indoor daylighting in the Orhan Gazi Mosque in compression with the Firuzaga Mosque. This assessment is simulated during summer solstice occurred when the sun is perimetering at its most northern position along the Tropic of Cancer. This study applies simulation analysis using Autodesk software known as 3DStudio Max Design 2011 programme. The weather data file was used to provide weather information and climate changes of the study area. The analysis shows that both mosques have mostly an evenly distributed illuminance level with Scale 3, 4 and 5. The Orhan Gazi Mosque has slightly higher illuminance levels compared to those of the Firuzaga Mosque. The study concludes that the pedentive dome mosque design has an effect on the mosque indoor daylighting. Having excellent illuminance level distributed at all the locations is one of the crucial reasons why the mosques with pedentive dome roof cover are built by Ottoman master builders.

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1. Introduction

The focus of this study is to identify the lighting performance in single pedentive dome mosque, and to find why this pedentive dome mosque is very popular design in the Balkan region especially during the Ottoman Empire. Assessment to obtain result of illuminance level in this research is to measure the lighting performance inside the buildings. The focus of this study is to compare results of indoor lighting performance between the Firuzaga and Orhan Gazi Mosque located in Istanbul. This study applies lighting simulation analysis generated in computer software known as 3dStudio Max Design 2011. Theof Firuzaga and Orhan Gazi Mosque have single's pedentive dome mosque design. Pedentive dome construction had made possible for a mosque design with vast interior and 'double space' in height; as a result, it is able to provide excellent daylighting inside the mosque as well as give reflect to its architectural grandeur. The dome design is an ingenious works of Ottoman master builders who reinvented the pedentive dome concept of Hagia Sophia's architecture. They translated the dome design which provides elaborated lighting performance from indirect sunlight in the mosque design (Necipoglu & Al-Asad, 1996).

The idea is to transmit the daylight into the mosque interior space through upper window openings at the projected domes besides intensifying a sense of sacredness inside the prayer hall (Hillenbrand, 1994). Mosques with 'pedentive dome' for roof construction are a popular Turkish architectural style. Pedentive dome design is a basic construction in Ottoman as well as Byzantium architecture. Pedentive dome is a construction of 'dome above dome' concept, dome design supported by four giant arches (Mango, 1976). The dome has load bearing system, therefore; it bears its own weight. The advantage of this construction is that it dematerialises of building material such as stones, bricks and marbles in the building construction.

There are six types of pedentive dome mosques in Ottoman architecture namely as single, earring, multiple, duplication, courtyard and earring courtyard pedentive dome plan design (Hassan & Mazloomi, 2010). The scope of this study however is limited to single pedentive dome plan design, which is the most basic plan unit design layout. This type of design is one of the most popularly built in Istambul.

With simple plan design, this single pedentive dome design comprises a square plan and dome. Referring to its plan layout, this square form is highlighted by lines of the building wall with door and window openings. It marks a confined space used as a prayer hall. The other element is a dome highlighted by a dotted circle line which represents a void with double volume space surmounted under pedentive dome as the roof cover. The dotted triangle lines refer to the squinched arches. Dimension of the prayer hall can be rectangular in shape. In this case, the plan design is outlined with an addition of dotted semi-circle line which represents attached half dome or semi-dome roof covers, known as riwaq (exterior corridor).

2. Materials and Methods

The indoor lighting performance is evaluated using illuminance level as the measurable scale. This illuminance level is measured in lux or lumen per metre square (lumen/m2), which means the amount of luminance (lumen) affected on a 1m x 1m surface area. By referring to this measurement, this study can determine the indoor lighting performance inside the mosque (Runsheng, Meir & Etzion 2009). Building design using daylight system is considered as having excellent passive lighting design. Daylight is lighting obtained from indirect sunlight source. It provides the best source which comfortably matches with human visual response. The projected dome above the dome concept allows sunlit penetration. The amount of daylight penetration into a building through sunlit area from windows and door openings provides dual functions not only of admitting natural light into the indoor area but also allowing the occupants to have visual contact with the outdoor environment (Chel, Tiwari, & Chandra, 2009; Chel, Tiwari & Singh).

3. The Case Studies

Like in other parts of the Ottoman Empire, the Orhan Gazi and Firuzaga Mosque play as an important symbol of the Turkish architecture, which portrays the belief, culture and politics of the Muslim community in this region (Saoud 2004). Location of the mosques is in Istanbul, Turkey at latitude 40°48'36"N and longitude 29°26'24"E (Gaisma, 2011). On 21 June 2010 when summer solstice occurs, sunrise in Istanbul is at 5:32am and sunset at 8:40pm with 15 hours 8 minutes day time (sunrise-sunset, 2011).

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Figure 1: Location of Istanbul, Turkey (source: Google Earth).

The location of the Orhan Gazi Mosque is at Gebze, an urban area of Istanbul City whereas the Firuzaga Mosque is located in the heart of Istanbul city. The Orhan Gazi Mosque (Figures 1 & 2), also known as the Gebze Orhan Mosque or Sultan Orhan Mosque, derived from the Ottoman Sultan (King) Orhan Gazi (also known as Orhan I or Orhan Bey) reigned from 1324 to 1361 AD (Wikipedia, 2011). During his reign in 1331, a famous cathedral of the Hagia Sophia was converted to mosque. According to its historical record, there is no information when this mosque was exactly constructed. The record only shows the date of the Orhan Gazi mosque renovation taken place on 1775 AD. According to investigation by Kuran, he argued that the Orhan Gazi Mosque was built in early 1400s AD by referring to the building material of coarse rubble stones without any brick construction in between, and Byzantine construction elements such as its column capitals and bases, which typify atypical design on that period. The mosque design has a dome and square wall construction with a minaret at the east wall adjacent to the building entrance on the north wall. The dome measurement based on the building plan and section has 6.15m in radius and the square wall height is 9.55m. The building height (dome with square wall) is 15.70m. The dome is supported by four arches covered as a part of the building stone walls with 1.15m in thickness. Squinches are places of a joint system between the dome and arch wall. There are 23 windows built at the building wall aligned in 4 tiers. A mihrab is a niche area located at the south wall.

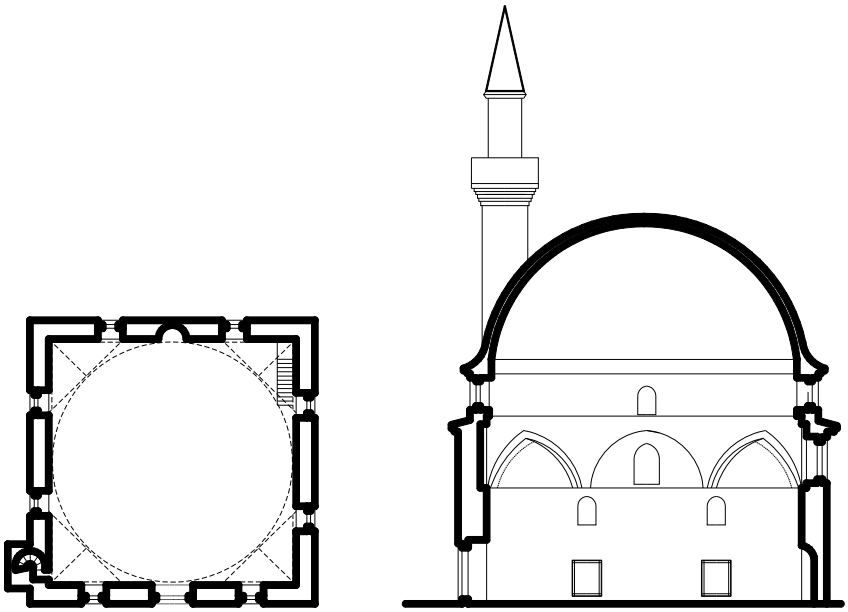

Figure 2: Plan (left) and section (right) of the Orhan Gazi Mosque.

Figure 3: Orhan Gazi Mosque.

The Firuzaga (Figures 3 & 4) mosque is one of the famous mosques in Istanbul. The mosque is located at Divanyolu, the main street overshadowed by the long queue of trees. It was built by the head treasurer of Sultan Beyazit II, Firuz Aga in 1491. Unlike other mosques, Firuzaga Mosque has a minaret placed to the left side of the wall while minarets of most mosques (single dome type) had to be on the right side on the wall. Although, the exact

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reason behind the minaret being placed on the left is still unknown, there are a number of stories relating different reasons for this.

This mosque was built during the first few years after Sultan Mehmet II conquered Constantinople in 1491. The Firuzaga Mosque has a square plan design with 13.5 m by 13.5 m and about 14 m high. The mosque is built with Bursa style and has a dome with eight sides with 5.20 m radius. The mosque is located in the neighbourhood of Sultanahmet which was considered to be the heart of Constantinople or known as Istanbul today.

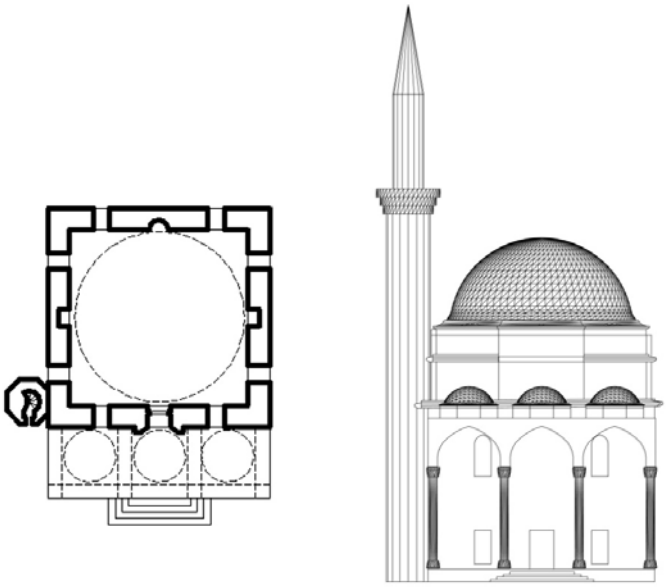

Figure 4: Plan (left) and elevation (right) of the Firuzaga Mosque.

Figure 5: Firuzaga Mosque.

4. Method of Simulation

The scope of this survey is to simulate the indoor lighting performance of the mosques and to do comparative analysis of the results among these mosques. This simulation (Figure 7) was conducted on 21st June 2010 on the occurrence day of winter equinox when the sun path is at perimeter along the Tropic Cancer. This daylight simulation deployed a computer-based calculation of the amount of daylight inside the building using 3dStudio Max Design programme. Before simulation analysis was conducted, three dimension drawings of these two mosques were created using AutoCAD software based on one to one scale illustrating exact measurement of the building form with reference to the mosque's two dimensional AutoCAD plan and section.

After that, these three dimension drawings were imported to 3D Studio Max 2010. A daylight system was created in this programme, and a camera view was set to the top view (perspective) before lighting analysis could be generated. A specific local daylight system was inserted in this programme using the available weather data file of Istanbul. This weather file was downloaded from weather data files (*.EPW) (EnergyPlus 2010), which contained annual data for typical climatic conditions at this site. It would provide data with respect to the local climatic condition.

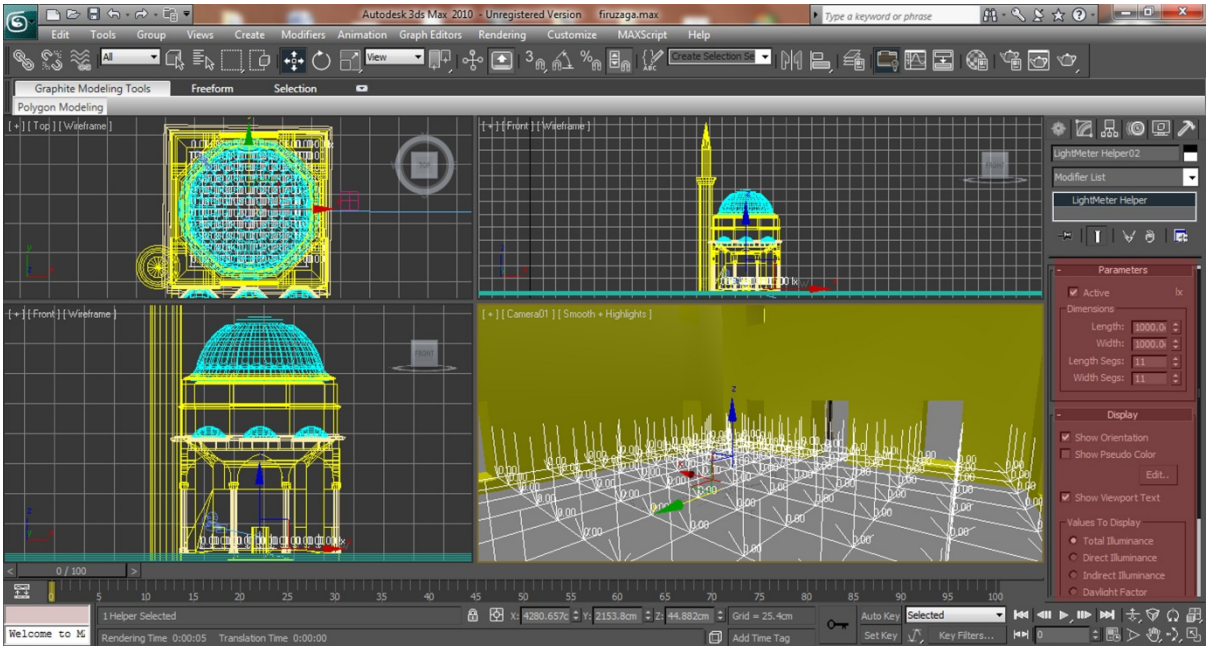

Figure 6: Lighting simulation in 3dStudio Max.

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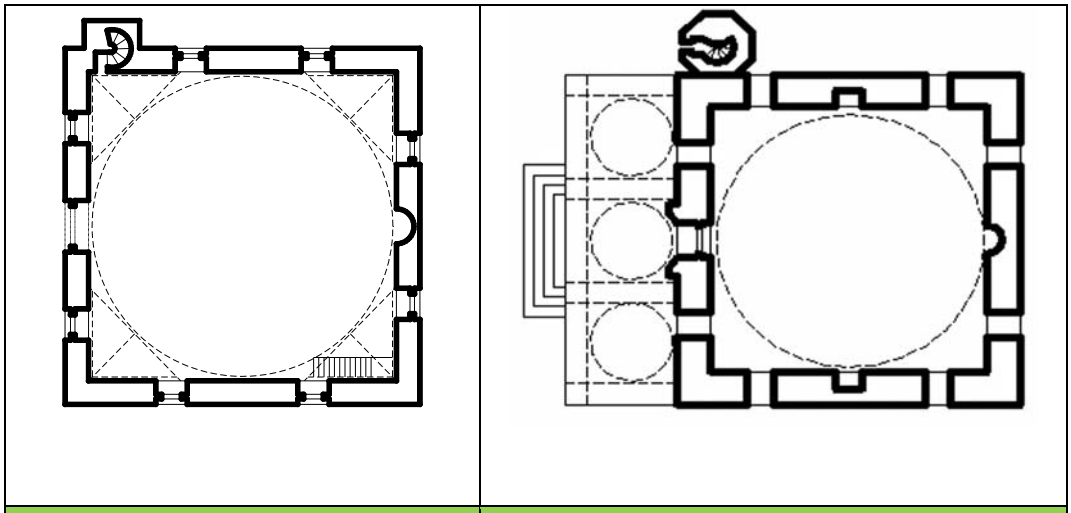

Orhan Gazi Mosque	Firuzaga Mosque

Figure 7: Location Point 1, 2, 3, 4 and 5 of the simulation.

Table 1: Measurable scales.

Scale	Illuminance (lux)	Level
1	0 - 20	Total darkness to dark
2	20 - 49	Do not demand a high visibility of the task (public areas)
3	50 - 99	Do not demand a high visibility of the task (orientation during short stop)
4	100 - 199	Do not demand a high visibility of the task (rooms not in permanent use and hallway brightness)
5	200 - 499	Details easy to see at normal brightness for reading or office area
6	500 - 999	Details difficult to see like intricate work for brightness
7	1000 - 1999	Tasklighting for highly demanding work - extremely fine details like microelectronic assembly
8	2000 - 10000	Tasklighting for highly demanding work - extremely fine details like special tasks in surgery (10000 lux is maximum brightness from sunlight to indoor area)
9	10001 - 100000	Outdoor area brightness (100000 lux is the maximum measurement)

A light metre was created by setting points of incidence which showed the illuminance level. Each subdivision represented a point at which incident illuminance normal to the grid (0.5 m x 0.5 m) would be measured (calculated). It provided overlaying a grid of illuminance results. This simulation was created after identifying a light meter at human body level 45 cm (when sitting on the ground while praying and listening to the Friday's sermon) above the

ground floor plan of the mosque. The results were based on its reference to this light meter's setting with modification of the daylight system to the selected weather file (Landry & Breton 2009). The simulation were done in selected points in the prayer hall in both of mosques , this simulation took 12 hours from, and it had been done every hour from 6:00am until 18:00pm on 21ts June 2010. The 5 selected points were (P1=entrance door; P2 centre prayer hall; P3=mihrab; P4=right/east side prayer hall; and P5=left/west side prayer hall) inside the building for each mosque (Figure 8). The results for each selected points were collected and then converted to tables and line charts. These results allowed us to have comparative analysis of lighting performances among these three mosques. This analysis referred to measurable scales (Table 1) which recommend ranges of minimal illuminance levels as follows: (Schlyter 2010, Wikipedia 2010, Krochmann *et. al* 1989)

5. Results of the Analysis

The results are illustrated in Tables 2 and 3, and Figures 8 to 12. This analysis comprises a comparative study between the Orhan Gazi and Firuzaga Mosque with reference to results of the simulation as follows:

Table 2: Indoor lighting performance of the Firuzaga Mosque.

Firuzaga Mosque 21 -6													
	6:00	**7:00**	**8:00**	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**
1	271.3	495.3	734.3	578.2	563.6	698.7	591.8	549.9	574.6	578.9	634.1	404.7	147
2	118.1	139	143.3	146.5	115.9	102.1	104.8	90.5	88.1	96	105.6	87.1	27.1
3	139.2	203.8	240	282.1	293.1	280.4	279.8	271.5	234.4	251.1	182.1	113.1	32.1
4	80.9	94.9	102.4	98.5	101.2	78.8	71.2	62.5	73.8	82.3	92.8	75.2	20.2
5	83.1	167.9	133.1	136.4	161.1	134.3	130.8	185	188.5	187.9	104.6	66.8	19.3

Table 3: Indoor lighting performance of the Orhan Gazi mosque.

Orhan Gazi Mosque 21 -6													
	6:00	**7:00**	**8:00**	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**
1	399	663	687.3	677.2	670.8	653	664.1	682	751.6	825.1	952.5	638.3	220.3
2	70.3	137	158.1	177.1	187.1	174.6	186	168.2	212.8	193.8	142.2	96.9	31.3
3	56	80.2	106	180.8	145.9	117.6	121.6	140	143.4	153.2	115.8	75.4	23.6
4	320.5	204.4	166.7	193.3	180.1	155.3	184.8	160	142.3	147	126.4	100	30.3
5	73.7	137.3	156.7	148.3	154.2	114.8	121.3	103.5	100.1	107.6	84.4	61.1	23.1

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(a). Point 1

Line chart in Figure 8 shows illuminance levels at Point 1 (near the mosque entrance) for both mosques. Illuminance levels at Point 1 have higher brightness level compared to the other locations at Point 2, 3, 4 and 5. The result shows that the average illuminance level at the Orhan Gazi Mosque (653 lux) is higher than that (525 lux) of the Firuzaga Mosque. In the Orhan Gazi Mosque, sunlight from 7:00 am to 5:00 pm provides illuminance levels higher than 630 lux equivalent to Scale 5. While in the other hand the Firuzaga mosque has the illuminance levels under scale 5 from 8:00 am to 4:00 pm. The Orhan Gazi has brighter illuminance levels than the Firuzaga Mosque throughout all simulations made from 6:00 am to 6:00 pm except at 8:00 am because of direct sunlight occurring at this point on in the Firuzaga Mosque. The Orhan Gazi Mosque has good illuminance levels from 6:00 am and 6:00 pm above 200 lux (Scale 5). Most readings of its illuminance levels is above 600 lux (Scale 6), which is from 7:00 am to 5:00 pm. The Firuzaga Mosque has good illuminance levels from 6:00 am with 271 lux and 495 lux at 7:00 am then 405 lux at 5:00 pm which go under (scale 5) to 6:00 pm with 147 lux (Scale 4) of the illuminance levels.

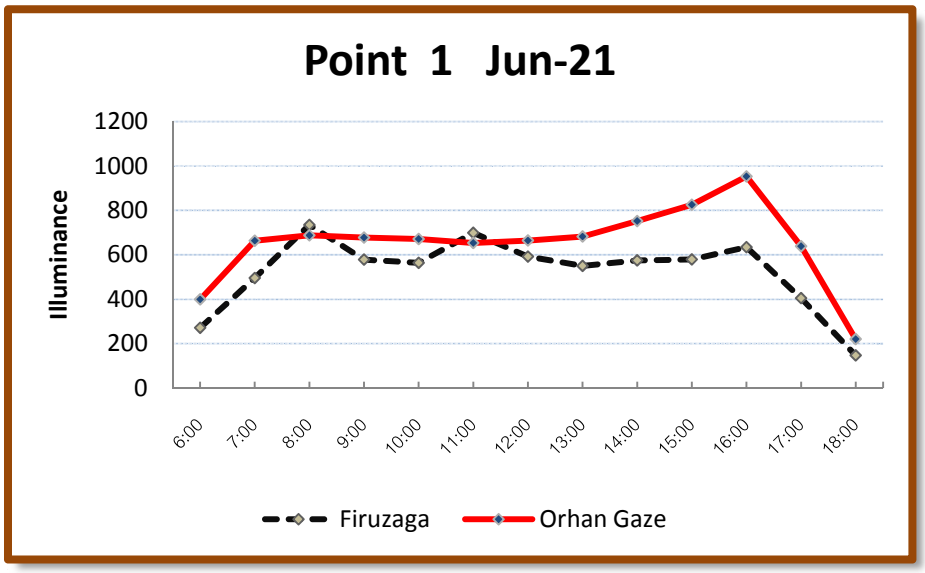

Figure 8: Line chart of Point 1.

(b). Point 2

Line Chart in Figure 9 illustrates illuminance levels at Point 2 (location at the central prayer hall). Like at Point 1, the Orhan Gazi Mosque has brighter illuminance level than the Firuzaga Mosque in throughout all simulations made from 8:00 am to 6:00 pm. The average of illuminance levels at the Orhan Gazi and Firuzaga Mosques are (149 lux) and (104 lux)

respectively. In the Orhan Gazi Mosque its illuminance level starts under the scale 3 with 70.3 lux at 6:00 am, then increases gradually from 7:00 am to 10:00 am to scale 4 (187.1 lux), after that the line chart fluctuate between 142.2 lux and 212.8 lux from 7:00 am to 4:00 pm which is the maximum illuminance level for Orhan Gazi Mosque (scale 5). Then the illuminance level drops at 5:00 pm to less than 100 lux (scale 3) and about 30 lux at 6:00 pm which is its minimum illuminance level scale 2. The Firuzaga Mosque on the other hand starts with higher illuminance level than those in the Orhan Gazi Mosque at 6:00 am with 118 lux. The two chart lines intersect at 7:00 am with less than 140 lux, then from 8:00 am to 6:00 pm the Firuzaga Mosque has lower illuminance level than those in the Orhan Gazi under 147lux at 4:00 pm. The results show that the illuminance levels in point 2 from the morning until the afternoon are under scale 4, while it is under scale 3 at 1:00, 2:00, 3:00 and 5:00 pm, and finally at 6:00 pm under scale 2.

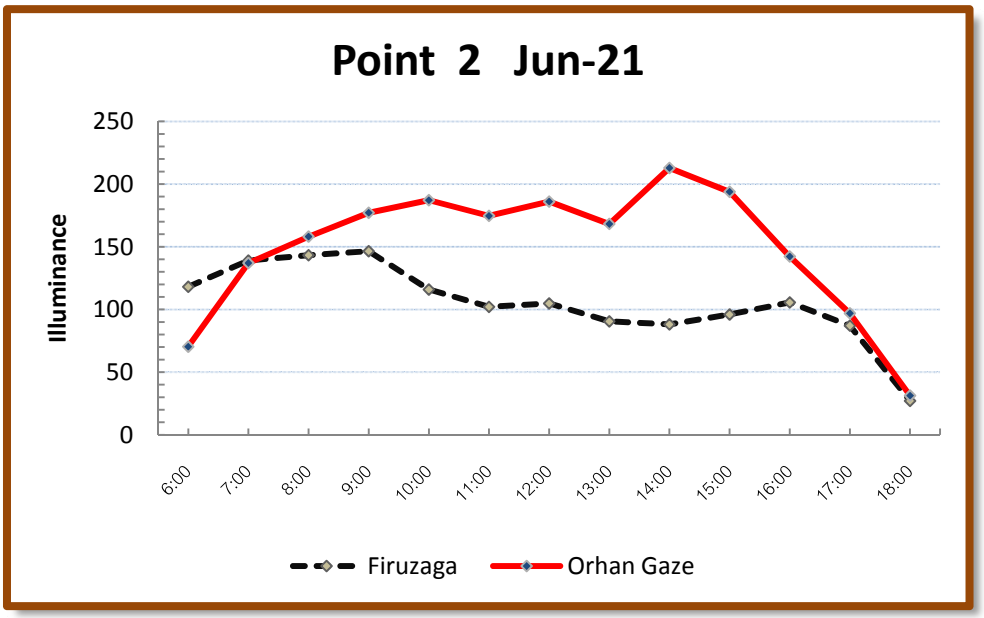

Figure 9: Line chart of Point 2.

(c). Point 3

Figure 10 is a line chart which shows the results of illuminance levels at Point 3, near the mihrab. The illuminance level at the Orhan Gazi ranges from 56 lux in the early morning, 181 at 9:00 am as a maximum illuminance level to 31 lux the minimum illuminance before sunset, whereas the Firuzaga Mosque has illuminance level ranging from 139 lux at 6:00 pm to 293 lux at 10:00 am with its minimum 32 lux at 6:00 pm. The result shows that the average

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illuminance level at the Orhan Gazi Mosque is 112 lux lower than that 215 lux of the Firuzaga Mosque. In the Orhan Gazi Mosque, there is a sunlight which provides illuminance level to Scale 3 and 4. The Orhan Gazi Mosque has lower illuminance level than that in the Firuzaga Mosque throughout all hourly intervals in these simulations. The Orhan Gazi Mosque has illuminance levels from 8:00 am to 4:00 pm above 100 lux Scale 4. The Firuzaga Mosque has higher illuminance levels from 6:00 am about 140 lux and from 4:00 pm to 5:00 pm above 100 lux (scale 4), then from 7:00 am to 4:00 pm above 200 lux (Scale 5), and finally at 6:00 pm with 32 lux scale 2.

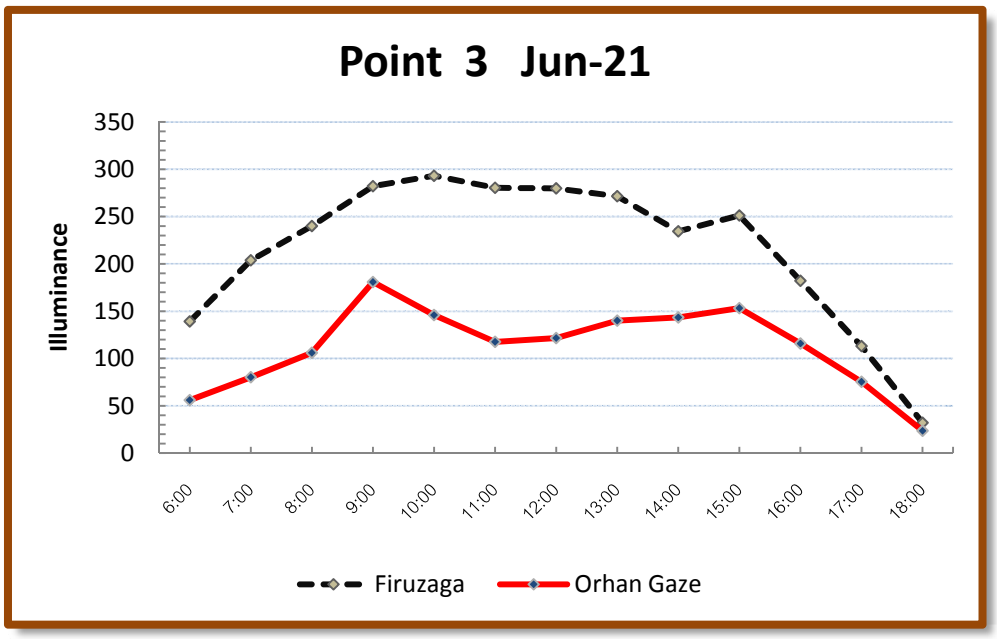

Figure 10: Line chart of Point 3.

(d). Point 4

Line Chart in Figure 11 illustrates illuminance levels at Point 4, location near west wall. The Orhan Gazi (the average of illuminance levels 162 lux) has brighter illuminance level than Firuzaga Mosque (the average of illuminance levels 80 lux) in all simulations made from 6:00 am to 6:00 pm. The illuminance levels at the Orhan Gazi ranges from the maximum illuminance level in the early morning at 6:00 am with 320 lux and 205 lux at 7:00 am (scale 5) then decreases to scale 4 from 8:00 am (167 lux) to 5:00 pm (100lux).Its minimum illuminance level is recorded with 30 lux at 6:00 pm under scale 2. On the other hand the Firuzaga Mosque has illuminance level most of the times under scale 3 from 6:00 to 5:00 pm except at 8:00 and 10:00 am under scale 4. The results show that the illuminance level starts

at 6:00 am with about 81 lux then fluctuate between 102 and 63 lux until 5:00 pm. The last hour of simulation at 6:00 pm becomes the minimum illuminance level of the Firuzaga Mosque with 20 lux scale 2.

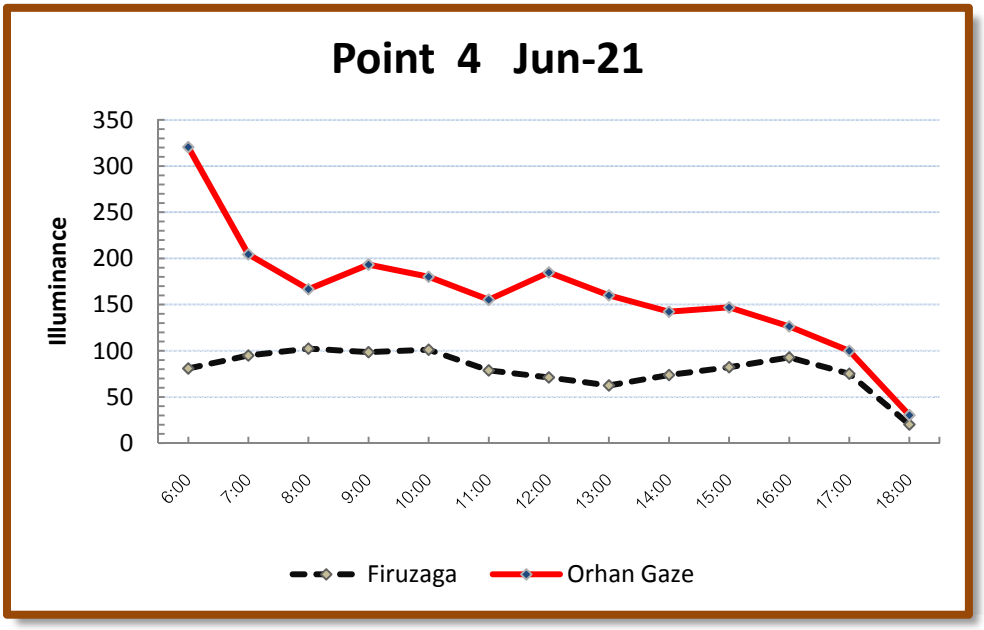

Figure 11: Line chart of Point 4.

(e). Point 5

Line chart in Figure 12 shows illuminance levels at Point 5 (location near east wall). Illuminance levels at Point 5 show that the chart lines of both mosques have almost the same behaviour. Illuminance levels at the Orhan Gazi and the Firuzaga Mosque start with scale 3 with 73 and 83 lux respectively then increase to scale 4 from 7:00 am to 3:00 pm for the Orhan Gazi and to 4:00 pm for the Firuzaga Mosque. Then both of the mosques are under scale 3 at 5:00 pm, and finally the Orhan Gazi chart line is under scale 2 at 6:00 pm, while the Firuzaga Mosque is under scale 1. The result shows that the average illuminance level at the Orhan Gazi Mosque (107 lux) is lower than the Firuzaga Mosque (131 lux). Figure 12 and Tables 2&3 show that the illuminance level starts in the Orhan Gazi Mosque with 74 lux at 6:00 am, then increases from 7:00 am to 10:00 am from 137to 154 lux. It starts fluctuating until 3:00 pm with the following amounts 115, 121, 104, 100 and 107 lux, which declines at 4:00, 5:00 and 6:00 pm with 84, 61 and 23 lux respectively. Whereas the Firuzaga Mosque chart line starts with 83 lux at 6:00 am then start increasing until 3:00 pm to189, and start decreasing at 4:00, 5:00 and 6:00 pm with 105, 67 and 19 lux respectively.

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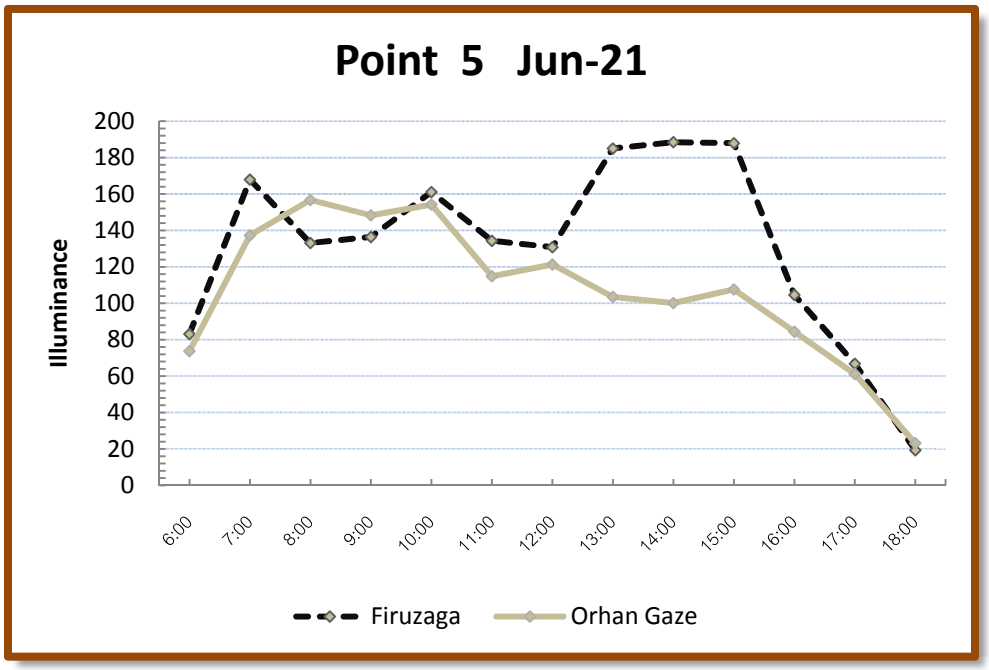

Figure 12: Line chart of Point 5.

6. Discussion

The study is able to identify the sacred index of the illuminance level provided in pedentive dome mosque design. Pedentive dome design has excellent illuminance levels inside the mosque in most hourly interval time equivalent to Scale 4 from 9:00 am to 4:00 pm taken throughout the simulations. No result of the simulations records the illuminance level below 20 lux equivalent to Scale 1 except at 6:00 pm (slightly before the sunset) in the Firuzaga Mosque at point 5. The findings from the results of analysis are as follows:

(a). Orhan Gazi Mosque has better results of illuminance levels at Point 1, 2, and 4 recorded throughout the simulations. Most illuminance levels higher than 200 lux (Scale 4) are at Point 1 in the Orhan Gazi and Firuzaga Mosque.

(b). Figures 13 and 14 show that results of simulation at Point 1 in both mosques have the highest illuminance levels compared to Point 2, 3, 4 and 5. Point 1 in the Orhan Gazi Mosque records higher illuminance levels than Point 1 in the Firuzaga Mosque. In the Firuzaga Mosque, Point 3 has the second highest followed by Point 5 and 2 whereas Point 4 has the lowest ranking.

(c). Figure 14 shows that in the Orhan Gazi Mosque, point 1 has the highest illuminance level, followed by point 2, 4 and 3, while point 5 has the lowest illuminance level.

(d). The findings show that large door openings for both entrances at the Firuzaga and Orhan Gazi Mosque become an important factor that provides high illuminance at Point 1.

(e). The research outcomes also show that upper windows opening built around the dome perimeter provide daylit factor which transmits daylight at Point 2 location at central prayer hall in the Orhan Gazi mosque. On the other hand the lack of the windows design in the Firuzaga makes the central of prayer hall with low illuminance level. This shows that the impact of the upper windows openings to pedentive dome design to the level of illuminance level at Point 2.

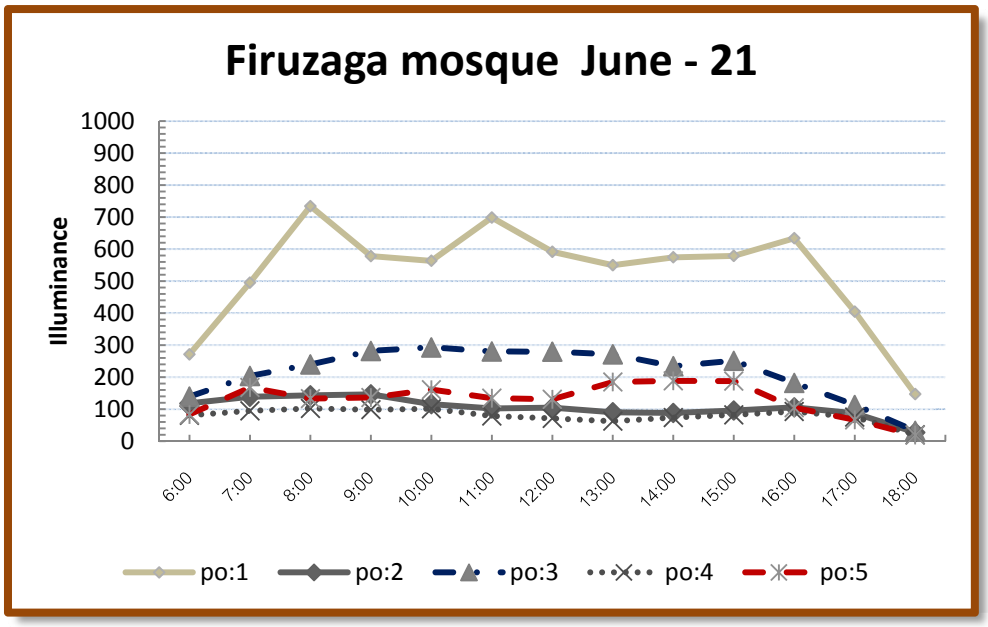

Figure 13: Line chart of the Firuzaga Mosque at Point 1, 2, 3, 4 & 5.

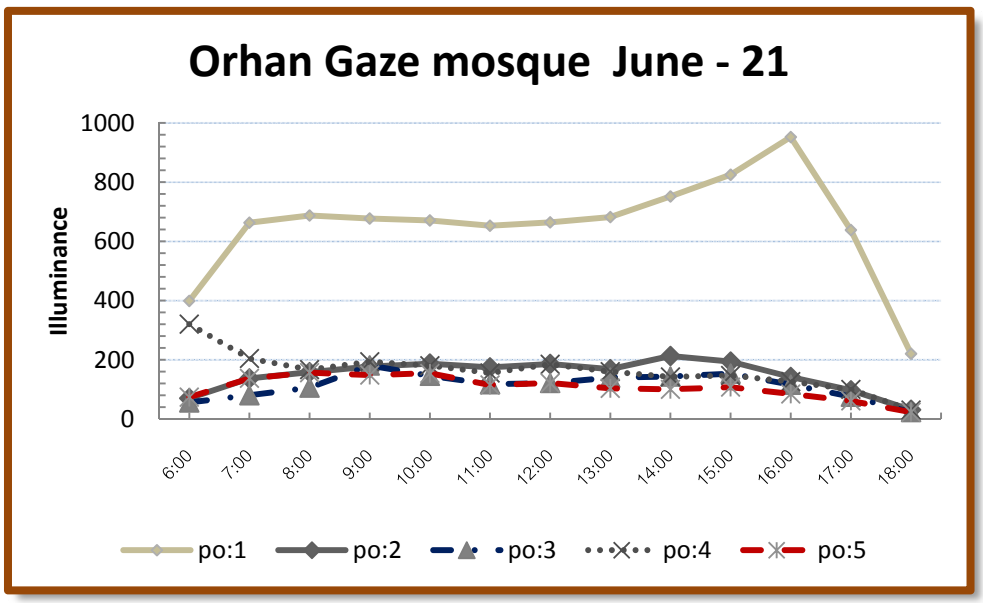

Figure 14: Line chart of the Orhan Gazi Mosque at Point 1, 2, 3, 4 & 5.

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7. Conclusion

This study concludes that single pedentive dome design creates sunlit factor to give additional brightness at central prayer hall inside the mosque. Besides due to sunlit factor by the sun perimetering at the Topic of Cancer from southern atmosphere, adding the upper windows openings surrounding the dome in the Orhan Gazi Mosque provides additional daylight especially in the centre of the prayer hall at point 2 in both cases of the mosques. As a result, the extra high ratio to the plan dimensions helps to provide the good illuminance levels through the windows from the walls in the Firuzaga Mosque even without the upper windows openings. However applying the pedentive dome style in both case studies offers illuminance level distributed at all locations inside the mosque which gives a better illuminance level in all locations inside these mosques. Applying this pedentive roof form gives inspiration to the master builders to design a mosque with a perfect lighting performance with sacred sense of worshipping activities in the mosques, and helps creating vast interior space plan layout without obstruction by walls and columns (Goodwin 1993). These offers the master builders to explore daylighting design as a source of scared expression a place of worship with a presence of divinity inside prayer hall.

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