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The effect of internal light shelf on quality of daylight distribution in space and lighting energy consumption reduction

Faramarz Fadaee[a], Amir Ebrahimi-Moghadam[b], Paria Ildarabadi[a,*]

[a:] *Department of Architectural Engineering, Khorasan Institute of Higher Education, Mashhad, Iran.*
[b] *Young Researchers and Elite Club, Mashhad Branch, Islamic Azad University, Mashhad, Iran.*
[*]*Paria.Ildarabadi@khorasan.ac.ir*

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A B S T R A C T

The optimal use of daylight in interior spaces of residential buildings leads to increase in space quality, comfort condition and optimal energy consumption. Present study investigates the daylight distribution aiming to reach the people's comfort condition and optimal electrical energy consumption of artificial lighting. For this reason, a zone from each orientation of Yas residential building (located at Mashhad city of Iran) was selected and light analysis was conducted in the interior environment for the baseline condition as well as 7 proposed light shelves (vertical light shelf for East and West orientations, horizontal light shelf for North and South orientations). Measurement criterion for daylight quality is Daylight Autonomy (DA) which a DA of 50% provides the amount of 300 lux light in the interior environment. Then, the amount of saving in lighting electrical energy, which consumes by the lamps during the day, was calculated considering the optimal light shelves. Results show that light shelf No. 3 provides the optimal comfort condition in zone A (west) and light shelf No. 2, No. 4 and No. 6 provide the optimal comfort condition in zone C (North) while the light shelf No. 5 is able to control some the light entering the zone D (East). In addition, considering the light shelves in the studied zones, the electrical energy consumption of the lamps reduced by 576.048 kWh/year.

1. Introduction

Due to the population growth, the energy consumption is increasing rapidly around the world and concerns regarding the energy resources have been raised. Decreasing energy resources and environmental issues such as global warming, ozone depletion and climate change are direct consequences of increasing energy consumption [1, 2]. Since energy production costs a lot of money for countries, therefore energy consumption reduction and energy saving potentials are significantly important. The share of energy consumption by transportation sector is 28%, by industry sector is 28%, agriculture sector is 4% and building sector is 40% [3, 4]. Therefore, the building sector has the highest energy consumption which most of the energy is consumed for people's thermal comfort condition. In recent decades, the performance of buildings has greatly improved in response to developing standards in building sector and to meet

*Paria.Ildarabadi@khorasan.ac.ir com

the growing demands for people's comfort condition [5].

Fossil fuel pollution and its resources depletion led to search for new approaches to supply the required energy. One approach is to use the renewable energy resources like daylight, wind, sea waves and other environmental factors utilized effectively in energy production. Due to its availability, the daylight plays the most important role among the other factors [6, 7]. For this reason, most of the researches in the area of energy production and optimization are on daylight. It is important to adopt proper strategies for daylight control in the interior spaces to optimize the people's comfort condition [8, 9]. However, development of daylight control systems for increasing the use of daylight energy is very limited, because many factors affect their performance and also it is difficult to design them [10, 11].

Today, the residential space is an important part of human life and as a shelter, provides the basic needs of human. With increasing the population, increasing height of the buildings and using glass façade, the daylight enters the interior space of the building directly and uncontrolled. Controlling the light entering the interior space of the building can provide the people's comfort condition [12, 13]. It is estimated that a large amount of electrical energy is wasted as lighting during 8 a.m. to 6 p.m. which mostly is due to the inappropriate design of the windows [14]. Most of the researches in this area have been focused on the effects of the window's location on façade, window's shape, visual understanding, canopy and window's dimension. Ma and Bian [15] analyzed the daylight illuminance, daylight factor and daylight autonomy based on measurement of long-term continuous daylight illuminance in a real daylight climate condition test room using scale model tests and computational simulations at Canton city of China. Their results showed that at least a DF of 1.8% is necessary to reach a monthly average daylight illuminance of above 300 lux and also the comparison of DA 300lux (%50) and DF can be used as a guide for sustainable building daylight design. In a research conducted by Raimondi [16] on existing shapes in office building, the levels of natural lighting were studied based on new facades. Results showed that with increasing the daylight autonomy percentage, the building's area is extended while it narrowed when the natural light condition is not good. Gutiérrez et al [17] simulated the performance of daylight in a louvre screen with specular aluminium and two types of ceramic finishes based on daylight factor, daylight autonomy and useful daylight illuminance metrics in order to decrease the environmental effects of the systems. According to their results, the ceramic can be considered as a promising finish in advanced daylighting technologies and the proposed louvre leads to increase in ecological impact and better daylight performance. Zomorodian and Tahsildoost [18] examined the daylight performance and people's visual comfort in four classrooms in two LEED™ silver certified buildings throughout a year using dynamic and static daylight and glare metrics based on perception of human subjective responses. It was found that there is a correlation between students' perceptions and dynamic daylight metrics of sDA300/50% and UDI300-3000/50%, and also due to the relation between occupants' ability to adapt to light and climate location, global surveys may be used for thresholds of metrics.

Considering the people's comfort, reducing energy consumption, light shelf, daylight autonomy and daylight as goals of current study, further researches are presents in this area. For instance, taking into account the daylight, people's comfort and building's energy consumption, Acosta et al. [19] evaluated the circadian stimulus autonomy in classroom based on climate condition according to the reflectance of desk and surfaces. In addition, the amount of lighting energy consumption was measured and the comfort conditions for students in the classroom were studied. Another research was conducted by Xue et al [20] on energy consumption optimization, DA and daylight based on people's comfort. Using questionnaire and simulation, the luminous comfort was examined and results indicated that the energy consumption reduced considering the metrics DA300. Wittkopf et al. [21] investigated the energy saving potential of anidolic integrated ceiling (AIC) in two cities of Singapore and Sheffield. Results of computational simulation showed that using anidolic integrated ceiling can lead to 21% and 26% electrical lighting energy saving in Singapore and Sheffield, respectively.

The literature survey shows that not much focus has been given to the daylight distribution in the interior space and energy consumption optimization using light shelves. For this reason, the present study investigates the effect of light shelves on daylight distribution and energy consumption amount. The main objectives of this study are optimization of daylight in the interior environment (proper light distribution in the interior environment) using light shelves, daylight analysis based on the climate and building positioning, and energy consumption due to optimal light shelves.

2. Research Methods

Providing comfort conditions using daylight distribution is an effective factor on people's satisfaction from interior environment. Therefore, the proper use of daylight can provide the thermal balance in the interior space, can increase the comfort condition for people and can decrease the building's energy consumption. In current study, the distribution of daylight is evaluated in order to increase the people satisfaction from interior environment and decrease the energy consumption. Information and data collection is based on library studies and publications conducted on daylight in the residential environment and optimization of building's energy consumption using simulation software.

The modeling of the case study is performed by means of Rhinoceros 6. In order to analyze the daylight and to find the energy consumption and people's comfort condition in residential environment, simulation is done using algorithmic software of Grasshopper. Moreover, the plugins of Honeybee0063 (Sep 2018) and Ladybug0066 (March 2018) are used for data analysis. It should be noted that the weather conditions data of Mashhad city are used as two formats of EPW File and STAT File. In addition, software analysis follows the ASHRAE 90.1 [22] as the reference for energy simulation study.

Using uniform glass facade in the building can guarantee the direct transmission of uncontrolled daylight to building environment. Due to the high volume of daylight in the interior environment which disrupts the occupants' comfort condition, people may use the curtains to prevent the daylight entrance and artificial lighting is then used for some of the daily activities that need light which increases the building's energy consumption [23, 24]. The researches in current study are divided into two parts; first part: the daylight distribution and the proposed light shelf, second part: the effect of optimal light shelf on building's energy consumption reduction.

2.1. The case study

The case study in this research is Yas residential tower located at Mashhad city of Iran. The plot area is 3715 m2, the total built up area is 43590 m2 and the total carpet area is 22326 m2. It has 20 floors above the ground, 4 floors under the ground and 2 half-floors. Second floor to seventeenth floor and eighteenth floor to twentieth floor have typical plans. Fig. 1 and 2 shows the location and a view of the building project and Location of the examined zones on the plan of Yas residential tower (the plan of tower is shown in Fig. 3 including the location of the studied zones of A in West side, B in South side, C in North side and D in East side of the eighteenth floor). A part of living room and sitting room are considered as zones A and D while the zones B and C are the private sitting room of the building. The details of the studied zones are listed Tables 1 and 2.

Figure 1. Location of the Yas residential tower, Mashhad, Iran.


Figure 2. View of Yas residential tower, Mashhad, Iran.

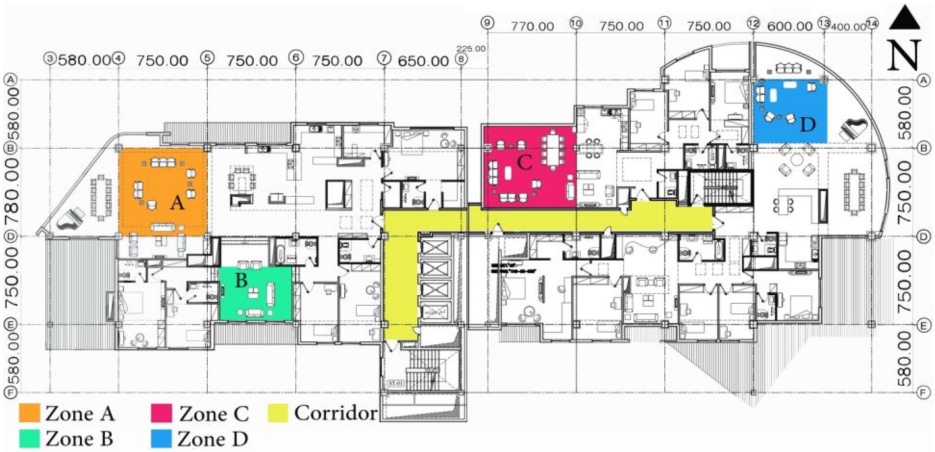


Figure 3. Location of the zones examined on the plan - 18th floor.

Table 1. The related case study data.

0.00 to the first floor	1.5 m
The thickness of the ceiling	0.35 m
First floor to the second floor	5.40 m
Second floor to the rooftop	5.40 m
The total area of the windows in the northern	10.40 m^2
The total area of the windows in the east	20.00 m^2
The total area of the windows in the west	10.80 m^2
The number of floors of the residental tower of Yas	20 floors + ground floor – 4 floors of the basement
The floor examined	18th floor
The height of floors 2-20	3.20 m
The thickness of the ceiling	0.35 m

Table 2. The zones studied of current work.

Zone name	A	B	C	D
Zone direction	West	South	North	East
OKB (m)	0.3	1.00	1.00	0.3
Floor area (m^2)	58.50	29.76	56.88	35.96
Wall area (m^2)	24.96	19.84	25.28	18.56
Window area (m^2)	22.62	5.76	7.92	16.82
Window ratio (%)	91	29	31	91

2.2. Sunlight analysis

In order to perform analysis in current work, the daylight simulation is first accomplished on exterior wall. Fig. 5 and 6 shows the sun path which is based on the longest and shortest day of the year on 22nd June and 22nd December during 11:00 am to 12:00 pm in kWh/m^2, respectively. Depending on the light intensity, the brighter spaces receive more light while the darker spaces receive less light.

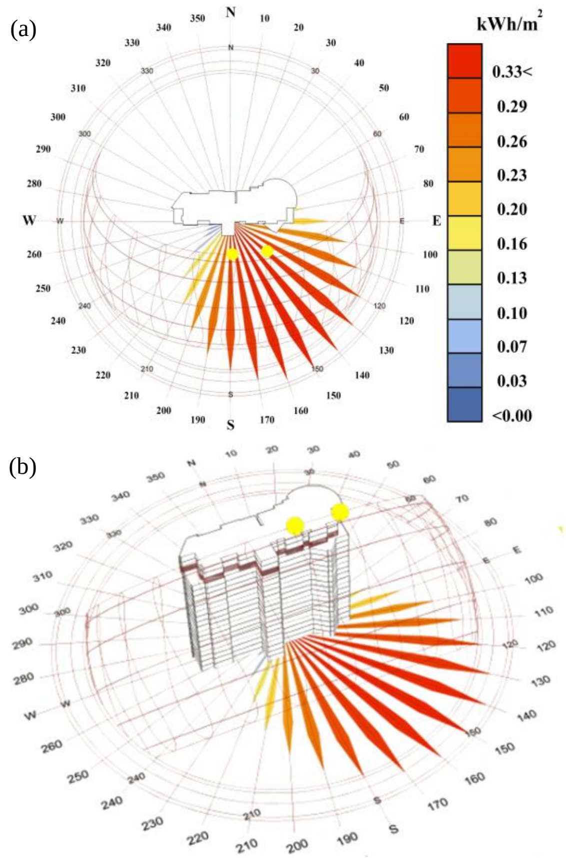


Figure 5. The diagram of sun path – Total radiation (kwh/m^2) - Mashhad - on 22 Jun; 11:00 – 12:00 - By HB-LB 2018. (a): Plan, (b): Perspective.

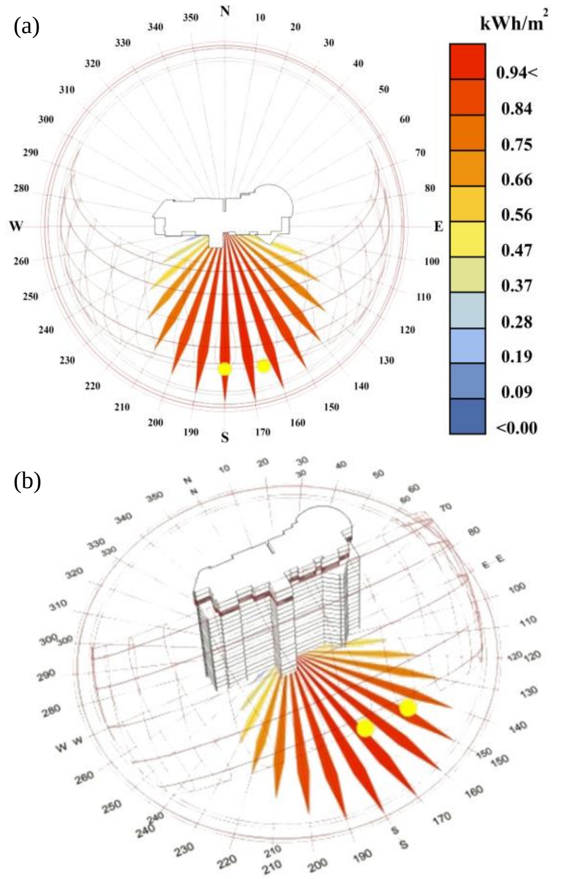


Figure 6. The diagram of sun path – Total radiation (kwh/m^2) - Mashhad - on 22 Dec; 11:00 – 12:00 - By HB-LB 2018. (a): Plan, (b): Perspective.

3. Results & Discussion

The mechanism of uniform light distribution in the interior space is significantly important. One of the main goals of daylight design in most of places such as official, residential and educational buildings is uniform distribution of light according to the standards in different interior spaces. What makes the use of daylight with desired quality possible for

the people is known as goals of daylighting design [25].

In present study, information and data analysis is performed in two parts: the first part investigates the light distribution in the interior environment which is conducted using some internal light shelves; and the second part evaluates the amount of electrical lighting energy reduction based on the optimal light shelf.

3.1. First part of analysis: light distribution in the interior environment

A classified framework is set to investigate the amount of light distribution in the space by optimization of the entrance light, taking into account the people's comfort condition. At first, the light distribution is evaluated in Base condition for the four orientations of the building as annual average during 12:00 pm to 01:00 pm. The obtained results are consist of the amounts and daylight autonomy graphs which present a deep and more realistic understanding of the daylight ability in the interior environment.

In order to investigate the light distribution in the interior spaces under study, six types of light shelves are proposed. Because of the North-South building being positioned in a non-angular manner relative to the movement of the sun, proposed light shelves in the west and east are provided vertically and the shelves of the northern and southern front are horizontally proposed. All analyzes are carried out to obtain the DA charts in all spaces with respect to light shelves. Fig. 7 shows the characteristics of proposed light shelves in the examined zone B and C. Because the light shelves in these two zones are horizontally of the same size, they have different widths. Fig. 8 shows the characteristics of light shelves in zone A and Fig. 9 shows the shelves characteristics in zone D [26].

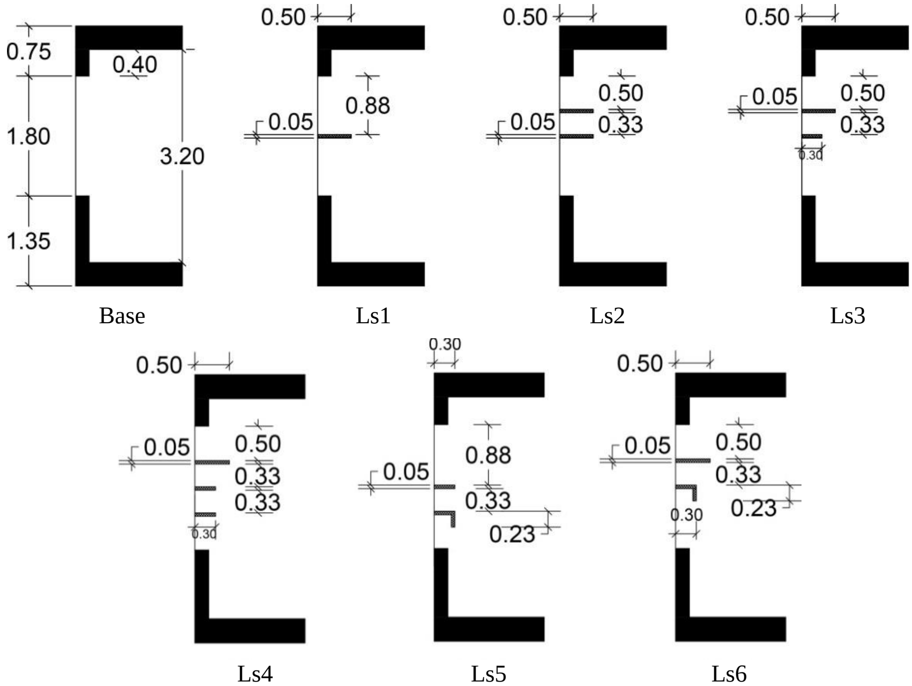


Figure 7. Suggested light shelves in the examined zone B (south) and C (north).

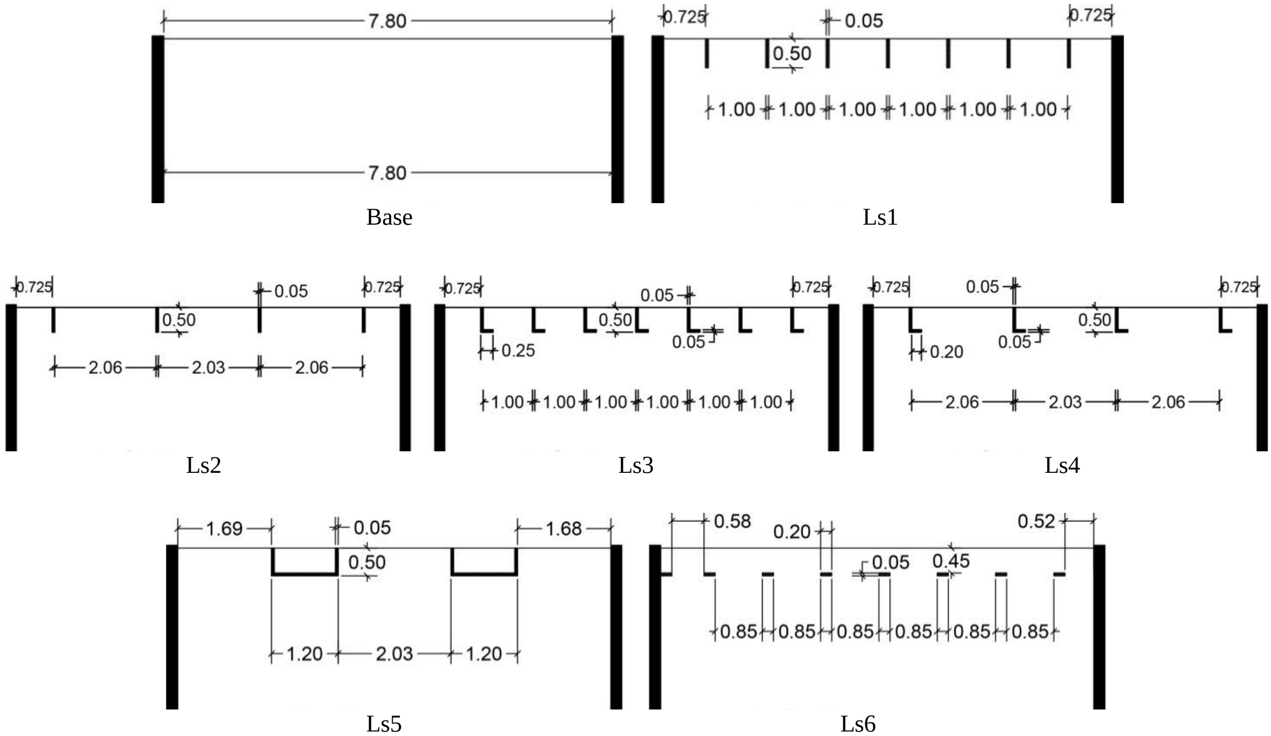


Figure 8. Suggested light shelves in the examined zone A (west).

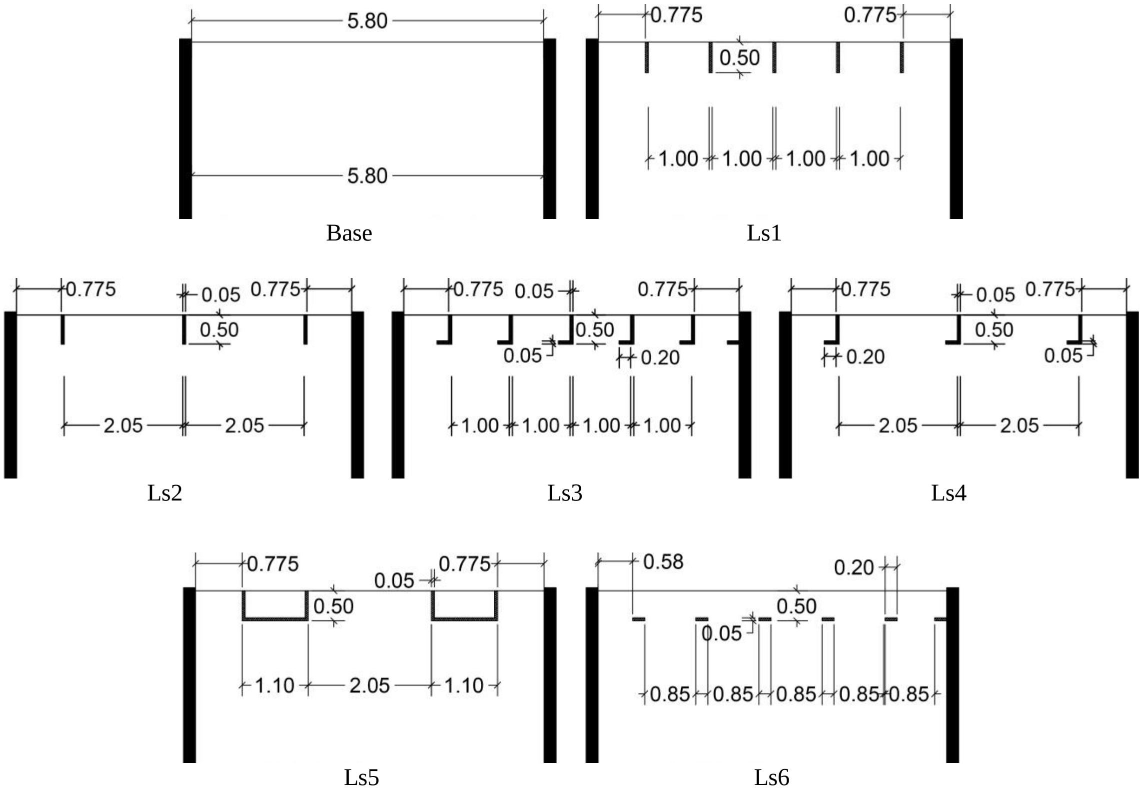
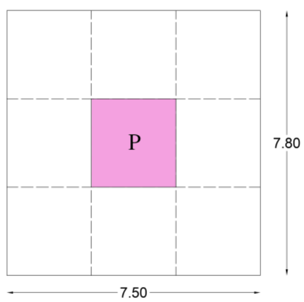
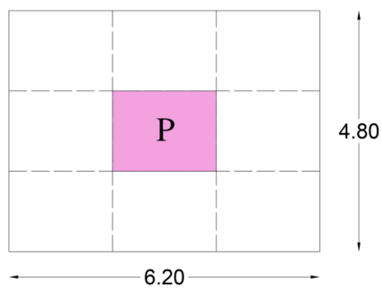


Figure 9. Suggested light shelves in the examined zone D (east).

It should be noted that for optimization of the entrance light to A, B, C and D zones, the light shelves are only placed in the interior environment of the specified zones.

For detailed evaluation of light distribution in the interior environment, the daylight is examined in the defined area P as shown in Fig. 10 [27, 28]. The measurement criterion for light distribution in the interior environment is light intensity percentage. Light distribution evaluation is considered at the height of 80 cm above the floor where the people do their activity on the living room sofa or table surface. Figs. 10 and 11 demonstrate the area P and the distance from the floor in the studied zones. This is a factor for evaluation of daylight distribution in the interior environment. The required light amount in the residential spaces is 300 lux and DA amount is given in percentage. In addition, 50% of DA provides an optimal space equal to 300 lux [22].





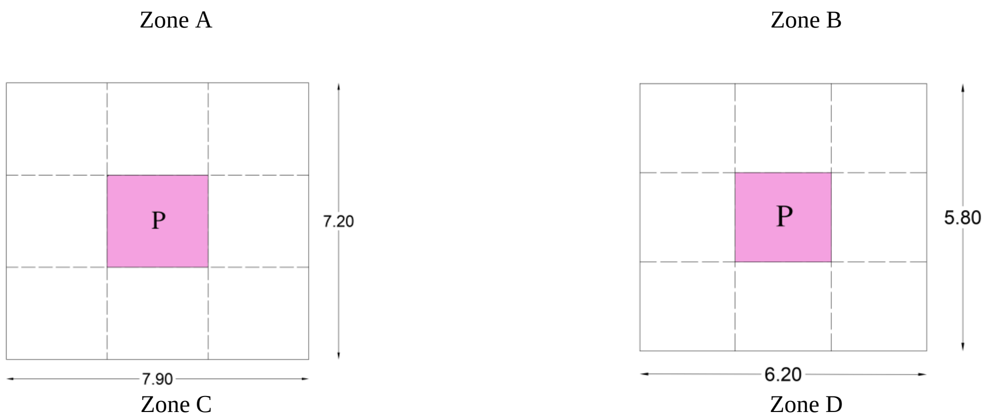


Figure 10. Defined area P in the studied zones.

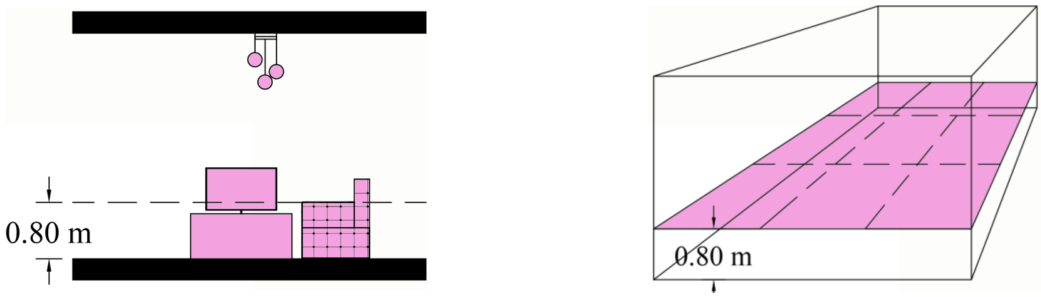
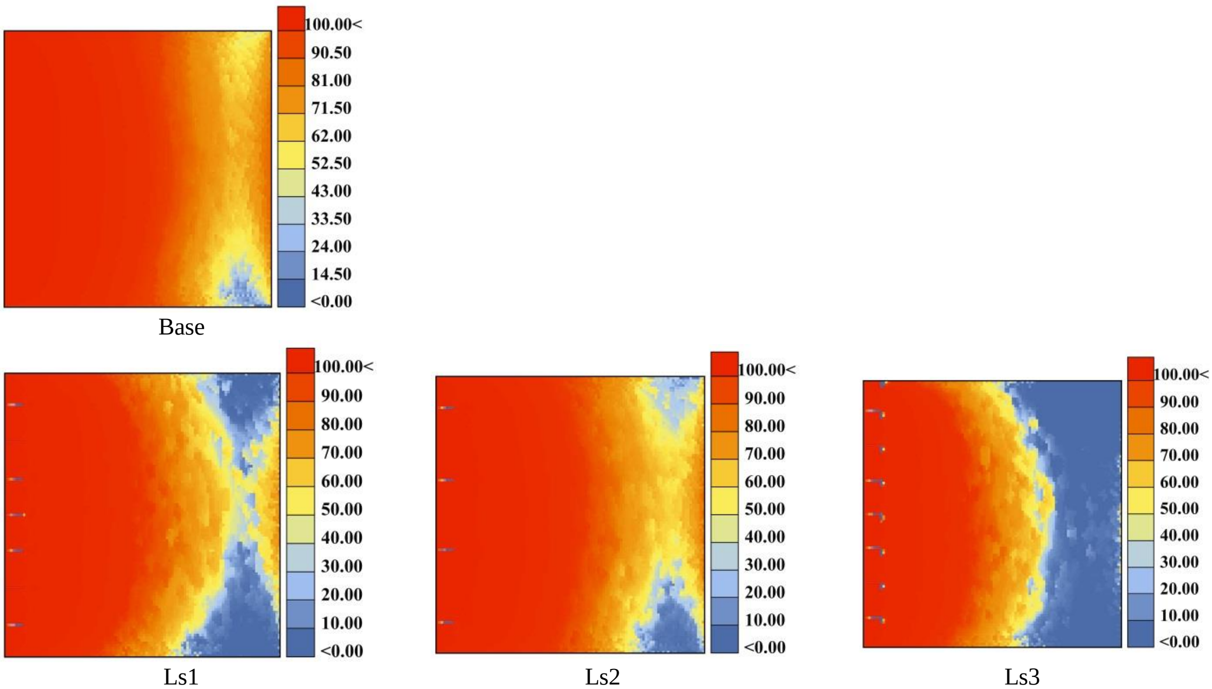


Figure 11. Light distribution evaluation at 80 cm above the floor.



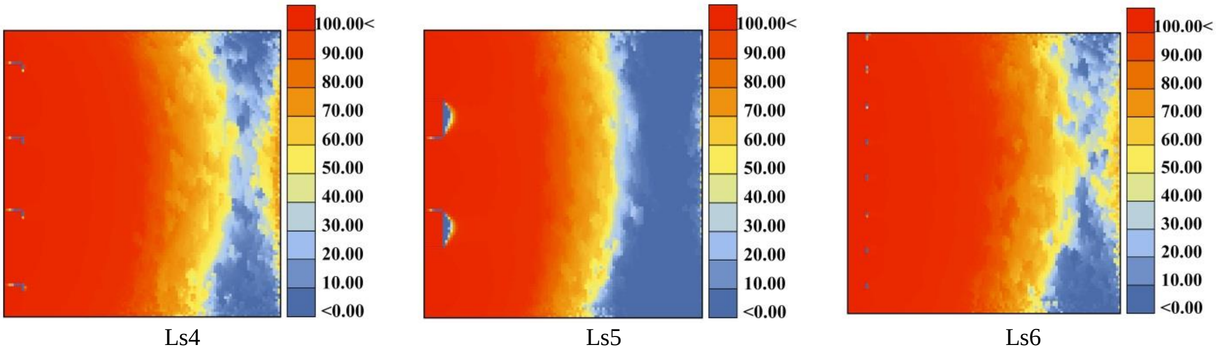


Figure 12. Rate analysis of the DA in Zone A; in current state and with suggested light shelves at hours 12-13; annual average.

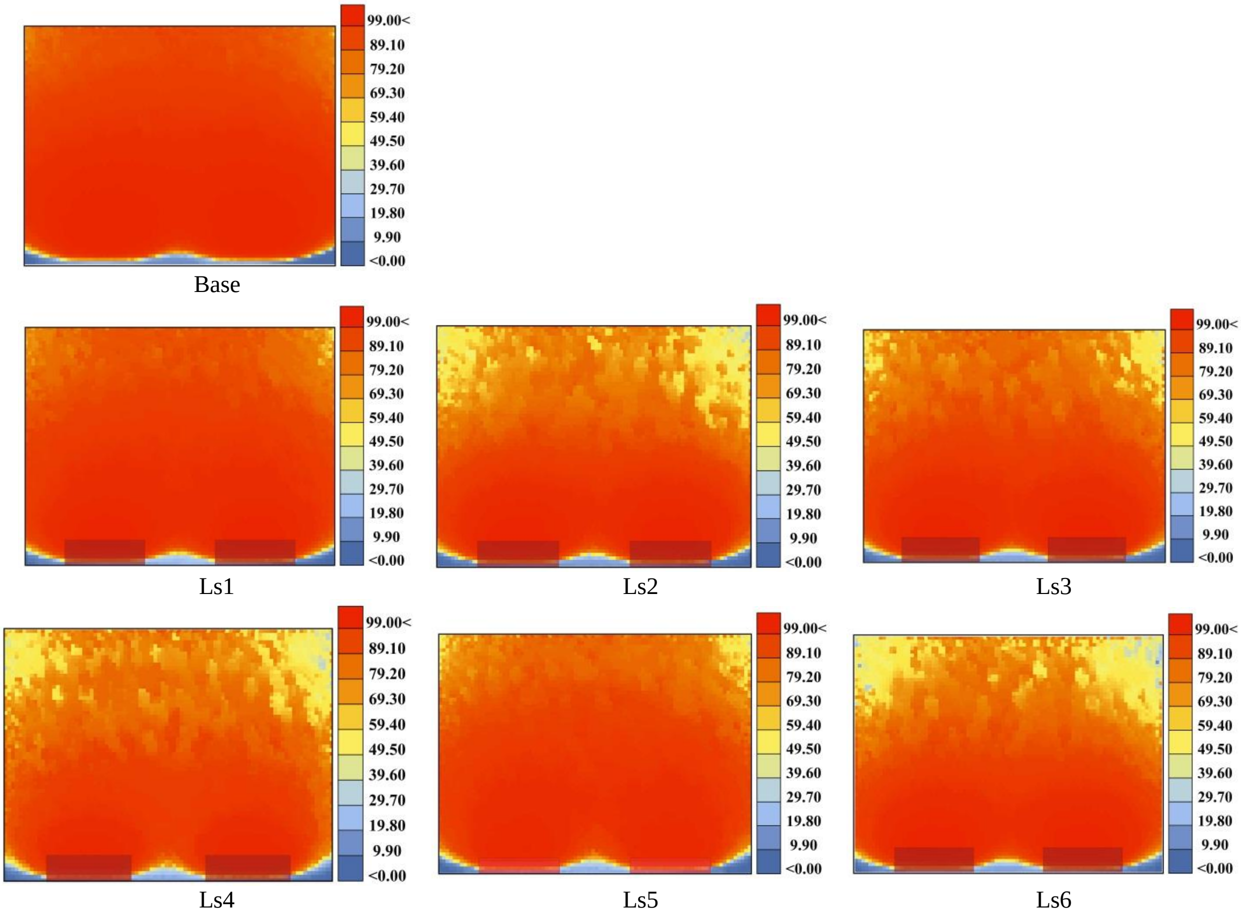


Figure 13. Rate analysis of the DA in Zone B; in current state and with suggested light shelves at hours 12-13; annual average.

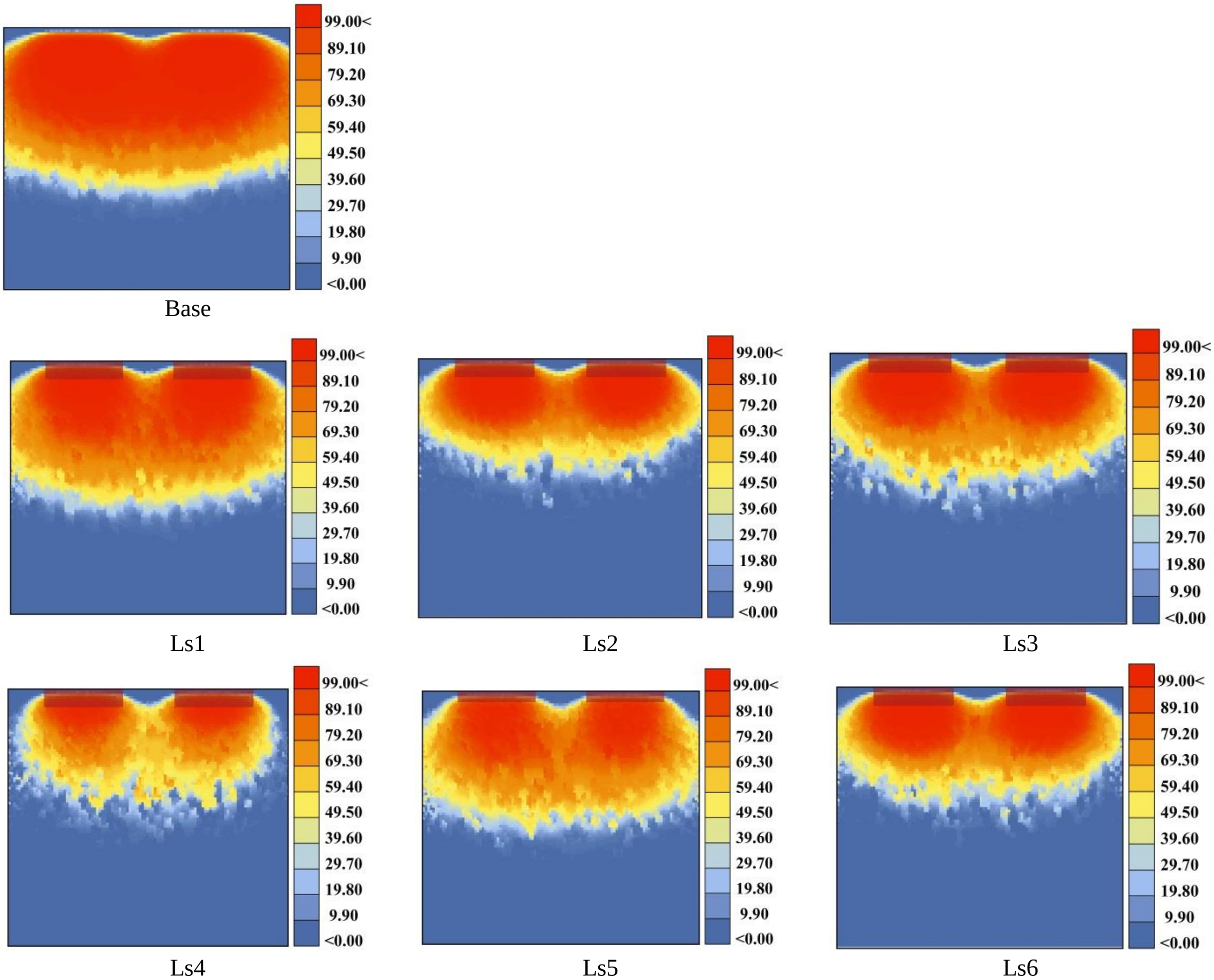
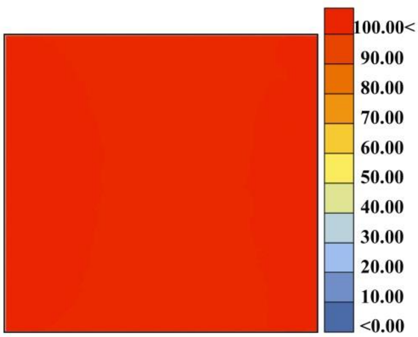


Figure 14. Rate analysis of the DA in Zone C in current state and with suggested light shelves at hours 12-13; annual average.



Base

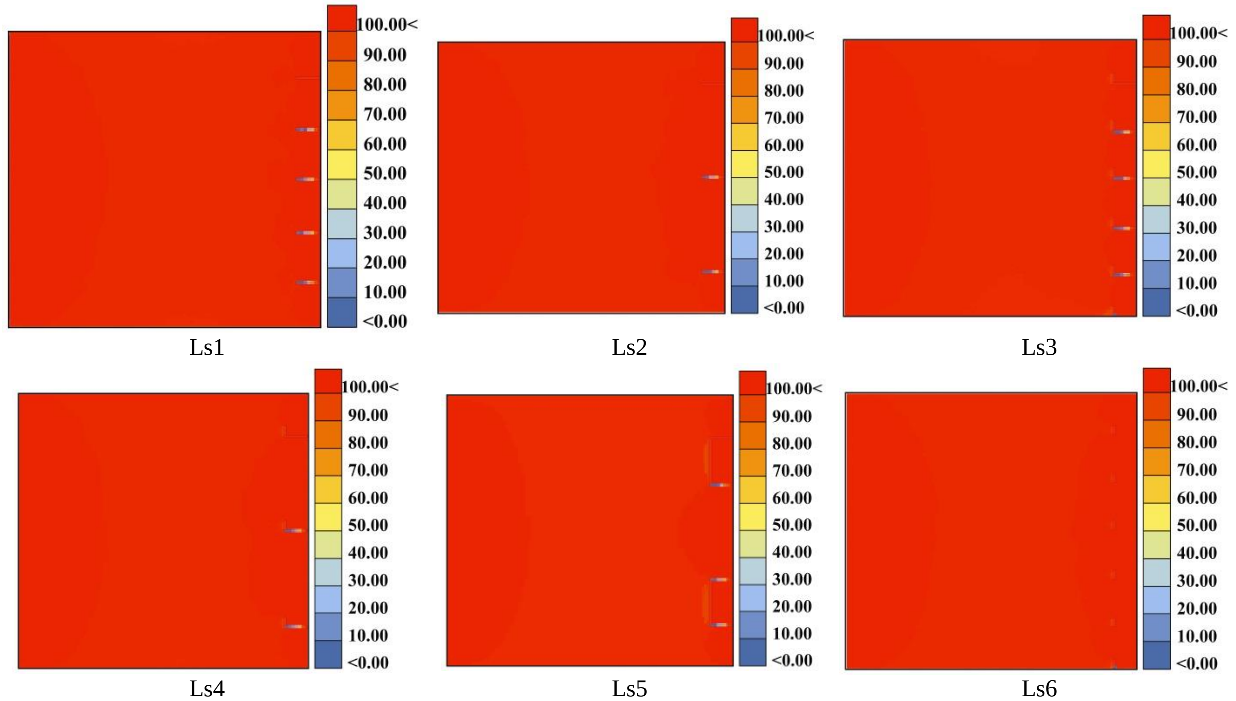


Figure 15. Rate analysis of the DA in Zone D in current state and with suggested light shelves at hours 12-13; annual average.

DA of the studied zone A (located at West side of the building):

According to Fig. 12, the variety of light shelves leads to variation in daylight distribution in the interior environment and all light shelves reduce the light intensity in the space. Compared to other light shelves, light shelf No. 3 and No. 5 allow less light to reach deep into the space as some parts of the space have DA of 0. Considering the defined area P and DA of 300 lux which is 50%, the light shelf No. 3 provides the optimal condition while the light shelf No. 1 and No. 4 provide the condition near to optimal condition.

DA of the studied zone B (located at South side of the building):

Fig. 13 shows that the studied zone B without light shelf has high light intensity. Considering the light shelf No. 1, the light intensity is better than the Base condition but the comfort condition is not provided. Moreover, the light shelf No. 3 and No. 5 makes the light to have better performance in the environment. Considering the defined area P and entrance light of 300 lux (the optimal criterion for daylight is DA of 50%), the light shelf No. 2, No. 4 and No. 6 control the distribution of the entrance light and create the optimal condition as the light shelf No. 4 provides the best condition compared to the other optimal light shelves.

DA of the studied zone C (located at North side of the building):

As it can be observed in Fig. 14, the intensity of entrance light to zone C is less than the other zones, because it is located at North side of the building and benefits from light reflection and indirect light. As seen, some part of the space without light shelf has DA of 0. Light shelves decrease the light penetration depth and more spaces have DA of 0. Light shelf No. 1 provides the optimal comfort condition based on the defined area P and DA amount of 300 lux. Generally, the light shelves can be avoided in zone C which does not benefit from direct light.

DA of the studied zone D (located at East side of the building):

Fig. 15 illustrate that the studied zone D locate in the East side of the building has the highest level of light intensity and light distribution. Although they can not be used as optimal light shelf but all the proposed light shelves, except the light shelf No. 5, make significant change in the intensity and distribution of light. The light shelf No. 5 provides better condition compared to the other light shelves and considering the defined area P and the optimal criterion of 300 lux and DA of 50%, it brings the people's comfort condition close to the optimal condition.

3.2. Second part of analysis: evaluation of the lamp's electrical energy consumption during the day based on the optimal light shelves

Understanding the consumption pattern of artificial lighting during the day can be used as a basis for energy consumption evaluation.

Considering the average sizes of the studied zones, four lamps are used in Zones A and C while three lamps are used in Zones B and D which each lamp has the power consumption of 50 W [24]. If the occupants need to use the artificial lighting during the day, two lamps can used for four hours in each zone. According to Table 3, the annual energy consumption of the studied zones is 576.048 kWh/year using two 50 W lamps for four hours during the day. Considering the optimal light shelves evaluated in the previous section, around 576.048 kWh/year saving in artificial lighting energy consumption of lamps can be obtained.

Table 3. The value of energy used by the lamps is in the study spaces.

Zone name	Zone A (west)	Zone B (south)	Zone C (north)	Zone D (east)	Total Yearly energy [kWh/year]
Number of lamps in space	4	3	4	3	576.048
Number of lamps used - daily	2	2	2	2	
Power [W]	50	50	50	50	
Daily use [hours]	4	4	4	4	
Daily energy [Wh/day]	400	400	400	400	
Monthly energy [kWh/month]	12.001	12.001	12.001	12.001	

4. Conclusions

The current study is presented in two parts: the first part investigates the people's comfort condition due to light distribution in the interior environment and the second part evaluates the energy consumption reduction of artificial lighting using lamps considering the light shelves. First, In order to reach the people's comfort condition, four zones are selected at four orientation of the building and daylight autonomy (DA) is evaluated at each zone. DA is presented in percentage which DA of 50% provides the desired condition of 300 lux in the residential environment. The light shelves are proposed in accordance with the zones as horizontal light shelves are used in North and South zones while vertical light shelves are used in East and West zones. All the specified zones are studied using six proposed horizontal and vertical light shelves; and the area P is considered as an evaluation basis for detailed investigation. Then, taking into account the optimal light shelves, the energy consumption reduction of artificial lighting using lamps is calculated in each zone. The main findings of the present research are as follows:

- The light shelf No. 3 in the studied zone A (West), the light shelf No. 2, No. 4 and No. 6 in the studied zone B (South) and the light shelf No. 1 in the studied zone C (North) control the light distribution in the interior environment and provide the comfort condition for the people.
- The light shelf No. 1 and No. 4 in the studied zone A (West) brings the people's comfort condition close to the optimal condition.
- The light shelf No. 5 in the studied zone D (East) controls the light the interior environment compared to the other light shelves.
- The maximum comfort condition is obtained for the occupants using the optimal light shelves in the studied zones.
- Using the optimal light shelves in the studied zones can lead to 576.048 kWh/year energy consumption reduction during the year.
- Using the internal light shelves is a simple and available approach for people to reach the comfort condition and energy saving.

Appendix

In Yas Residential Tower, Fig. A1 to A5 shows the average amount of received daylight (in hour) during the day which denotes the duration that the specified zones are in direct contact with the daylight.

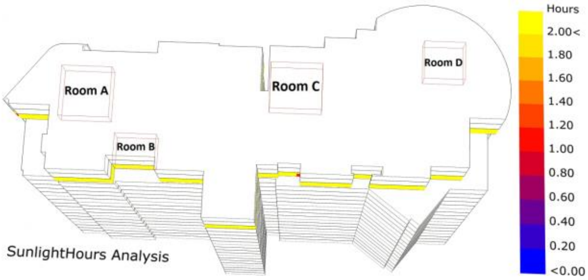


Figure A1. Sunlight Hours Analysis.

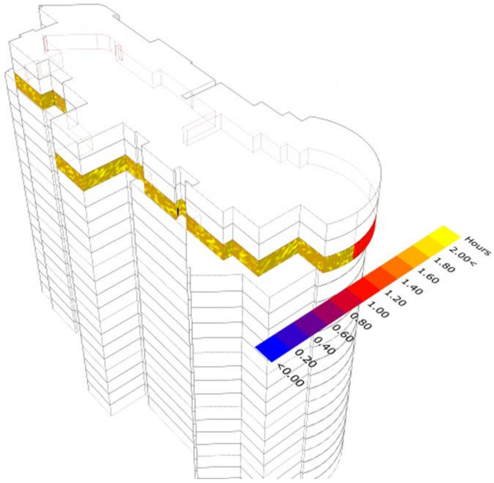


Figure A2. Sunlight Hours Analysis.

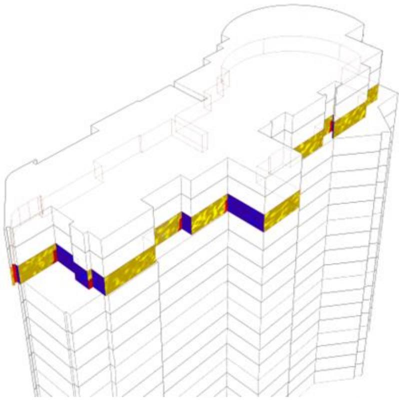


Figure A3. Sunlight Hours Analysis.

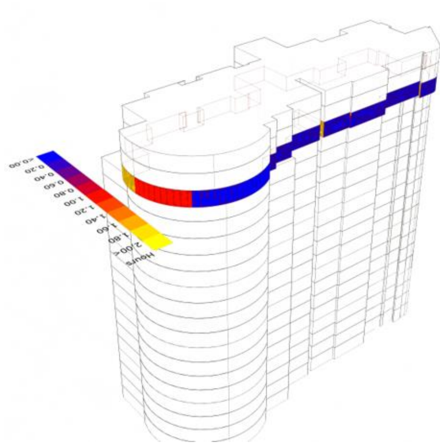


Figure A4. Sunlight Hours Analysis.

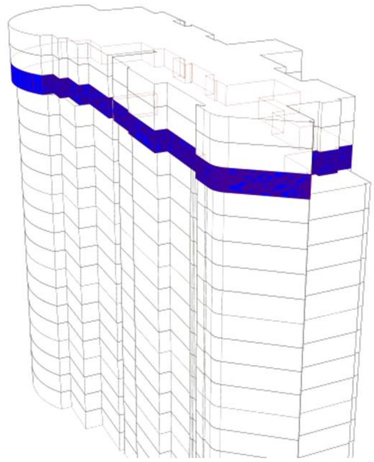


Figure A5. Sunlight Hours Analysis.

As it was mentioned in the paper, weather conditions data of Mashhad city was used for analysis. Fig. A6 to A9 shows some of the daylight graphs of Mashhad city.

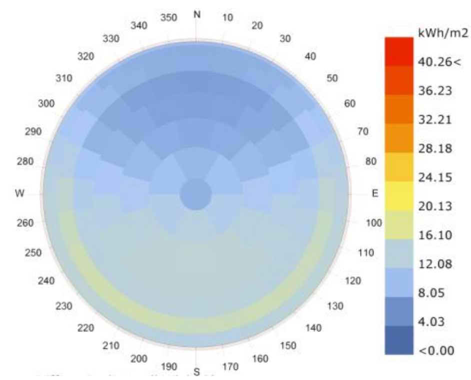


Figure A6. Diffuse radiation; kWh/m^2; Mashhad; 1 JAN 01:00 – 31 DEC 24:00.

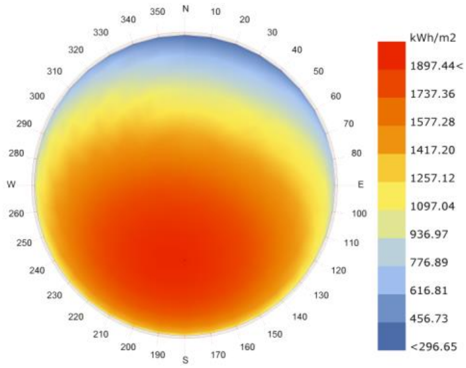


Figure A7. Radiation calla dome; kWh/m^2; Mashhad; 1 JAN 01:00 – 31 DEC 24:00.

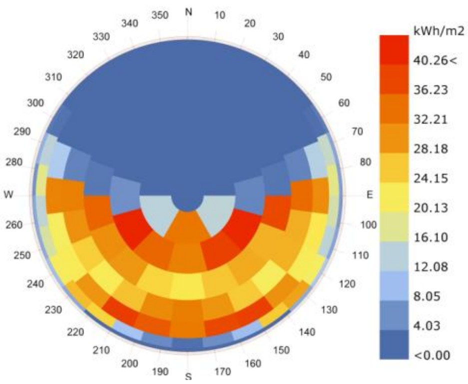


Figure A8. Direct radiation; kWh/m^2; Mashhad; 1 JAN 01:00 – 31 DEC 24:00.

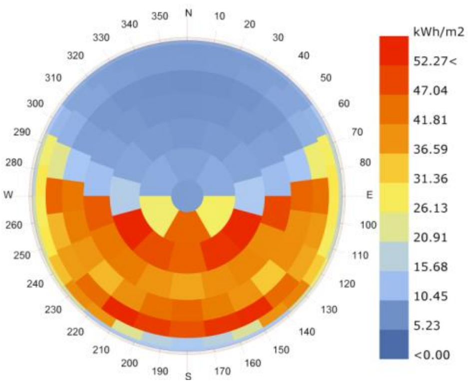


Figure A9. Total radiation; kWh/m^2; Mashhad; 1 JAN 01:00 – 31 DEC 24:00.

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