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Evaluation of Quality of Daylight in a Contemporary Residential Building with a Central Courtyard in Kerman, Iran

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A B S T R A C T

The research aims to develop sustainable daylighting strategies for contemporary buildings by drawing inspiration from traditional vernacular housing solutions. In this study, the daylight factors of a contemporary residential space with a central courtyard which is located in Kerman, Iran is evaluated. After modeling the building in Design Builder software, the U-values of the external walls, roof, floor and windows based on the available materials in the market of Iran are calculated. The results of daylight simulations are presented in term of Average DF (%), Work plane Illuminanace (Lux) and Uniformity Ratio as well as annual Indicators of daylight such as sDA and UDI. Zone 3 in the ground floor which is a space under top lit atrium acts as a source of daylight. Although, Zone 5 in the ground floor has reasonable daylight factor, the uniformity ratio is not acceptable due to simultaneously existing the areas of little and high illuminance. Zone 7 in the first floor as a public sapce can provide large potential for daylight utilization with DF equal to 2.6% and average WPI with 826 Lux because there is a possibility to receive daylight from east direction with designing central courtyard in the first floor plan.

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INTRODUCTION

Achieving sustainable daylighting is essential to enhance visual comfort indoors, reduce energy consumption on artificial lighting, and improve the psychological well-being of occupants. Although several studies (1, 2) have been conducted on sustainable daylighting; there has been limited focus on vernacular architecture (3), which has evolved over hundreds of years to create comfortable habitats using locally available materials and established construction techniques. This climate-responsive design approach is being undermined by universal architecture in emerging countries like India, which prioritizes modernity over traditional practices. As a result, there is a need to revive and integrate vernacular architecture into contemporary building design to promote sustainable daylighting and preserve cultural heritage.

Acosta et al. (4) presented a method for determining daylight factors in courtyards and atriums to improve energy efficiency and lighting design. The method involves defining daylight factors using measurements in scale models and values obtained in real courtyards under real overcast skies. The sky component is defined based on earlier studies and Tregenza algorithms. The proposed method is compared with previous measures and offers an average accuracy of over 90%. Finally, the energy saving in electric lighting is quantified following the predictive method established.

The daylight quality of traditional courtyard houses in a hot and dry region of Iran, using the Yazdanpanah House as a case study was investigated by Tayari and Nikpour (5). The study calculates the average work plane illuminance and uniformity ratio in five separate rooms around the courtyard. The findings suggest that all rooms

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surrounding the courtyard have the ability to achieve work plane illuminance of more than acceptable value, with one room facing the south direction achieving more than 500 Lux work plane illuminance. The research concludes that these findings could be used to design more comfortable rooms in contemporary houses in terms of daylight quality by creating central courtyards. The paper emphasizes the importance of daylighting in providing visual comfort in buildings and reducing energy consumption.

Sudan et al. (6) presented a new daylight performance metric, Daylight Illuminance Ratio (DIR), for evaluating the amount of direct and diffuse daylight in an atrium space. The metric is experimentally validated and shows good agreement between theoretical and experimental values. The paper discusses the impact of various factors such as the orientation and geometry of the atrium, the roof system and fenestration, and the interior wall and floor reflectances on the daylight illuminance levels inside the atrium and adjoining spaces. This study also discusses the limitations of the static daylight factor metric and the advantages of dynamic daylight metrics such as Climate-Based Daylight Modeling (CBDM) metrics. The presented metric can be used to predict vertical illuminance at a given point on the atrium walls.

Acosta et al. (7) discussed a predictive method for calculating daylight factors in square courtyards under overcast sky conditions. It presents the calculation method for the sky component based on earlier studies and Tregenza algorithms. The article also includes a simulation of daylight factors in courtyards using different lighting computer programs. The internally reflected component is quantified based on the theory of the integrating sphere. The study highlights the importance of courtyards in providing natural light and ventilation in buildings.

Gunasagaran et al. (8) conducted a simulation study to determine the optimal configuration for improving the environmental conditions of a courtyard space in a hot and humid climate. The study used a terrace house with a courtyard design in Penang as a case study. Four different courtyard configurations were evaluated through daylight and computational fluid dynamics (CFD) simulations. The findings indicated that a semi-enclosed courtyard design with a shading device demonstrated the best results in terms of creating favorable environmental conditions in the courtyard space of a terrace house in a hot and humid climate.

Indoor thermal and luminous environments in courtyard buildings located in an arid region were discussed by Guedouh and Zemmouri (9). The study aims to identify daylighting strategies and thermal comfort conditions in this type of building. Monitoring campaigns were conducted during summer and winter seasons to collect temperature and illuminance data. The findings highlight the high potential of courtyard buildings in providing natural lighting and thermal control. The study also emphasizes the interaction between courtyard buildings and their adjacent spaces in enhancing thermal and luminous performances.

A study conducted by Priya and Kalaimathy (3) investigated climate-based daylighting techniques in traditional houses with four different roof typologies in Tamil Nadu, India. The research focused on examining the impact of the total number of door and window openings on the uniformity ratio and daylight factor. The study utilized simulation with Design Builder software and experiments with an illuminance meter. The findings revealed that wind catcher houses, courtyard houses, and clear storey houses provided better visual comfort compared to tiled roof houses.

Vaisman and Horvat (10) discussed the influence of internal courtyards on energy load and illuminance in row houses in Toronto. It explores the benefits and drawbacks of using internal courtyards in cold climates to improve energy performance, natural light, and occupants' well-being. The study shows that internal courtyards significantly improve the hours of illuminance in row house interiors, especially during shorter winter days. The window-to-wall ratio does not have a major impact on daylight penetration. The research aims to provide design information for new construction and retrofits of row houses, considering energy efficiency and daylight enhancement.

Elsiana et al. (11) discussed the daylight performance of courtyard wall designs in low-cost flats located in the tropics. The existing courtyard walls in these flats are typically protected with a shaded corridor, which reduces the daylight level in adjacent dwelling rooms. To improve the daylight level and control excessive light penetration, a modification of the courtyard wall using a sloped light shelf is proposed. The study uses simulation experiments to compare the illuminance value, Daylight Factor, and uniformity ratio of the base case (courtyard wall with louvers) and the proposed design (courtyard wall with a sloped light shelf). The results show that the modification reduces excessive illuminance in the corridor and improves illuminance in the dwelling rooms, thereby enhancing daylight quantity and quality in low-cost flats in the tropics.

The native architecture of Iran has unique characteristics that makes it timeless and survive. Among the fundamental characteristics of this architecture, three things can be refered: The adaptation to the climate of the region and the optimal use of natural light, introversion and space-oriented. Introverted architecture is a spatial pattern that tends to hide what is or happens inside and relies on maintaining the privacy of the home and therefore the beauty of the architecture can be seen when you are inside or in its courtyard.

The most important features of Iranian architecture, especially in desert areas, is the issue of climate (interaction with summer heat and winter cold) and the maximum use of suitable natural light. To achieve this goal, the architecture of this area has been implemented in the form of interlocking blocks on an urban scale, and the surface of external walls has been minimized. Therefore, in order to use optimal light, an empty space is built in the center of every house, which is called the central courtyard. The central courtyard allows adequate light to reach all the interior spaces around it. Nowadays, in the contemporary urban planning of Iran, due to several reasons, including: the increase in the population of cities, the existence of cars, migration, etc., the residential land has been separated in such a way that according to the municipal regulations, the category of the central yard has basically disappeared. The municipal rules allow the construction of sixty percent of the land, which is chosen from the north side, and it is practically not possible to create a central courtyard. Therefore, it is difficult to use natural daylight for all spaces. Some contemporary architects have made many creative efforts to deal with these criteria and provide maximum light for interior spaces.

One of the projects in contemporary residential space with a central courtyard is a house in Kerman, which, despite the rule of sixty percent (sixty percent land construction) of Kerman municipality, has managed to create a small central courtyard on the upper floor of the building. This central courtyard has made it possible for all the main spaces of the house to benefit from natural light. To the best of author's knowledge, investigating the daylighting parameters of central courtyard buildings considering the urban regulation of 60% construction in Iran has not been carried out. Therefore, the purpose of this study is to investigate the daylighting status of this house as a successful design to take sufficient advantage of natural light according to the strict conditions of the municipal regulations.

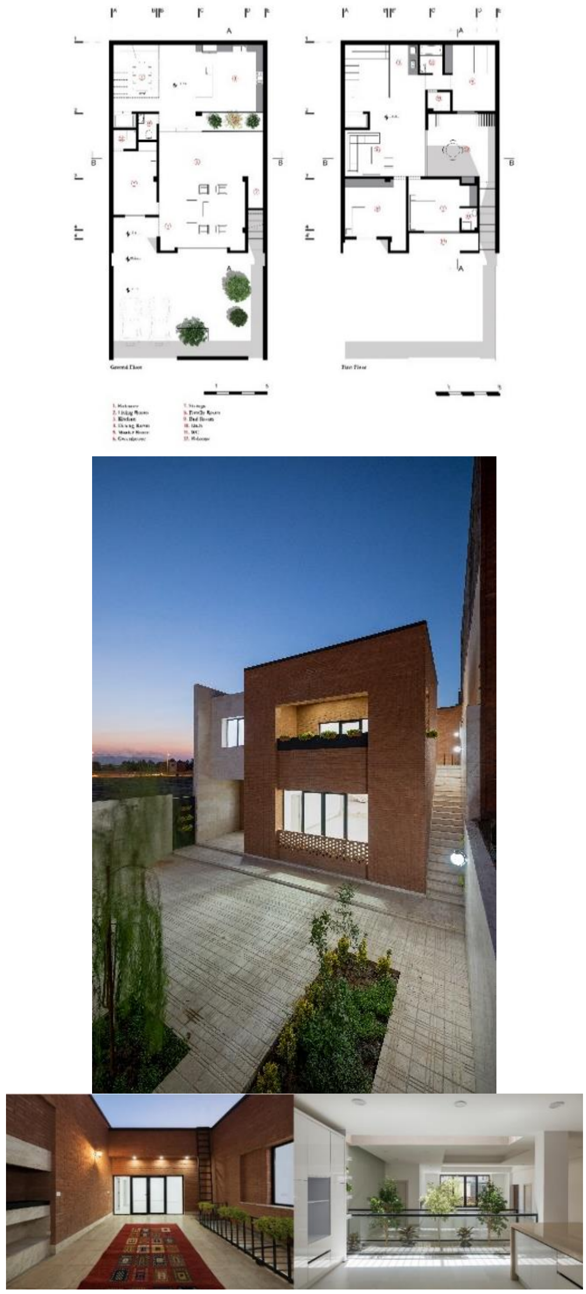

Figure 1. The central courtyard building under consideration

RESEARCH METHODOLOGY

The central courtyard building under consideration is depicted in Figure 1. It is aimed to evaluate the daylight factors of this building which can be considered as a typical building in 60% construction limitation in urban areas.

For daylight evaluation of architectural spaces different indicators were applied. The most important indicators are:

Daylight factor (DF): It refers to the ratio of the indoor daylight illuminance (Ei) at a specific point within the space in comparison to the outdoor illuminance (Eo) at that point under the same open overcast sky, calculated in percentage as follows (12):

$$DF = \left({E_i}/{E_o}\right) \times 100\% \quad (1)$$

The illuminance of daylight is the sum of the direct light from the sky in lux (SC), externally reflected component (ERC) and internally reflected components of solar radiation (IRC) as following (13):

$$\text{Illuminance} = \text{SC} + \text{ERC} + \text{IRC} \quad (2)$$

Table 1 shows the range of daylight factor and illuminance (14) parameters.

Spatial Daylight Autonomy (sDA)

A technique called Spatial Daylight Autonomy has been devised to assess the adequacy of daylight illuminance in

Table 1. Range of daylight factor and illuminance (14) parameters

Daylight factor	
< 1%	Unacceptable
1-2%	Acceptable
2-5%	Preferable
>5%	Ideal for paper work/ too bright for computer work
Illuminance	
<100 lx	Too dark for computer and paper work
100-300 lx	Too dark for paper work/ acceptable for computer work
300-500 lx	Acceptable for paper work/ ideal for computer work
>500 lx	Ideal for paper work/ too bright for computer work

a given area. It involves calculating the percentage of floor space that meets a specified illuminance level for a certain number of hours throughout the year. For instance, sDA (300, 50%) indicates the proportion of space where the illuminance exceeds 300 lux for 50% of the time (15).

Useful Daylight Illuminance (UDI)

The Useful Daylight Illuminance stands for the amount of light that falls in a given area during the course of the year as a distribution to reach a predetermined illumination goal in the range of 100-3000 lux (15). Table 2 shows daylight Illumination based on UDI.

For the purpose of daylight evaluation of the contemporary built house, the whole building was modeled in Design Builder software for simulation. Figure 2 shows the modeled building under consideration in Design Builder.

As it can be seen in Figure 3, the ground floor plan was drawn with five thermal Zones under “Block 1” and First Floor Plan was drawn with 8 Thermal Zones under “Block2”. In the Design builder software, the construction details of materials such as Exterior walls, floor, Roof and windows were identified based on available material in the market of Iran. Thermal resistance coefficients of different layers of building

Table 2. Daylight Illumination based on UDI (16)

Daylight level	Definition
Non-dayligt	UDI<150 lux≥50% of occupancy time
Partially daylight	UDI 150-300 lux≥ 5%of occupancy time
Full daylight	UDI 300-3000 lux≥ 50%+UDI 3000, <5% of occupancy time
Overlit	UDI> 3000 lux ≥ 5% of occupancy time

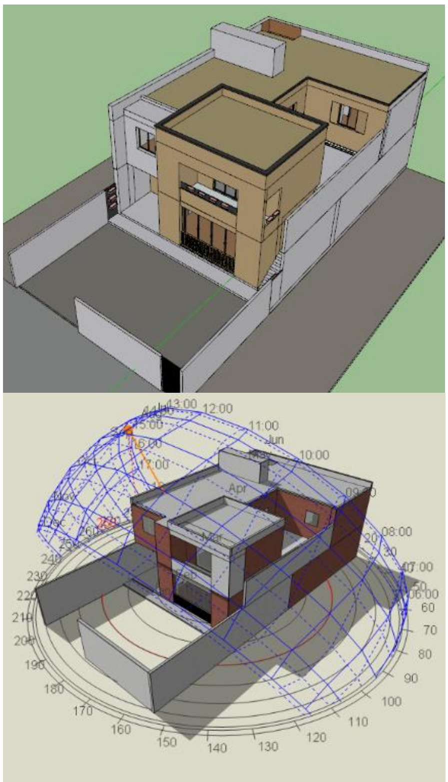

Figure 2. Modeled building in Design Builder software

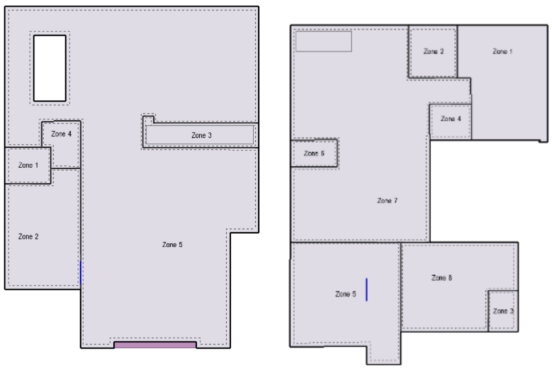

Figure 3. Different zones in ground floor (left) and first floor (right) of the building in Design Builder software

envelope are derived from the Topic 19 of National Building Regulations of Iran and final U-value of different envelopes imported to the design building construction section.

Table 3 Shows different layers of the project’s External walls and other characteristics which used for calculation of the U- value of the external walls.

In Figure 4, details of the U- value of the External walls in Design Builder software can be seen.

Table 4 Shows different layers of the project’s roof and other charactristices which used for calculation of the U- value of the roof.

Table 3. Details of the calculation of the U- value of the External walls

No.	Main group	Sub group	Technical Characteristics	Thermal conductivity coefficient	Thickness (mm)	Thermal Resistance	
	Resistance of external air Layer					0.05	0.05
1	Brick for Facade	1 layer			30	0.03	0.03
2	Cement plaster and mortar	Cement	Density 1800 to 2000	1.30	50		0.038
3	Clay block wall	3 rows of cavities			150	0.3	0.3
4	Cement plaster and mortar	Cement	Density 1800 to 2000	1.30	20		0.015
5	Gypsum	Internal lining	Density less than 1000	0.4	10		0.025
	Resistance of Internal air Layer						0.09
	R			0.409 m^2.k.W			
	Rt			0.549 m^2.k.W			
	U- Value			1.822 W/m^2.k			

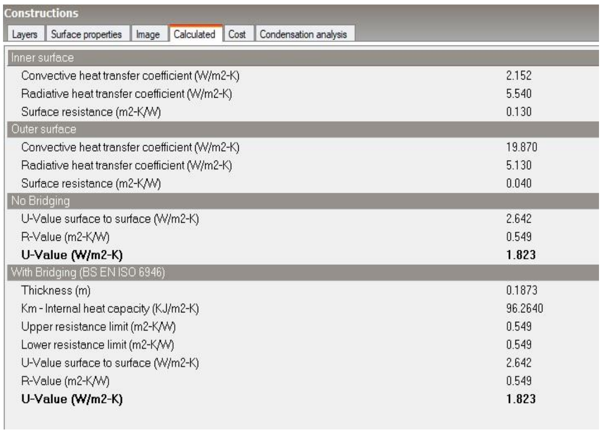

Figure 4. Determining the U- value of the External walls in Design Builder software

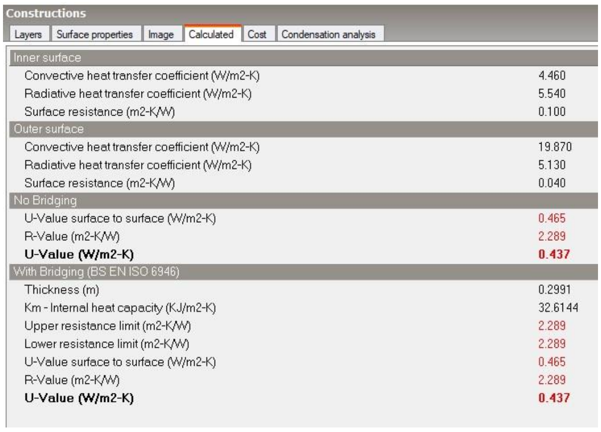

Figure 5. Determining the U- value of Roof for Design Builder software

Figure 5 shows details of Determining the U- value of the Roof in Design Builder software.

As the windows in the project are double pane windows with 6 mm thickness of glass and 13mm cavity which filled by argon gas, the U-value of windows is determined in Design Builder software as 2.511 W/m^2.K (Figure 6). In addition, the U- value of floor is considered 0.250 W/m^2.K as it has been shown in Figure 7.

Therefore, the U-values of the external wall, roof, floor and windows of the project were determined in Design Builder software are 1.822, 0.435, 0.250 and 2.511 W/m^2.K, respectively. In addition, Weather data of Kerman city was used for daylighting simulations. The daylighting analysis is interpreted and discussed in the next section.

Figure 6. Determining the U- value of the double pane window in Design Builder software

RESULTS AND DISCUSSION

The results of daylight simulations of Ground floor were tabulated in Table 5 in term of Average DF (%), Work plane Illuminanace (Lux) and Uniformity Ratio as well as annual Indicators of daylight such as sDA and UDI.

Table 4. Details of the calculation of the U- value of the Roof

No.	Main group	Sub group	Technical Charactristices	Thermal conductivity coefficient	Thickness (mm)	Thermal Resistance	
	Resistance of external air Layer					0.05	0.05
1	Stone	Limestone	Hard	1.700	20		0.012
2	Cement plaster and mortar	Cement	Density 1800 to 2000	1.30	30		0.023
3	Concrete and concrete products	Light weight concrete	With natural pumice or porous expanded slag (density 1750) - with fine particles or sand - density 1200 to 1400	0.440	100		0.227
4	Moisture insulation	Reinforced modified bitumen prefabricated sheet	Density 1000 to 1100	0.230	10		0.043
	Expanded polystyrene beam and block with heel 30 (ceiling)	Block height: 120, beam heel width 95 to 124	The distance between the axles is 550 to 600		300	1.820	1.820
5	Gypsum	Internal lining	Density 1000 to 1200	0.570	20		0.035
	Resistance of Internal air Layer						0.09
Total	R			2.161 m^2.k.W			
	Rt			2.301 m^2.k.W			
	U- Value			0.435 W/m^2.k			

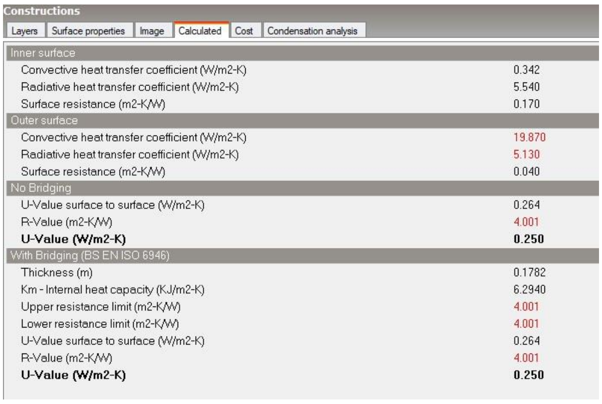

Figure 7. Determining the U- value of the floor in Design Builder software

Table 5. Simulation results in term of different indicators of daylight for ground floor

Block	1	1	1
Zone	2	3	5
Floor area (M2)	17.604	5.554	135.207
Average daylight factor (%)	0.85	6.24	1.846
Average illuminance (Lux)	382	596.6	952.55
Uniformity ratio (Min / Max)	0.019	0.648	0
sDA area in range (M2)	4.74	5.554	73.776
sDA area in range (%)	26.92	100	54.57
UDI area in range (M2)	16.153	5.554	99.446
UDI area in range (%)	91.76	100	73.55

Zones 1 and 4 are services area of house such as bathroom and toilet and these spaces do not have any windows therefore daylight analysis of these spaces is not shown. Zone 3 with area 5.55 m^2 in the ground floor is a space under top lit atrium. Therefore, this space acts as a source of daylight. Zone 2 in the ground floor as a bedroom receives 382 lux as Average Work plane Illuminance. This space also has average DF, 0.85%. This means this space has negligible potential for daylight utilization. However, this space has large window area facing to the South, the projection of the upper floor on this floor is around 2 meters and indentation of the south wall respect to adjacent wall is around 3 meters that cause little penetration of daylight to this space. Despite of breadth of zone 5 as a public space of the house, there is enough potential for daylight utilization with 1.8 % as DF. Although Zone 5 has large exposed window to the South, and it has different source for receiving daylight, the amount of uniformity in this space is not acceptable. This is due to that some places receive direct light and some places with high distance relative to the window, do not receive any daylight. Therefore, it is inferable that the uniformity ratio equal zero because Uniformity ratio is calculated by dividing Min / Max Illuminance.

Zone 3 in the ground floor has sDA 100% and that means this room has daylight autonomy along a year and also it has 100% as UDI that means this room is considered as full daylight spaces. Zone 5 in the ground floor has ability to achieve sDA, 73% which is not perfect daylight autonomy, but with 73.55% as UDI, this space is considered as full daylight space based on classification of space based on UDI. Figure 8 shows contours of daylight factor in the ground floor.

The results of daylight simulations of spaces in the First floor were tabulated in Table 6 in term of Average

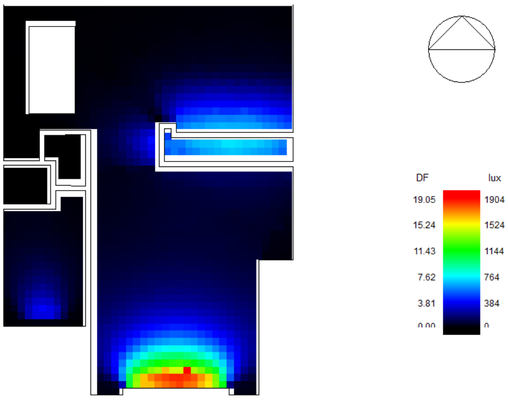

Figure 8. Daylight analysis of the ground floor in terms of DF

DF (%), Work plane Illuminance (Lux) and Uniformity Ratio as well as annual Indicators of daylight such as sDA and UDI.

The Zones 2, 3, 4 and 6 in the first floor are not main spaces of the house and do not need to receive daylight. However, Zone 1 is a bedroom which is located in the North direction and because of the rules of urban planning and neighboring land, there is no possibility to receive daylight, architect of this house with designing void as courtyard in first floor, provides the potential to receive daylight from the south direction for this space. This space can reach to the minimum of acceptable range of DF with 1.18%. Furthermore, this space can receive 381 Lux as WPI, which is in the acceptable range, but in term of Uniformity there is no potential observed.

Zone 5 and 8 as bedrooms also receive daylight from south window which faced to the main yard without any obstacles. They achieve DF 2.6 and 1.5 percent which means there are large potential for daylight utilization in these spaces. The average WPI in zone 5 and 8 are 450 and 361, respectively which is acceptable, but in term of uniformity ratio, there is a long way to reach an acceptable value. However, Zone 7 as a public section of this house has more than 63 m^2 as an area. This space can provide large potential for daylight utilization with DF equal to 2.6% and average WPI with 826 Lux because there is a possibility to receive daylight from east direction with designing central courtyard in the first floor plan. Same as other spaces in Zone 7 also there is a long distance to reach acceptable value of uniformity which as at least 0.5. Therefore, there is a need to design more comfortable places in terms of visual indicators such as uniformity.

However, sDA of Zones 1,5, 7 and 8 in the first floor of this house are 30.63%, 47.56%, 74.1 % and 58.29%, respectively but in terms of UDI, all these zones can achieve the level of fully daylight based on UDI classification with UDI greater than 50%. Figure 9 shows contours of daylight factor in the first floor.

Table 6. Simulation results in term of different indicators of daylight for the first floor

Block	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
Zone	1	2	3	4	5	6	7	8
Floor Area (m2)	22.766	5.015	2.06	2.693	25.798	2.28	63.574	19.459
Average Daylight Factor (%)	1.184	0	0	0	1.594	0	2.627	2.066
Average Illuminance (lux)	381	0	0	0	361	0	826	450
Uniformity ratio (Min / Max)	0.009	0	0	0	0.008	0	0.003	0.014
sDA Area in Range (m2)	6.973	0	0	0	12.27	0	47.051	11.343
sDA Area in Range (%)	30.63	0	0	0	47.56	0	74.01	58.29
UDI Area in Range (m2)	15.075	0	0	0	24.435	0	60.753	17.993
UDI Area in Range (%)	66.22	0	0	0	94.72	0	95.56	92.46

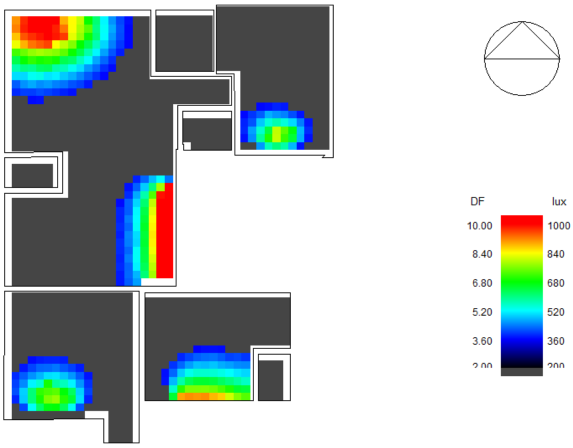

Figure 9. Daylight analysis of the first floor in terms of DF

CONCLUSIONS

Evaluation of the quality of daylight in a contemporary residential space with a central courtyard which can be considered as a typical building in 60% construction limitation in urban areas has been carried out. The main concluding remarks are as follows:

- Zone 5 as a public space in the ground floor has enough potential for daylight utilization with acceptable daylight factor, but the amount of uniformity in this space is not acceptable. It can be concluded that both daylight factor and uniformity ratio should be considered simultaneously in designing the building.
- In some zones such as zone 1 in the first floor, due to the rules of urban planning and neighboring land, there is no possibility to receive daylight, designing void as courtyard provides the potential to receive daylight from the south direction for this space. This point is an advantage of designing a residential space with a central courtyard.
- More various strategies should be applied to reach the acceptable range of uniformity in life spaces such as shading devices and light shelf, etc.

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Persian Abstract

چکیده

هدف این تحقیق توسعه استراتژی‌های پایدار در استفاده از روشنایی روز برای ساختمان‌های معاصر با الهام گرفتن از راه‌حل‌های سنتی مسکن بومی است. در این تحقیق فاکتورهای نور روز در یک فضای مسکونی معاصر دارای حیاط مرکزی، که در شهر کرمان واقع شده، مورد ارزیابی قرار گرفته است. پس از مدلسازی ساختمان در نرم‌افزار دیزاین بیلدر، U-value دیوارهای خارجی، سقف، کف و پنجره‌ها بر اساس مصالح موجود در بازار ایران محاسبه می‌شود. نتایج شبیه‌سازی‌های نور روز برحسب میانگین فاکتور نور روز (DF) و میزان روشنایی سطح کار (Lux) و نسبت یکنواختی و همچنین شاخص‌های سالانه نور روز مانند sDA و UDI ارائه شده‌اند. محدوده شماره ۳ در طبقه همکف، که فضایی در زیر آتریوم با نورگیری از سمت بالا است، به عنوان منبع نور روز عمل می‌کند. اگرچه محدوده شماره ۵ در طبقه همکف دارای ضریب روشنایی مناسبی است، اما نسبت یکنواختی به دلیل وجود همزمان مناطق با نور کم و زیاد قابل قبول نیست. محدوده شماره ۷ در طبقه اول به عنوان یک فضای عمومی می‌تواند پتانسیل زیادی برای استفاده از نور روز با فاکتور نورروز معادل ۲/۶٪ و میانگین روشنایی سطح کار با ۸۲۶ لوکس فراهم کند زیرا با طراحی حیاط مرکزی در پلان طبقه اول امکان دریافت نور روز از جهت شرق وجود دارد.