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Daylight performance of a naturally ventilated building as parameter for energy management

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Abstract

Daylight is an important element of energy efficient buildings. Energy savings from artificial lighting during the daytime can have significant impact on the energy sustainability residential buildings. For a city like Mumbai, where the buildings have limited access to daylight due to the sprawling of densely packed high rise buildings, energy saving from daylighting can be an effective driver of sustainability. Under this purview, it is prudent to evaluate the effects of various building design elements like orientation and window-to-wall ratio (WWR) on energy saving potential through daylighting. In this study, two parameters of daylight incidences: Useful Daylight Illuminance (UDI) and annual light exposure, were studied to understand the daylight performance of a high rise residential building. UDI values were then reiterated by varying the orientation and WWR. The results showed that the building performed best at the South-East orientation with a WWR of 50% which allowed 63% more ambient illuminance in the functional space. This study also unveils the paradigm that ambient illuminance inside the functional space of the building may be independent of total incident annual light exposure in the rooms. That means more annual exposure does not necessarily means better lighting conditions within the indoor functional space. Hence, this study creates a way forward in designing energy efficient buildings using UDI as a daylight performance metric.

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Keywords: Urbanization; daylighting, energy management; useful daylight illuminances; window-to-wall ratio

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1. Introduction

India is experiencing urbanization faster than the anticipated rate. Non-compliances to building codes and inefficient building designs have transformed the building sector into a high energy demanding sector. The building energy demand is growing at an unprecedented rate of 8% of which residential sector itself accounts for 25% [1] of the total energy consumption. The majority of this energy is consumed for artificial lighting, cooling and ventilation through fans.

Daylighting can be a useful strategy for energy efficient buildings. It can be a key driver of energy sustainability in residential as well as commercial buildings, with energy saving potential upto 45% [2]. It has been proven to have positive impact on the occupants' health and efficiency [3], [4]. The prediction of daylighting illuminance is a critical factor in daylight designing. Traditional methods in predicting daylighting illuminance such as daylight factor (DF) and daylight autonomy (DA) has limitations in terms of its flexibility in illuminance calculations owing to the dynamic nature of sky condition and the sun path [5]. On the other hand, climate based approach, such as the Useful Daylight Illuminance (UDI), not only predicts hourly daylight data for sensor points, but also reduces the computation time of the overall simulation. UDI gives a range of daylight illuminances, which has more realism in terms of daylight dynamics throughout a day and year, rather than assigning a threshold value of 500lux, which is the daylight autonomy (DA) [5]. UDI categorizes the indoor illuminances into UDI-supplementary and UDI-autonomous. While UDI-supplementary (100-200 lux) might trigger the need for artificial lighting within the indoor space, UDI-autonomous (200-2000 lux) represents the visually ambient range where the occupants can perform daily activities in day-lit conditions [6].

Mumbai, in India, being one of the most densely populated cities in the world, is facing huge challenges in catering to the growing housing demands. This has resulted in the sprawling of densely packed high rise buildings throughout the city. While such development is better from the point of minimizing energy usage for transportation, the close proximity of the high-rises pose a severe threat to sky and daylight penetration. This in turn affect the quality and the quantity of daylight received, especially at the lower floors [5]. Using the principles of building design for maximizing daylight penetration, multiple scenarios can be designed to simulate the performance of buildings based on the various combination of building design elements like orientation and window- to-wall ratio (WWR). These simulations are performed to study the overall effect of such design elements on the useful daylight illuminance on the building.

Hence, the hypothesis of this study is that with more UDI inside the room artificial lighting needs can be reduced for better energy management. The objectives of the study are:

- To understand the effect of different orientation on the percentage of UDI in the building.
- To understand the effect of varying WWR on UDI₁₀₀₋₂₀₀₀(%).

Table 1 Physical parameters of the building

Parameters	Values
Building type	Residential
Construction Type, No. of floors	RCC, 11
Location	Powai, Mumbai
Coordinates	19.13 (N),72.91 (E)
Floor area	839.63 m ²
Orientation	North
Window-to-wall ratio	20%
Cooling and Ventilation	Fans and Natural Ventilation
Artificial Lighting Load	834.6kWh/annum

Nomenclature	
UDI	Useful Daylight Illuminance
DA	Daylight Autonomy
DF	Daylight Factor
WWR	Window-to Wall ratio

2. Study Area

The residential building chosen for this study is located in the suburb of Mumbai at 19.13(N), 72.91(E). The building has 11 floors with four apartments of each floor (see Fig 1). An apartment from the ground floor was chosen for daylight study. The building is at North-South orientation with a WWR of 20%. The building is naturally ventilated with ceiling fans for air-circulation and ventilation. The annual lighting load is 834.60 kWh. The details of the building studied here is represented in Table 1.

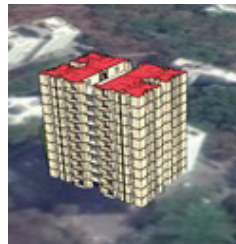


Fig 1. CAD model of the building studied

3. Data and Methodology

This study involved daylight performance analysis with respect to UDI and annual daylight exposure. Analysis of the simulated result involved UDI to the annual light exposure trend along the different orientation of the rooms with varying WWRs. The methodology adopted is illustrated in the Fig 2.

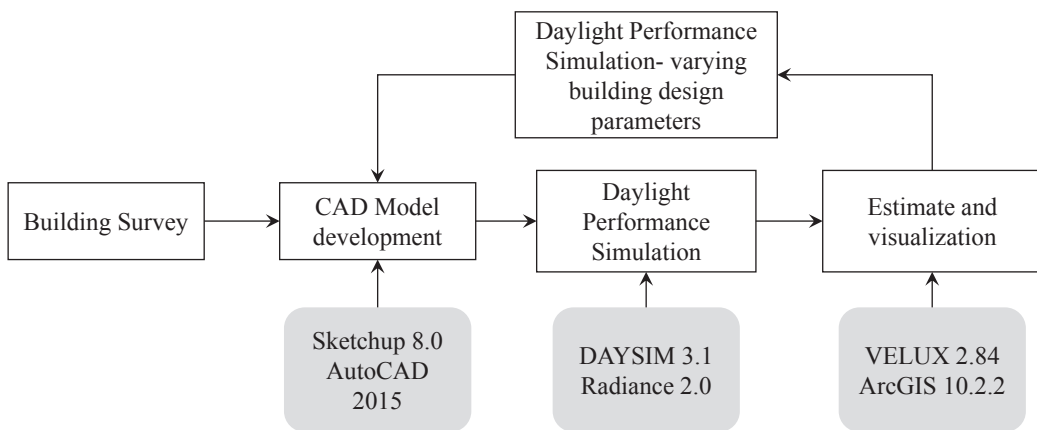


Fig 2. Methodology adopted

3.1. Modelling and Simulation

The commercial modelling package SKETCHUP 8.0 was used in this work. SKETCHUP is widely used by professional architects and engineers to build 3D models. The building internal space layout is illustrated in Fig 3. Moreover, in order to make the model simulation more realistic, true materials of the building were applied on the 3D model. Then the SKETCHUP model was imported using a DAYSIM plugin, ‘su2ds[†]’. Photo sensor points were created using this plugin with a grid spacing of 0.5m (see Fig 4) at a desk height of 0.9m. DAYSIM uses RADIANCE engine for the daylighting calculations. RADIANCE uses ray tracing technique for the calculation of annual illuminance and useful daylight illumination [7]–[10]. The assumptions that are used in the simulations are stated in the Table 2. In order to accurately calculate UDI, DAYSIM recommends to use its own material library for the modelling of the building. Therefore, before initializing simulation, the modelled building was re-assigned with DAYSIM materials.



Fig 3. Building space layout (Source: [16])

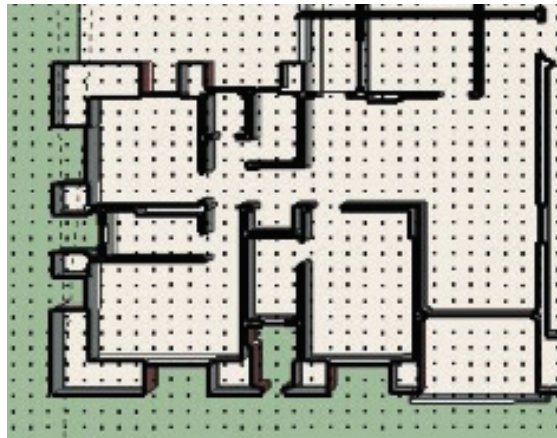


Fig 4. Photo-sensor points

[†] su2ds was created by Josh Kjenner for Manasc Isaac Architects, and is supported in part by the National Research Council's IRAP. Available online at <https://code.google.com/p/su2ds/>

Table 2. Assumptions used in simulation

Site description		
Site	Mumbai (19.14 N/ 72.92 E)	
Weather file	IND_Mumbai.430030_ISHRAE	
Daylight savings time	April 1 st to October 31 st	
User description		
Zone occupancy time	8:00 to 17:00	
Occupancy days	Monday to Friday	
Total annual hours	1563	
Minimum illuminance level	500 lux	
Lighting and blind control	Manual on/off switch	
Simulation parameters	Values	
ab	ambient bounce	5
ad	ambient division	1000
as	ambient super samples	20
ar	ambient resolution	300
aa	ambient accuracy	0.1
DAYSIM materials		
Floor	Reflectance	0.20
Ceiling	Reflectance	0.80
Walls	Reflectance	0.50
Exterior ground	Reflectance	0.20
Glazing	Transmittance	0.76

3.2. Daylight analysis using DAYSIM v3.1

DAYSIM is validated and is widely used in daylight simulation studies [11], [12]. DAYSIM produced three metrics - UDI, Daylight Factor (in percentage) and annual illuminance level. DAYSIM evaluates UDI (e.g. hourly) illuminance levels according to three illuminance ranges: 0-100 lux, 100-2000 lux and above 2000 lux. Studies suggests that if the daylight illuminance is within 100 lux needs for supplementary light while UDI-within 100-2000 lux indicates that daylight alone is sufficient for carrying out daily activities. UDI >2000 signifies direct sun exposure, due to no roofing in those regions and its usability within the habitable space is debatable. This study assumes that the minimum light level in the room is 500 lux, which is the bare minimum for visual comfort, without straining the eyes for carrying out daily activities [13]. Therefore, UDI (100-2000 lux) was taken as the daylight performance marker in this study.

Annual illuminance level is the sum of available illuminance in the room throughout the year over a range of sunny, overcast and clear skies [5]. However, the amount of usable illuminance light levels is determined by the UDI.

3.3. Visualization of the results

The results are visualized using VELUX v2.0 [14], for illustrating various illuminance levels based on different orientation of the apartment.

4. Results

The intention of this study was to understand the variation in UDI₁₀₀₋₂₀₀₀ (%) with respect to orientation of the building and WWR. The minimum luminance level was set at a 500 lux, which is the ambient light required for the performing desk job without straining the eyes, especially for elderly people. The data was analyzed in two sets:

firstly $UDI_{100-2000}$ (%) was analyzed for different orientation, to check the most suitable orientation for harnessing the daylight. Secondly, effectiveness of this UDI was investigated by varying WWR for different orientation.

4.1. Daylighting analysis

4.1.1 Useful Daylight Illuminance based on the orientation of the building

Pertaining to the dynamic nature of the sun, the distribution of sunlight in the room, varies greatly throughout the day. The size of the windows and the orientation of the room plays a major role in the distribution of light in the room. The CIE uniform overcast sky model, which is widely used in the daylight factor calculations, becomes non convergent when realistic time varying daylight illuminances are needed [5]. It can be seen that in the usability pattern of $UDI_{100-2000}$ (%) to the annual light exposure level (luxh) of Fig 5 that even though all the rooms receive a similar amount of daylight, throughout the year, the usability of light varies with the orientation.

Table 3 UDI variation on the basis of building orientation

Parameter	Building orientation							
UDI (%)	N	S	E	W	NE	SE	SW	NW
<100	54.74	54.18	47.99	46.56	69.11	71.71	73.52	79.03
100-2000	5.55	4.89	6.07	5.71	7.87	9.38	7.23	6.54
>2000	39.58	40.80	45.791	47.53	22.93	18.84	19.17	14.4
Mean annual light exposure (luxh) $\times 10^7$	56.47	58.61	70.57	73.12	19.30	19.59	19.30	16.17

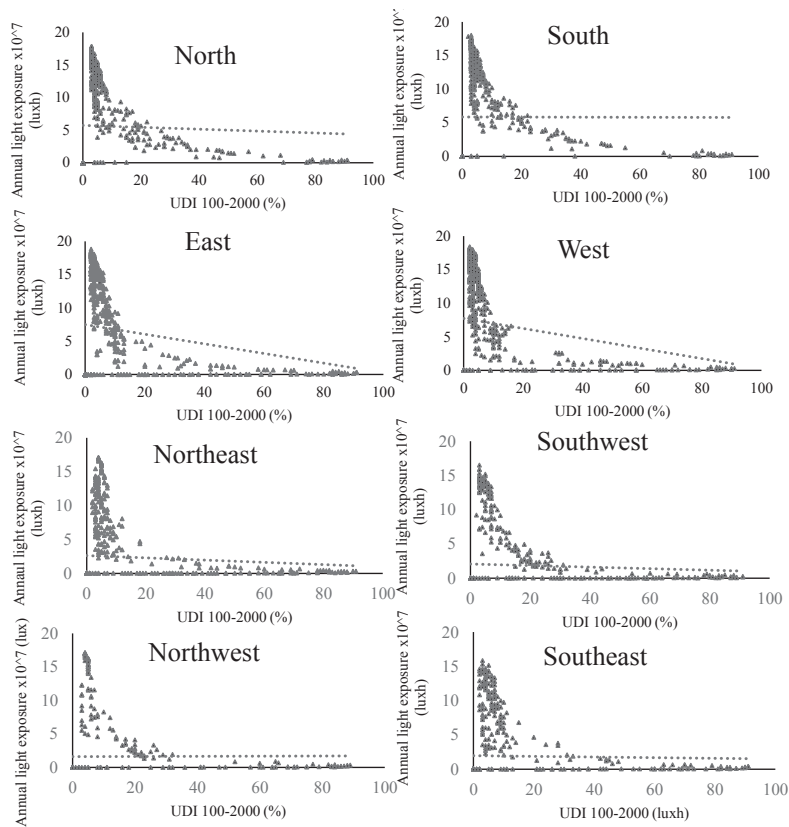


Fig 5. Usability of the annual exposure

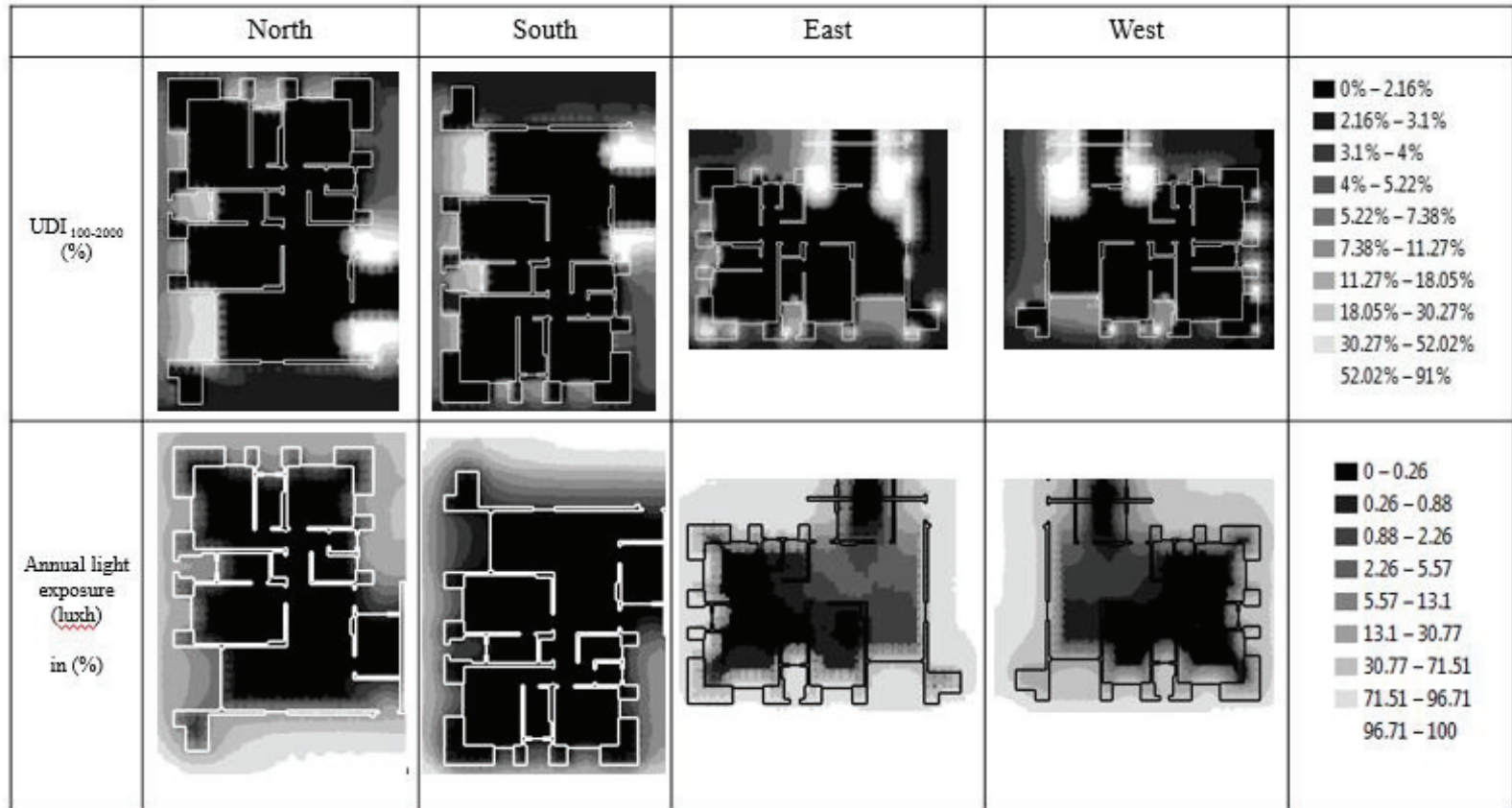


Fig 6. Useful Daylight Illuminance (%) and annual light exposure (luxh) in the room at different orientations.

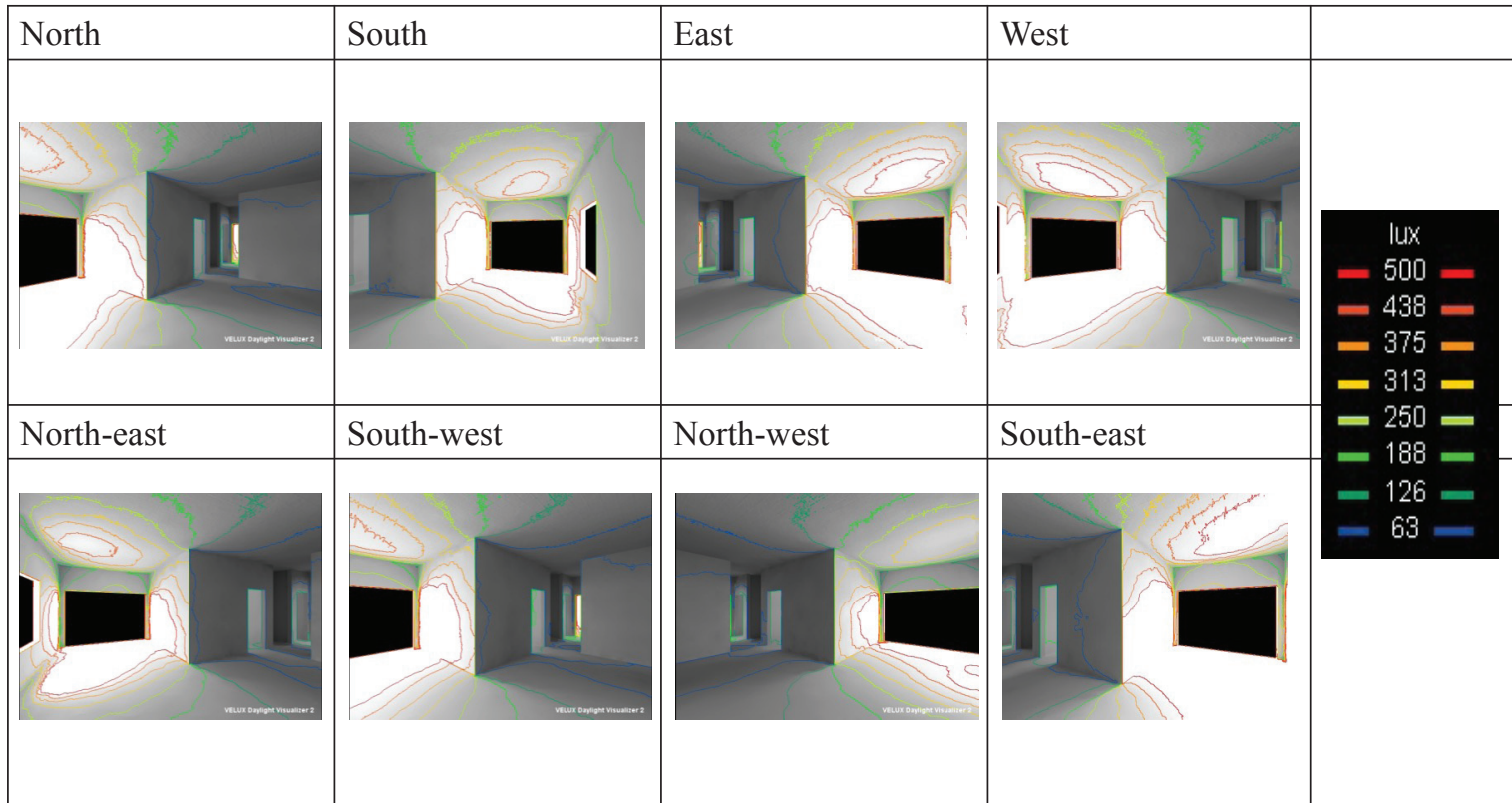


Fig 7. ISO contours of illuminance in the living room at 12:00 PM, CIE Clear Sky at different orientation.

Table 3 shows the percentage of mean useful daylight illuminance inside a room. The room is rotated as per cardinal points and also along 45° angle with respect to its original axis of north-south. 54.74 % of the photo sensors detected illuminance below 100 lux in the original orientation of the building: NS, which can cause visual discomfort and mood changes [12]. On the contrary, the same building configuration has 39.58 % of areas over-exposed to sunlight, with lux levels above 2000. Meanwhile, the ambient light levels which is between 100-2000 lux is 5.55% of the total floor area. Similar trend follows the South, West and East directions. But when the entire floor is rotated by 45° angle, the rooms in NE, SE and SW orientation had the highest percentage of lux levels below 100 lux. Fig 5 shows this trend with annual light exposure levels. RADIANCE calculates the annual exposure levels based on the weather file provided and the assumptions that have been taken during the initialization of the simulation (refer Table 2).

Fig 6 shows the paradigm between UDI₁₀₀₋₂₀₀₀ (%) and the annual light exposure level in grayscale. The lighter shades of the UDI₁₀₀₋₂₀₀₀ (%) shows that the regions which are near the windows and balcony, has a higher percentage of UDI₁₀₀₋₂₀₀₀. The annual light exposure level shows that the living room receives 50% of total light exposure. The Table 3 shows that while East and West orientation also receives higher light exposure, their corresponding UDI₁₀₀₋₂₀₀₀ (%) is low. On the contrary, SE and NW orientation despite having low annual light exposures, had high UDI₁₀₀₋₂₀₀₀ (%). This indicates that irrespective of higher annual illuminance levels, the room fails to distribute ambient illuminance of UDI₁₀₀₋₂₀₀₀. Hence, it can be concluded that orientation of the building plays a significant role in the availability of UDI₁₀₀₋₂₀₀₀ levels. Simulation results have shown that the annual light exposure on the ground floor is about 18×10^7 luxh irrespective of the orientation. But the UDI varied over a great range as evident from Table 4.

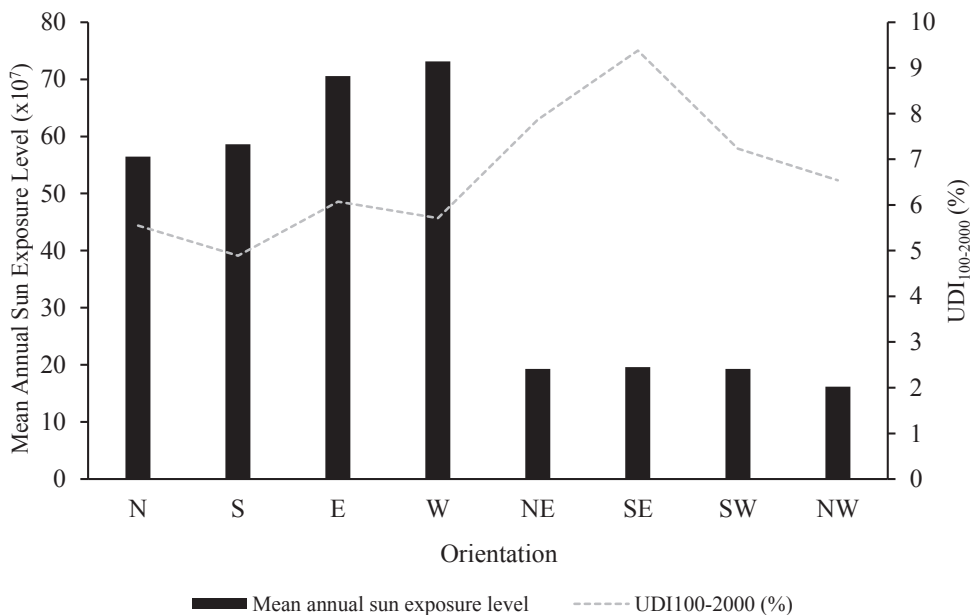


Fig 8. Trend between mean annual exposure and UDI₁₀₀₋₂₀₀₀ (%) based on different orientation

Another distinct pattern that can be inferred from the daylight analysis of the building is the inverse relationship between the useful daylight illuminance and the annual light exposure, especially when the building is rotated by 45°. Fig 8 represents this trend, with South-East side having the highest percentage (approx. 10%) of lux levels between 200 and 1000. UDI₁₀₀₋₂₀₀₀ (%) is 40% higher than that of the North. The ISO lines in the Fig 7 shows the variance of useful illuminance from the windows towards other rooms. A similar pattern of UDI < 100 can be seen in this figure. The blue contour lines show the region of extremely low illuminance, which cause visual discomfort.

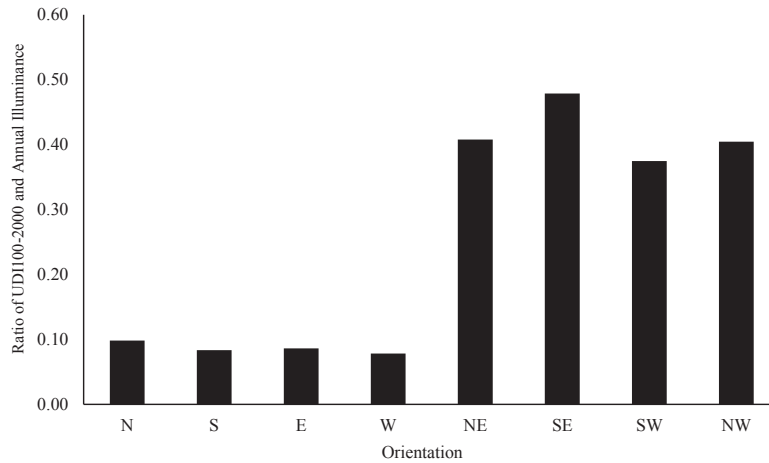


Fig 9. Ratio between UDI₁₀₀₋₂₀₀₀ (%) vs annual light exposure

An overall trend has been calculated and is illustrated in Fig 9, which infers that the usability of indoor illuminance due to daylighting increases drastically in the NE, SW, SE and NW orientation respectively. Therefore, we visualized each room under a clear October sky at 12:00 hrs, and obtained ISO patterns (see Fig 7).

4.1.2 Useful Daylight Illuminance based on the WWR of the building

After analyzing the usefulness of the illuminance inside the rooms based on the orientation, Fig 8, shows the ratio of light in a room to its usefulness is highest in the south-eastern direction. Therefore, this section analyses the WWR with respect to different orientation. The Table 4 represents the mean value of usable daylight as per the changing WWR. 50% window-to-wall ratio in the south-east direction shows an increase of 42% in the useful daylight illuminance levels, as compared to the default window to wall ratio of 20%. Increasing the WWR beyond 50% makes the building structurally unstable and interior spaces unusable as per the design functions.

Table 4. Mean UDI₁₀₀₋₂₀₀₀ (%) with respect to change in WWR

WWR	UDI ₁₀₀₋₂₀₀₀ (%)		
	NS	EW	SE
20%	2.15	3.33	3.5
30%	3.77	3.1	2.53
40%	2.85	4.59	2.58
50%	4.63	5.58	6.02

There is a general dip in the ambient illumination level inside the room, when WWR is raised to 30% from its original 20%. This pattern is illustrated in Fig 9 and Fig 10, which can be an indicator that, just by allowing more light into the room cannot be a sustainable lighting solution. The quality and quantity of light is the key for an effective and efficient naturally lighted house.

Since in this study, a naturally ventilated building is considered, therefore, optimizing the availability of light with its usability can facilitate better energy management.

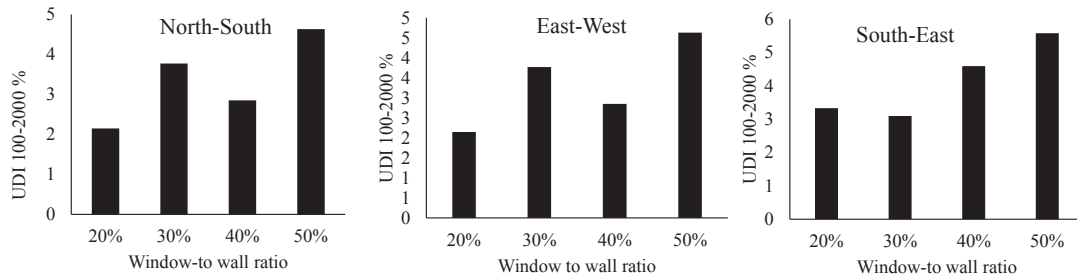


Fig 10. Change in UDI₁₀₀₋₂₀₀₀ (%) with respect to WWR

Table 5. Floor area (m²) having UDI₁₀₀₋₂₀₀₀ (%) greater than the 500 lux with respect to different WWR and orientation.

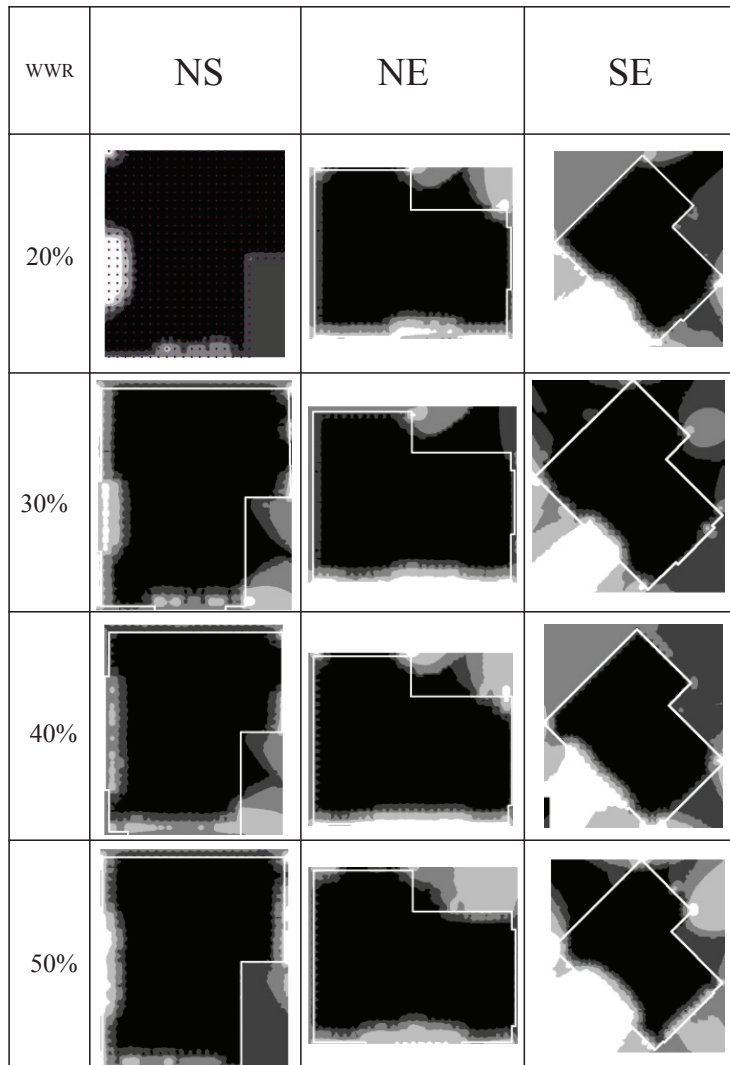
WWR	NS	EW	SE
20%	12	26	25
30%	15	30	22
40%	22	27	30
50%	30	31	67

Table 5 shows the values of ambient illuminance levels in the living room with respect to varying WWR. Upon varying the WWR, from 30% to 50%, the amount of floor area exposed to ambient illuminance levels increased. Fig 11 is quantified in table 6, and validates the visualization pattern. With the default WWR of 20%, the difference between illuminated floor spaces with more than 500 lux illumination was 54% and 52% in the east-west and south-east direction respectively.

When comparing UDI₁₀₀₋₂₀₀₀ (%) with varying WWR (30-50%), the room received 63% more ambient illumination. Hence, both the annual illumination and UDI₁₀₀₋₂₀₀₀ increased significantly. Therefore, optimizing WWR can be a cost effective energy saving strategy.

5. Discussion

This study was an attempt to link energy sustainability using natural light in residential buildings. The daylight performance on the ground floor of a high-rise naturally ventilated residential building was used as the base-case scenario. This study explored the paradigm between illumination levels and its usability in the functional space of the base case apartment. The results showed that a well illuminated room, need not necessarily be a visually comfortable room as illustrated in Table 3 and Table 4. The analysis was performed in two steps, first, by changing the orientation of the apartment, and then, on the basis of daylight usability values (UDI₁₀₀₋₂₀₀₀ %), the WWR was changed and daylighting performance was re-simulated. Results, were coherent with the objective of the study, i.e. increase in WWR from generic 20% to 50%, increased the useful illuminance in the room by almost 63%. However, we could not increase the WWR further 50%, as that would have led to the structural infeasibility in the building. This study can help architects, researchers and engineers, to understand and evaluate daylight performance of residential buildings, which is a good strategy for energy management. Daylight in the indoor space improves mood and well-beings of the occupants [13].

Fig 11. UDI₁₀₀₋₂₀₀₀ (%) pattern with different WWR.

6. Conclusion

In India, 42% of total residential electrical energy is spent on indoor lighting needs [16]. The building energy consumption is rising at 8% per annum as a consequence of rapid urbanization in India [1]. However, optimal integration of lighting technologies including natural lighting in buildings fabric, can save up to 45% residential electrical energy use [2]. This study showed that estimating the usability of illuminance levels of daylight, in the functional space, is much more effective than solely relying on annual incident illuminance levels as the metric for energy management through daylighting. Here, we have used a daylight performance metric called Useful Daylight Illuminance that showed the effectiveness of design parameters like building orientation and WWR in saving lighting energy through daylight. However, the occupants lighting energy use scheduling was not considered in the simulations. Future work lies in considering human dynamics in energy saving calculations from daylighting, and designing appropriate daylight inclusive building bye-law using metric like UDI that can foster energy efficient houses, at the early design stages [16].

Acknowledgement

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