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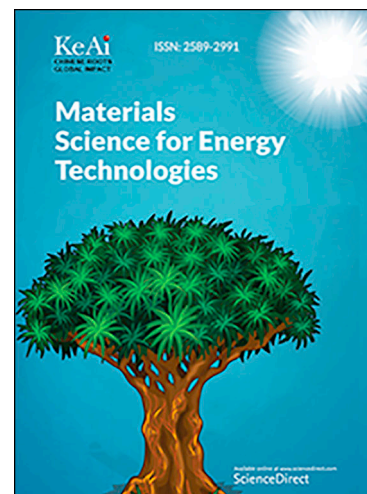
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PII: S2589-2991(21)00035-5  
DOI: <https://doi.org/10.1016/j.mset.2021.08.008>  
Reference: MSET 250

To appear in: *Materials Science for Energy Technologies*

Received Date: 10 July 2021  
Revised Date: 20 August 2021  
Accepted Date: 21 August 2021



Please cite this article as: O. Prakash, A. Ahmad, A. Kumar, S.M. Mozammil Hasnain, A. Zare, P. Verma, Thermal performance and energy consumption analysis of retail buildings through daylighting: a numerical model with experimental validation, *Materials Science for Energy Technologies* (2021), doi: <https://doi.org/10.1016/j.mset.2021.08.008>

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# Thermal performance and energy consumption analysis of retail buildings through daylighting: a numerical model with experimental validation

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## Abstract

The simultaneous impact of a building's electricity consumption and thermal performance is analyzed in this paper by taking a thermal model of a retail building located in Ranchi, India. A Baseline design of retail building having a rectangular footprint area is compared with four buildings with different footprint areas (Rectangular, T, L, H and U), in the South-West orientation. The thermal models for lighting of retail building are developed using eQuest software, and results obtained were validated experimentally. Intensity of light is reduced by 35% in baseline building corresponding to the amount of energy saved by upgrading to a T8 fluorescent fixture from a T12 fluorescent fixture. Average daylight factor of retail building in hot summer was found to be 34.80% experimentally and 28.98% through simulation. Based on energy consumption it is found that, for temperate buildings with rectangular footprints, buildings with L footprints, and buildings with H footprints are preferable when targeting net-zero energy status. The results encourage architects and engineers to work out an effective framework to enhance the use of natural illumination energy and suitable lighting according to buildings layout.

**Keywords:** Building shape; electricity consumption; Building orientation; energy efficiency; daylight factor.

## 1. Introduction

A significant increase in energy consumption in buildings has been observed over the past decades due to development and living standard. The constructed infrastructure in India was 21 billion sq ft. in 2005, and that figure is expected to grow to approximately 104 billion sq. ft. by 2030, which predicts an increase of approximately 395% in 25 year [1]. Majority of building construction occurs for residential and commercial sectors and very few for historical. By 2030, cities are expected to consume about 73% of the total energy production [1]. Moreover, residential apartment uses about 30% of total electricity and this figure is increasing by 8% every year [2]. Energy consumption caused by heating and cooling load is 20-50% for residential buildings [3]. About 80% of total electricity consumption in retail commercial building happens in following area i.e. lighting, airing out, and central air conditioning [3-5]. However electricity consumption in buildings is a major concern for the government and entrepreneur. In retail commercial buildings, some amount of electricity were used to decorative lightning to attract more customers into the malls, such lightning can be minimized to save energy [6-8].

Building energy consumption can be reduced by using thermal storage, Trombe walls and internal hollow composite walls within building envelopes. The studies were conducted on the analytical and experimental application of Trombe walls by Briga-Sá et al. [9]. It was found that there would be a temperature decrease of over 30 °C between the internal and external surfaces of the wall when equipped with an occlusion device and significant heat delay is also expected when the ventilation openings are switched off. Wang and Shi [10] created a novel exhaust air insulation wall characterized by an air-permeable porous layer. Results from the thermal performance indicated that the exfiltration process of the exhaust air flowing across the porous layer could extensively reduce the inward conductive heat flux through the wall. Furthermore, Peng et al. [11] studied the influence of diverse ventilation modes on thermal and power performance of a ventilated photovoltaic DSF. The results portrayed the ventilation design to cause a higher reduction of heat gain and improve energy generation. A simulation study by Peng et al. [11] was also presented to explore the overall energy performance of the building structure, proving that it could efficiently reduce solar radiation. The possible increase in dynamic thermal performance of different multi-layered walls was experimented by Leccese et al. [12], where the impact of thermal insulation was recorded against thermal performance. Also, the thermo physical characteristics, incorporation methods and application of phase change walls were studied by Huo et al. [13].

The main test for energy conservationists in buildings would be to devise a way to streamline energy use. Proper daylighting can contribute well to indoor illumination from daylight, control solar heat gains, reduce glare and at the same time it improves thermal comfort [14]. This can be achieved by adopting and effectively using building orientation, daylight factor model and sunlight distribution analysis [15]. Good orientation plays a crucial role in minimizing the need for subsidiary heating and cooling, which curtails energy bills and greenhouse gas emissions and increases comfort and convenience [16]. This often increases satisfaction and productivity (effective and efficient use of space in energy-saving) [17]. Variations in an angle towards east and west can prove to be advantageous in hotter climates. In cold climates, however, for orientations with west-facing buildings, the south-facing side of the building obtains solar gains in the afternoon. This results in the desired comfort required in the evenings [17].

After going through the various literature surveys, it is found that very few researches happens in energy consumption analysis of the commercial retail building in India. However, no research happens in the energy consumption analysis in humid subtropical climatic condition of India.

In this communication, there are two major sections. In the first section, five prominent baseline shape of commercial building in the humid subtropical climatic is being selected. An annual energy consumption analysis has been done for these building. Rectangular shape building found to be more energy efficient in this climatic condition. Hence a detail analysis has done on this building in the second section of manuscript. Thermal model and daylight factor has been evaluated and validated with experimental data.

## 2. Methodology

By considering the commercial retail building located in Ranchi capital city of Jharkhand, India as a model for performing the building energy simulation. Five different baseline shapes of the retail building has been modelled and simulated. For analysis, the climate data for the software was set to the weather details of Ranchi, which comes under the humid subtropical climatic zone. This type of climatic condition of Ranchi has summer season, which is hot and humid and very cold winters where the temperature is between 10 to 15°C and in summer season the temperature is 30 to 35°C. Fig. 1 (a) and Fig. 1 (b) show the front side and wide aperture view of the Commercial retail building from the inside environment.

**Fig 1a.** Front side and ceiling of Commercial retail building from the inside environment.

**Fig. 1b.** The ceiling of Commercial retail building in a wide aperture view from the inside environment.

The building shape, size, annual electricity consumption, and daylight factor for different building types are designed and studied, shown in Fig.2 (a-e). The shape of the first building is a rectangle and the second building shaped in the form of a 'T'. The third, fourth and fifth buildings represent the shapes of the alphabet's 'L', 'H' and 'U' respectively. The building areas vary from 30,000 ft<sup>2</sup> to 45,000 ft<sup>2</sup>, with a perimeter zone depth of 5 ft. All the buildings were designed to be five floors, with the floor to floor height is 15 ft, and the floor to ceiling height of 11 ft. The orientation of all the buildings considered for simulation was South-West. The building footprint dimension is represented in Table 1 a.

Building orientation was effectively utilized to maximize thermal comfort and to use the sun's free energy efficiently. The standard number of hours of sunlight received by any building atrium is at least two and these two hours can be in between 10 a.m. to 3 p.m. during winter seasons [18]. However, implementing this in real-life situations can be very complex as there are many practical complications. This complex process can be carried out with ease by simulating it with a suitable software. An orientation to the east of the south can warm the buildings more effectively in the mornings, and the building orientation for this analysis is set at South-West.

**Fig. 2.** Details of the building area of the baseline.

**Table 1(a). Building Footprint dimensions**

Shape	Building Orientation	Footprint Dimension (Meters)
Rectangle	South West	Perimeter Zone Depth - 1.524 $X_1 - 45.72$ $Y_1 - 91.44$
T-Shaped	South West	Perimeter Zone Depth - 1.524 $X_1 - 45.72$ $X_2 - 11.58$ $Y_1 - 91.44$ $Y_2 - 53.34$
L-Shaped	South West	Perimeter Zone Depth - 1.524 $X_1 - 45.72$ $X_2 - 22.86$ $Y_1 - 91.44$ $Y_2 - 91.44$
H-Shaped	South West	Perimeter Zone Depth - 1.524 $X_1 - 45.72$ $X_2 - 15.24$ $X_3 - 15.24$ $Y_1 - 91.44$ $Y_2 - 30.48$ $Y_3 - 30.48$
U-Shaped	South West	Perimeter Zone Depth - 1.524 $X_1 - 45.72$ $X_2 - 15.24$ $X_3 - 15.24$ $Y_1 - 91.44$ $Y_2 - 91.44$ $Y_3 - 30.48$

## 2.1. Effect of wall materials on building thermal performance

Walls are considered a predominant and efficient part of the building. A building's thermal performance is determined by passively regulating the indoor environment, which depends on materials configuring the building wall. The wall materials that can thermo-regulate the building but accessible and feasible materials should be used for the economic construction of a building. The materials (with thickness) used and assembly of materials (sequence of arrangement) in this study is shown in Fig. 3. The other important factor in choosing wall material is the thermal properties, which plays a crucial role in thermal comfort and electrical energy conservation. In this research, the assembly of different (multi-layered) materials has been used.

Heat transfer through an infinite wall is given by Eq 1:

$$\frac{q}{A} = \frac{k}{b}(T_1 - T_2) \quad 1$$

For the (multi-layered) composite wall in series having thermal conductivities  $k_1, k_2, \dots, k_n$ , heat flux is evaluated in Equation 2:

$$\frac{q}{A} = \frac{T_1 - T_2}{\frac{b_1}{k_1} + \frac{b_2}{k_2} + \frac{b_3}{k_3} + \dots + \frac{b_n}{k_n}} \quad 2$$

And the overall heat transfer coefficient is given by  $U$ , as shown in Equation 3:

$$U = \frac{q}{A(T_1 - T_2)} \quad 3$$

Therefore, for composite walls (multi-layered materials in series) the overall heat transfer coefficient is given by Equation 4:

$$\frac{1}{U} = \frac{b_1}{k_1} + \frac{b_2}{k_2} + \frac{b_3}{k_3} + \dots + \frac{b_n}{k_n} \quad 4$$

**Fig. 3.** Materials used in walls and their conductivity values.

### 3. Overview of energy performance analysis

#### 3.1. Model verification

Ranchi's Commercial retail building has been represented as a model for the buildings' footprint details. This Mall proves to be an excellent example of a retail building in the heart of Lalpur, Ranchi City, Jharkhand, India with the coordination of  $23.3772^\circ$  N latitude,  $85.3315^\circ$  E longitude, 644m altitude. The first shape considered in the simulation was a rectangle resembling the building in Commercial retail building; however, the four other building footprints varied in shape and area. Although the shapes may be different, the overall area of the rectangular building is the largest and the following four building variations have areas that can all fit inside that of the rectangular footprint. The red outline in Fig. 4a represents the footprint used for the rectangular variant. Side view of the proposed building is shown in Fig. 4b.

The model used in this simulation has been analyzed in the eQUEST 3-65 software. eQUEST was intended to permit a detailed comparative analysis of building designs and advances by applying modern building energy use simulation procedures. This is done by joining schematic

and design improvement building creation wizards, an energy efficient measure (EEM) and graphical outcomes show module with a total state-of-the-art DOE-2 (variant 2.2) building energy simulation. This software is widely popular in countries like the USA and it is being validated by many researchers. All the buildings under consideration in this analysis are of 5 stories and have the same construction and enveloping characteristics. Thus, we aim to analyze electricity consumption by changing a building's footprint shape. For the analysis, the weather data in this simulation is set for Ranchi (23.3441° N, 85.3096° E), which comes under the humid subtropical climatic zone.

All the buildings were considered to be retail buildings and models for the buildings were fairly standard since the design of the retail building was majorly constructed based on rectangular shaped, L shaped, U shaped and H shaped. Default relevant data were used in defining the building characteristics corresponding to the prescribed climatic zone data. The building envelope construction of the above-grade walls consisted of 8 inches heavyweight. The exterior finish of the roof is the standard built-up type, whereas the exterior finish of the above-grade walls is Stucco/Granite in white colour. There is no exterior insulation in the roofs, and the ground floor exposure is over the parking garage. On the other hand, the interior ceiling finish is that of lay-in acoustic tile with vertical wall frame type, and the interior finish for the floors is ceramic or stone tile. Four revolving glass doors were described in which one revolving glass is in the North orientation and remaining three are in the South orientation while the dimensions and constructions of the doors and glasses were set to default data. The exterior windows glass category was defined as Single PPG (Pittsburgh Plate Glass), and the window width was fixed to five feet. PPG SSB 28x32 is a single strength high-quality float glass sheet that is 32 inches in length 28 inch in width, and 2.5 mm in thickness. All exterior windows were equipped with overhangs and fins with shade depths of two feet in every orientation. The areas of activity and occupied loads were allocated as per the default data. The heating, ventilation and air conditioning system's (HVAC) definitions were defined in two types. One type had chilled water coils and no heating for the cooling source and heating sources, respectively. Conversely, the second system had DX coils as their cooling source and no heating source like the first system. Both systems had a direct return air path. All the HVAC system's supply and return fans' efficiency were set to standard. The HVAC system is installed with reinforced carbon create at the roof of the building, isolated against transmission of vibrations to the building structure. The central plant HVAC system is connected to the bathroom and other kitchen based shops. The exhaust of air was done through hoods equipped with grease filters, duct network. An exhaust blower cleared out the fumes from the bathroom and other food based shoppes. The heater used for domestic non-residential water heating was of the instantaneous type operating on electricity as the heater fuels. The other characteristics of building components include a ventilation system the building is constructed as per the minimum standard set for ventilation rate according to CPW (Central Public Works Department, India). Table 1 b represents the ventilation where CMF is cubic feet per minute and L/s m<sup>2</sup> liters per second-meter square. Table 2 and Fig. 5a shows occupancy and usage schedules of the building (i.e. how many people, time throughout the day)

**Fig. 4 a.** Commercial retail building aerial shot    **Fig. 4 b.** Commercial retail building side view

**Table 1 b.** Ventilation rate in the building



Occupant Category	cfm/ person	L/s person	cfm/ft <sup>2</sup>	L/s·m <sup>2</sup>	1000 ft <sup>2</sup> /100 m <sup>2</sup>
Building Lobby	7.5	3.8	3.8	0.3	120
Office Space	5	2.5	0.06	0.3	25
Bathroom	5	2.5	0.12	0.6	50

**Table 2 a.** Occupancy and usage schedules of the building

Time of the day	Occupant present
10:00 AM	37
11:00 AM	94
12:00 PM	131
1:00 PM	97
2:00 PM	73
3:00 PM	77
4:00 PM	107
5:00 PM	171
6:00 PM	209
7:00 PM	356
8:00 PM	228
9:00 PM	119
10:00 PM	58
11:00 PM	26

**Fig 5a.** Graphical variation of occupancy with respect to time of day

### 3.2. Application of EEM wizard on internal loads

The energy efficiency measure wizard was used to optimize the internal loads, particularly focusing on the lighting power density. In this efficiency analysis, the T12 fluorescent fixtures were replaced by the T8 fixtures in specific activity areas to optimize lightings and reducing costs. Fluorescent lights as they are likewise known, are arranged by their wattage, shape and measurement. The "T" in T5 shows the bulb which is cylindrical moulded, while the "5" indicates that it is having a measurement of five eighths inch. The other basic lights are the bigger T8 (eight eighths inch = 1") and T12 (twelve eighths inch = 1½" tubes). The average cost of T8 bulb is 350 Indian Rupees while T12 bulb average cost is 560 Indian Rupees. The activity areas considered for the fluorescent fixture upgrades were offices, corridors, lobbies and conference rooms. The areas not considered for lighting upgrade were restrooms, mechanical and electrical rooms, as their contribution to the overall building energy conservation analysis was rather insignificant because the area for these specific activities was quite minimal when compared to the other areas that were considered for the energy efficiency measure wizard. All the lighting intensities for the considered activity areas were reduced by around 35%, corresponding to the amount of energy saved by upgrading to a T8 fluorescent fixture from a T12 fluorescent fixture.



### 3.3 Daylight factor

Daylight factor (DF) is the availability of natural light inside the building atrium. Architects do estimation of sufficient internal building daylighting after calculating the daylight factor of the building. Daylighting allows a more energy-efficient building design by providing further flexible building facade design strategy, and different atrium building features make up the DF (daylight factor) [19]. These features include the atrium shape, the sun orientation, atrium roof transmittance, surface reflectivity of the atrium and the penetration of daylight into adjoining spaces. The size, position and orientation of fabrics (windows/ doors/ vents), optical phenomenon (skylight and the sky illuminance) distributions all contribute to the illuminance level received inside of a building.

The daylight factor is made of three different constituents, which are the sky component (SC), the externally reflected component (ERC), and the internally reflected component (IRC) [20]. The sky component is the light received from the sky. The externally reflected component is the part of light received from skylight reflected by a reflective impediment [21]. The internally reflected component is the constituent of the light reflected by the interior facades of the building. The addition of all these parameters results in the daylight factor [22]. Daylight received by a vertical surface is the sum of direct-beam, externally reflected components and sky-diffuse [22]. For designing a wall window in clear sky conditions, the daylight factor can be computed by considering both direct and diffuse components illuminance level on a given point in a living space. Useful daylight illuminance (UDI) is an annual occurrence of illuminance, i.e. daylight is within the range of 100-2000 lux [23]. The UDI conspire is both useful and complex. While UDI is based essentially on human factor contemplations, high estimations of UDI related to low vitality use for electric lighting and cooling. UDI does not show any correlation between electric lighting use and achieved UDI for office spaces with controlled shades [24]. The daylight factor continues as the predominant assessment metric because of its simple and realistic approach used by an organization such as LEED.

### 3.4 Building Orientation

The orientation of the building is conveyed as one of the most important factors in daylighting. To achieve living comfort during both hotter and colder days, proper orientation is required. Ranchi's Commercial retail building has an orientation of South-West. As a part of this analysis, we have modelled the rectangular baseline building in different orientations. The orientation is decided upon the direction of the main entrance facing. This was done to examine the effect of varying the orientation of a building have on its electricity consumption.

The building variation considered for this part is the rectangular baseline building. The building was modelled in six different orientations, namely, East, West, North, South East, North West and North East. No other parameter of the building was altered other than its orientation.

## 4. Results and discussion

The simulated daylight factor is validated with an experimental value measured at the different floors of the proposed building. Monthly and annual electricity consumption was recorded based on area lighting, miscellaneous equipment, pumps and auxiliaries, ventilation fans, water

heating, space cooling and heat rejection. Readings were obtained in kilowatt-hours (kWh) x 106. The five different types of buildings differed from one another by their footprint shapes. The rectangular building can be considered a baseline for all the other four buildings in terms of area. It is used as a live model of Commercial retail building Ranchi with coordinate's 23.3772° N latitude 85.3315° E longitude, 644m altitude. The four variations of the rectangular footprint include T-shaped, L-shaped, H-shaped and U-shaped buildings. Otherwise, the number of floors, cooling systems, HVAC systems, and other building parameters are identical.

#### 4.1. Effect of wall materials on building thermal performance

Heat transfers take place from higher temperatures to lower temperatures. In buildings, heat transfers were mostly from walls and roofs. Wall is a predominant part of the building, so choosing wall material is very important to increase thermal comfort inside buildings. In this conventional research material is used, the U-value obtained is 1.37 w/m<sup>2</sup>k which is shown in Fig 5b., then the middle layer of the wall is replaced with a new layer (vacuum insulation). From this, the U-value decreased by 2.85 times and became 0.48 w/m<sup>2</sup>k as shown in Fig.5c. The decreased U-value increases the thermal comfort inside the building envelope. The U- values were validated physically from the given equations used in this research. The U- value decreases as the conductivity of vacuum insulation is smaller than that of polystyrene foam.

**Fig. 5b.** U- value obtained with the conventional wall material.

**Fig. 5c.** U- value obtained with innovative wall material (vacuum insulation).

#### 4.2. Simulation Result

Simulated is performed to find out the electricity consumption in each building monthly and annually. Daylight factor of a retail building (Commercial retail building) of Ranchi city is compared with experimentally measured values

##### 4.2.1 Monthly electricity consumption comparison of building alternatives

The gross annual and monthly electricity consumption readings were gained from the simulation of each of the five buildings. It can be concluded by analyzing Figures 6 (a) to (e) that May is the most electricity consuming month of the year, as the peaks of the bars are highest in May, regardless of the type of building. This is understandable as May and June are the hottest months of the year in Ranchi. The bulk of the electricity consumption, 36.4%, of the rectangular baseline building is used in space cooling for occupants' comfort in the hot summer days of June.

**Fig. 6 a.** Rectangular building simulated footprint and monthly electric consumption data

**Fig. 6 b.** T-shaped building simulated footprint and monthly electric consumption data

**Fig. 6 c.** L-shaped building simulated footprint and monthly electric consumption data

**Fig. 6 d.** H-shaped building simulated footprint and monthly electric consumption data

**Fig. 6 e.** U-shaped building simulated footprint and monthly electric consumption data

#### 4.2.2 Annual electricity consumption of building alternatives

On an annual basis, electricity consumption ranged from 2.559 million kWh (L-shaped building) to 3.219 million kWh (U-shaped building). All the buildings averaged 2.869 million kWh of electricity annually. From Tables 2 (b) to (f) and graphically shown in Fig. 7 (a-e), it is evident that the U-shaped building consumes the most amount of energy. It is followed by the rectangular baseline building, T-shaped, H-shaped and L-shaped buildings as the second, third, fourth and fifth ranking respectively in consuming the most electricity. The U-shaped building consumes about 6% more electricity than the rectangular baseline building's second most electricity-consuming building.

As mentioned earlier, space cooling is the system that consumes the most amount of electricity in all the buildings, except for the rectangular alternative. Area lights consume  $1.33 \times 10^6$  kWh, which amounts to 44% of total annual electricity consumption. The area lighting is followed by space cooling, which consumes about 31% of the annual electricity. Furthermore, miscellaneous equipment consumes around 5% of the annual electricity. Vent fans use 5%, and 10% is used by pumps and auxiliaries, while the remaining 5% of annual electricity is used by hot water supply and heat rejected.

It is evident from Fig. 6 (e) that the U-shaped building consumes proportionately more electricity annually for space cooling than the other building alternatives. On the other hand, the L-shaped building consumed the least amount of electricity annually for area lights than the other building alternatives; this can be analyzed through Fig. 6 a, b, c and d.

The annual electricity consumption for uses such as heat rejection, hot water, vent fans and pumps and auxiliaries were more or less the same for every building alternative. It is important to know that the energy efficiency measure wizard was not put into effect to calculate the annual electricity consumption of building alternatives.

**Table 2 b:** Annual energy consumption of the rectangular building for different uses.

Electricity Use	Electricity kWh (x1000)
Space Cool	959.1
Heat Reject.	128.8
Hot Water	24
Vent. Fans	148
Pumps & Aux.	291.3
Misc. Equip.	163.1
Task Lights	0
Area Lights	1,332.70
Total	3,046.90

**Table 2 c:** Annual energy consumption of the T- shaped building for different uses.

<b>Electricity Use</b>	<b>Electricity kWh (x1000)</b>
Space Cool	1,064.30
Heat Reject.	65.8
Hot Water	49.9
Vent. Fans	277.6
Pumps & Aux.	119.9
Misc. Equip.	479.9
Task Lights	3.5
Area Lights	802
Total	2,863.00

**Table 2 d:** Annual energy consumption of the L- shaped building for different uses.

<b>Electricity Use</b>	<b>Electricity kWh (x1000)</b>
Space Cool	968.60
Heat Reject.	56.3
Hot Water	44
Vent. Fans	253
Pumps & Aux.	103.3
Misc. Equip.	423.7
Task Lights	3.1
Area Lights	707.7
Total	2,559.80

**Table 2 e:** Annual energy consumption of the H- shaped building for different uses.

<b>Electricity Use</b>	<b>Electricity kWh (x1000)</b>
Space Cool	1,036.90
Heat Reject.	55.7
Hot Water	18.6
Vent. Fans	271.5
Pumps & Aux.	108.1
Misc. Equip.	126.9
Task Lights	0
Area Lights	1,036.50
Total	2,654.30

**Table 2 f:** Annual energy consumption of the U- shaped building for different uses

<b>Electricity Use</b>	<b>Electricity kWh (x1000)</b>
Space Cool	1,233.40
Heat Reject.	67.8

Hot Water	54.8
Vent. Fans	327
Pumps & Aux.	124.3
Misc. Equip.	527.7
Task Lights	3.9
Area Lights	880.30
Total	3,219.30

**Fig. 7a.** Percentage annual energy consumption of the rectangular building

**Fig. 7 b.** Percentage annual energy consumption of T-shaped building

**Fig. 7 c.** Percentage annual energy consumption of L-shaped building

**Fig. 7 d.** Percentage annual energy consumption of H-shaped building

**Fig. 7 e.** Percentage annual energy consumption of U-shaped building

#### 4.2.3 Effect of EEM wizard on the electricity consumption of building alternatives

The EEM wizard was applied to all the building alternatives and the results are shown in Fig. 8 (a) to (e). After decreasing the lighting intensity of an important building area by 35%, it is seen that electricity consumption has reduced considerably, as shown by the difference in length of the blue and orange horizontal bars, representing the T12 to T8 lighting EEM results and the baseline simulation results respectively, in Figure 8.

The area most affected by this lighting EEM analysis is the area lights, showing the highest decrement of electricity consumption, regardless of the building alternative.

**Fig. 8 a.** Annual electricity consumption comparison between baseline and lighting EEM rectangular building

**Fig. 8 b.** Annual electricity consumption comparison between baseline and lighting EEM T-shaped building

**Fig. 8 c.** Annual electricity consumption comparison between baseline and lighting EEM L-shaped building

**Fig. 8 d.** Annual electricity consumption comparison between baseline and lighting EEM H-shaped building

**Fig. 8 e.** Annual electricity consumption comparison between baseline and lighting EEM U-shaped building

### 4.3. Daylight factor

The average daylight factor of the retail building was found to be 34.80% experimentally during the hot summer, as shown in Table 2a. Table 2a also represents the sunshine (in lux) from the front window and the top ceiling of the Commercial retail building. From the simulation, the average daylight factor during a year obtained is 28.98% shown in Fig. 9. It varies between 0-60 %. The figure analyzed that there is no need for external lighting in the front and middle part of the building, but there is a need for external lighting in the back part of the proposed building as daylight factor at that point is low. The recommended daylight factor for the retail buildings is below 10%. The higher daylight factor indicates that a building majorly depends upon artificial lighting during darkness and nighttime. The walls with higher reflectance increased the daylight factor. Simulation results showed 30.84 % daylight factor. The daylight factor increases in the direction perpendicular to the atrium and external windows. The recommended design for sky illuminance for the composite climate is 8000 lux. The experimental average indoor illuminance through the luxmeter was 2400 lux. Table 2b shows the variation of daylight factor values on different floors during the year. It is observed that the daylight factor decreases with height. The experimental daylight factor measured is compared with a simulated value which is shown in Fig.10. It is seen that there is a close agreement between experimental and simulated values, root means square error found between these two values is 5.167 during summer days and 2.97% at noon on cold winter days.

**Table 3 a:** - Experimental daylight factor value of Commercial retail building on hot summer days.

Time	Sunshine from top ceiling	Sunshine from the front window	Overall sunshine	Daylight factor
At 1 pm	11000	25000	36000	50%
At 4 pm	9600	4500	14100	19.60%
Overall Daylight factor				34.80%

**Table 3 b:** - Daylight factor value at different floors of the retail building (Commercial retail building).

Months	Daylight factor (%)				
	Floor- 1	Floor- 2	Floor- 3	Floor- 4	Floor- 5
March	61.19	29.03	24.56	24.65	24.87
August	61.19	29.24	24.94	25.03	25.03
December	61.19	29.21	24.79	25.50	24.87

**Fig. 9.** Thermal model of Commercial retail building with daylight factor value**Fig. 10.** Daylight factor value measured experimentally and through simulation during a day.

#### 4.4. Building Orientation

The rectangular baseline building was simulated at different orientations, and their results are represented by Tables 3 (a-f). The live model or Ranchi Commercial retail building has an orientation of South-South-West. The simulated models have East, West, North, South East, North West, and North East orientations. Fig. 11 shows the comparison of electric consumption in all the orientations in kWh (kilowatt-hour).

Surprisingly, the South-South-West configuration of the building, which is the original orientation of the live model, consumes the second most amount of electricity. Only the building with its orientation set to North had higher electricity consumption despite a very small difference. The building with an orientation of East consumes relatively the least amount of electricity shown in Fig 11. Rectangular-shaped buildings consume less energy because they fit as a fiddle and give a more comparative moulded house.

**Fig. 11.** Annual electricity consumption of rectangular building with every orientation considered**Table 4 a:** Annual electricity consumption of rectangular building with an orientation of East

Electricity Use	Electricity kWh (x1000)
Space Cool	914.4
Heat Reject.	122.3
Hot Water	24
Vent. Fans	147.4
Pumps & Aux.	269.7
Misc. Equip.	163.1
Task Lights	1,332.70
Area Lights	2,973.50
Total	914.4

**Table 4 b:** - Annual electricity consumption of rectangular building with an orientation of West

Electricity Use	Electricity kWh (x1000)
Space Cool	923.40
Heat Reject.	123.70



Hot Water	24.00
Vent. Fans	147.50
Pumps & Aux.	273.90
Misc. Equip.	163.10
Task Lights	1,332.70
Area Lights	2,988.30
Total	923.40

**Table 4 c:** -Annual electricity consumption of rectangular building with an orientation of North

Electricity Use	Electricity kWh (x1000)
Space Cool	959.90
Heat Reject.	128.80
Hot Water	24.00
Vent. Fans	147.90
Pumps & Aux.	292.00
Misc. Equip.	163.10
Task Lights	1,332.70
Area Lights	3,048.30
Total	959.90

**Table 4 d:** - Annual electricity consumption of rectangular building with an orientation of South East

Electricity Use	Electricity kWh (x1000)
Space Cool	930.70
Heat Reject.	124.50
Hot Water	24.00
Vent. Fans	149.50
Pumps & Aux.	276.70
Misc. Equip.	163.10
Task Lights	1,332.70
Area Lights	3,001.00
Total	930.70

**Table 4 e:** - Annual electricity consumption of rectangular building with an orientation of North West

Electricity Use	Electricity kWh (x1000)
Space Cool	935.60
Heat Reject.	125.30
Hot Water	24.00
Vent. Fans	149.70
Pumps & Aux.	278.80
Misc. Equip.	163.10

Task Lights	1,332.70
Area Lights	3,009.10
Total	935.60

**Table 4 f:** - Annual electricity consumption of rectangular building with an orientation of North East

Electricity Use	Electricity kWh (x1000)
Space Cool	937.70
Heat Reject.	125.70
Hot Water	24.00
Vent. Fans	149.10
Pumps & Aux.	280.00
Misc. Equip.	163.10
Task Lights	1,332.70
Area Lights	3,012.10
Total	937.70

## 5. Conclusion

In this study, annual energy consumption analysis of the retail building in the humid subtropical climatic zone has been taken place for five different baseline shapes (Rectangular, T, L, H and U). Twelve different source of energy consumption is being considered for this study namely Space Cool, Heat Reject., Hot Water, Ventilation Fans, Pumps & Aux, Misc. Equip., Task Lights, Area Lights, Task lighting, Exterior usage, Refrigeration and space heating. Study reveals that for humid subtropical region where annual energy consumption is high for space cooling, space heating and hot water. In such condition, rectangular shaped building is found to be more efficient in comparison with other building.

In order to enhance the thermal comfort in buildings, energy efficient building material is being used in simulation. The results were validated through simulation when the conventional wall material is replaced by innovative (vacuum inside) with a similar thickness of 290mm. The simulation results show a decrease of thermal lag from 16.48 to 11.12 and an increase in thermal decrements from 0.02 to 0.18. It was found that energy-efficient measure wizard (EEM) plays a particularly prominent role in energy savings, and T8 fixtures should replace all the T12 fluorescent fixtures since T8 consume 35 watt while T12 consume 150 watt. For monthly electricity consumption, May was the most electricity consuming month of the year, regardless of the types of building. In May, the highest amount of space cooling was required to increase the occupancy comfort level. On an annual basis, the most electricity consuming building was the U-shaped building which consumed 3219.30 kWh overall annually. The list followed by the rectangular i.e. 3046.90 kWh, T-shaped i.e. 2863 kWh, H-shaped i.e. 2654.30 kWh and L-shaped buildings i.e. 2559.80 kWh. The application of EEM wizard has positively impacted the electricity consumption of buildings by reducing the consumption in specific building areas, thus reducing the total energy consumption by 15 to 20 %. The maximum reduction in energy

consumption was seen in the rectangular-shaped buildings (by 19%). The average daylight factor showed that there was no artificial lighting needed in the proposed model. Based on the error analysis between experimental and simulated daylight factors, the results were found realistic in close agreement. The root means square error is found between these two values is 5.167 from March to June and 2.97% at noon from October to January. The daylight factor was maximum at 4 pm in the Commercial retail building. The use of artificial lighting system can be avoided during this time. The east orientation of the rectangular building in the Ranchi composite climate area consumed the least amount of electricity. This methodology can connect high and low-level parameter to acquire a comprehensive framework of the energy performance of the building, assisting with understanding what ought to be done to improve it and where further investigations to be led.

**Conflict of Interest:**

On behalf of all authors, the corresponding author states that there is no conflict of interest.

## References:

1. Yao, Q., Cai, W., Li, M., Hu, Z., Xue, P. and Dai, Q. Efficient circadian daylighting: A proposed equation, experimental validation, and the consequent importance of room surface reflectance. *Energy and Buildings*, 210, p.109784 (2020).
2. Su, X., Zhang, L., Liu, Z., Luo, Y., Lian, J. and Liang, P. Daylighting performance simulation and analysis of translucent concrete building envelopes. *Renewable Energy*, 154, pp.754-766 (2020).
3. Ahmad, A., Kumar, A., Prakash, O. and Aman, A. Daylight availability assessment and the application of energy simulation software—A literature review. *Materials Science for Energy Technologies*, 3, pp.679-689 (2020).
4. Chi, D. A., Moreno, D., & Navarro, J. Correlating daylight availability metric with lighting, heating and cooling energy consumptions. *Building and Environment*, 132, 170-180 (2018).
5. Xuan, Q., Li, G., Lu, Y., Zhao, B., Wang, F. and Pei, G. Daylighting utilization and uniformity comparison for a concentrator-photovoltaic window in energy saving application on the building. *Energy*, 214, p.118932 (2021).
6. Sheng, Y., Miao, Z., Zhang, J., Lin, X., & Ma, H. Energy consumption model and energy benchmarks of five-star hotels in China. *Energy and Buildings*, 165, 286-292 (2018).
7. Sun, Y., Wilson, R., Liu, H. and Wu, Y. Numerical investigation of a smart window system with thermotropic parallel Slat-Transparent Insulation Material for building energy conservation and daylight autonomy. *Building and Environment*, p.108048 (2021).
8. El-Abd, W., Kamel, B., Afify, M., & Dorra, M. Assessment of skylight design configurations on daylighting performance in shopping malls: A case study. *Solar Energy*, 170, 358-368 (2018).
9. Briga-Sá, A., Boaventura-Cunha, J., Lanzinha, J. C., & Paiva, A. Experimental and analytical approach on the Trombe wall thermal performance parameters characterization. *Energy and Buildings*, 150, 262-280 (2017).
10. Wang, J. J., & Shi, D. Spectral selective and photothermal nano structured thin films for energy efficient windows. *Applied energy*, 208, 83-96 (2017).
11. Peng, J., Curcija, D. C., Lu, L., Selkowitz, S. E., Yang, H., & Zhang, W. Numerical investigation of the energy saving potential of a semi-transparent photovoltaic double-skin facade in a cool-summer Mediterranean climate. *Applied energy*, 165, 345-356 (2016).
12. Leccese, F., Salvadori, G., Asdrubali, F., & Gori, P. Passive thermal behaviour of buildings: Performance of external multi-layered walls and influence of internal walls. *Applied Energy*, 225, 1078-1089 (2018).
13. Huo, H., Shao, J., & Huo, H. Contributions of energy-saving technologies to building energy saving in different climatic regions of China. *Applied Thermal Engineering*, 124, 1159-1168 (2017).
14. Freewan, A. A. Impact of external shading devices on thermal and daylighting performance of offices in hot climate regions. *Solar Energy*, 102, 14-30 (2014).

15. Ajaji, Y., & André, P. Thermal comfort and visual comfort in an office building equipped with smart electrochromic glazing: An experimental study. *Energy Procedia*, 78, 2464-2469 (2015).
16. Antonis, K., & Aris, T. The impacts of a dynamic sunlight redirection system on the energy balance of office buildings. *Energy Procedia*, 122, 38-43 (2017).
17. Ghosh, A., & Neogi, S. Effect of fenestration geometrical factors on building energy consumption and performance evaluation of a new external solar shading device in warm and humid climatic condition. *Solar Energy*, 169, 94-104 (2018).
18. Fasi, M. A., & Budaiwi, I. M. Energy performance of windows in office buildings considering daylight integration and visual comfort in hot climates. *Energy and Buildings*, 108, 307-316 (2015).
19. Casquero-Modrego, N. Optical fiber light scattering outdoor tests for interior daylighting. *Energy and Buildings*, 198, 138-148 (2019).
20. Bian, Y., & Ma, Y. Analysis of daylight metrics of side-lit room in Canton, south China: A comparison between daylight autonomy and daylight factor. *Energy and Buildings*, 138, 347-354 (2017).
21. Lim, G. H., Hirning, M. B., Keumala, N., & Ghafar, N. A. Daylight performance and users' visual appraisal for green building offices in Malaysia. *Energy and Buildings*, 141, 175-185 (2017).
22. Mangione, A., Mattoni, B., Bisegna, F., Iatauro, D., & Zinzi, M. (2018, June). On the validity of Daylight Factor for evaluating the energy performance of building. In 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe) (pp. 1-4). IEEE.
23. Li, D. H., & Lou, S. Review of solar irradiance and daylight illuminance modeling and sky classification. *Renewable Energy*, 126, 445-453 (2018).
24. Nabil, A. and Mardaljevic, J. Useful daylight illuminances: A replacement for daylight factors. *Energy and buildings*, 38(7), pp.905-913 (2006).
25. Merini, I., Molina-García, A., García-Cascales, M.S., Mahdaoui, M. and Ahachad, M. Analysis and Comparison of Energy Efficiency Code Requirements for Buildings: A Morocco–Spain Case Study. *Energies*, 13(22), p.5979 (2020).

## Appendix [25]

- Root mean square deviation is given by:

$$E = \sqrt{\frac{\sum(e_i^2)}{N}}$$

Where,  $e_i = \left[ \frac{x_i - Y_i}{x_i} \right] \times 100$