EFFECT OF BUILDING FORM ON DAYLIGHT AND ENERGY EFFICIENCY FOR EDUCATIONAL BUILDING IN COMPOSITE CLIMATE

Pushpendra Chaturvedi, Dr. Nand Kumar, Dr. Ravita Lamba, Pushkar Nachan

Malaviya National Institute of Technology, Jaipur, India

Abstract

Adequate daylight design with balanced energy consumption is the prime concern of architectural principles, especially in educational buildings. It not only reduces the building's operational energy demand but also enhances pupils' learning productivity and reduces mental stress by maintaining a healthy indoor environment. This paper presents a parametric simulation approach using the Rhinoceros' Grasshopper tool to investigate the visual comfort and energy efficiency of a school building situated in the semi-arid composite climate of Jaipur (India). Useful Daylight Illuminance (UDI), Daylight Autonomy (DA), Uniformity Ratio, Average Lux, Cooling Energy Demand (CED), and Heating Energy Demand (HED) are assessed as performance indicators with nine different building forms in each orientation. The building forms include single and double line I shapes, L, U, square, hexagonal, rectangle, H, and circle shapes, and their effectiveness on building visual and energy performance has been investigated. This research demonstrates that optimal building form enhances the UDI and uniformity ratio by 35.83% and 293%, respectively, and reduces cooling and heating energy demand by 22.82% and 23.93%, respectively. This analysis provides decision-making support for architects and engineers for building form design in the early design stage to ensure visual and energy performance.

Keywords: Visual comfort, Cooling and heating energy demand, Building form, Rhinoceros' Grasshopper

1. Introduction

School is a very imperative educational space where students spend 50% of their time to sharing information, learning, and interacting with tutors [1]. Creating a healthy indoor environment is a crucial aspect of architectural design principles [2]. Numerous past studies demonstrate how comfort (visual and thermal) levels in surroundings have a significant impact on learning [3]. Better daylight in school helps to create a pleasant learning environment, promotes better health, and provides significant energy savings [4]. Therefore, the provision of daylight in educational spaces is internationally recognized. Moreover, it is the most crucial design challenge in architecture. Visual comfort is the subjective sensation of contentment with the visual system that defines the occupant's perceived satisfaction with lighting conditions, levels, and views in the occupied space for performing specific tasks [5]. Visual comfort is affected by various factors, such as environmental, human, and physiological. The environmental factors are mapped as illumination level, glare, colours, and uniform distribution of light. The human factor includes exposure time, susceptibility to glare, and age. The physiology factor encompasses motivational and transient adaptations [6–7]. There are several indexes available to evaluate the many aspects that influence visual comfort, including the amount of daylight, consistency, quality, and glare of the light. The assessment criteria to measure daylight is the quantity of natural light. Meanwhile, various metrics are available to quantify the daylight. To assess the quantity of daylight, illuminance, daylight

10.18086/swc.2023.06.03 Available at http://proceedings.ises.org

factor (DF), daylight autonomy (DA), useful daylight illuminance (UDI), continuous daylight autonomy, intensity of visual comfort, etc. are available. Besides, illuminance uniformity was used to measure the uniform distribution of daylight in the space [8-10]. Many past studies were available that focused on the investigation of daylight by exploring various envelope design variables through simulation and parametric optimizations. Szentesia et al. (2022) investigate the provision of a uniform distribution of daylight in the classroom building. This research illustrates that the integration of light shelves and skylights enhances the uniformity ratio of daylight [11]. Mushtha et al. (2019) examined daylight factor, glare, and cooling load for the 15 existing school buildings and found that most of the buildings failed to achieve a sufficient luminous level inside the space. Therefore, it is the cause of higher energy demand [12]. Mohammad and Zahra (2016) illustrate that the placement of a lighting shelf at an optimized angle can reduce the glare in the space and enhance the work plane area by 2-40%. It also reveals that southern façade glazing with the integration of a light shelf can reduce the lighting load by 60% in arid climates [13]. Aniela (2020) shows that the orientation of the classroom has a significant impact on operational energy demand. This research investigates the effect of daylight on lighting energy demand with the placement of lighting sensors. It reveals that an optimum orientation of building spaces can achieve 28% energy savings [14]. Mohamed et al. (2022) examined the effect of automatic shading strategies on the indoor thermal visual environment of school buildings [15]. Khaoula et al. (2021) investigate the effect of envelope design, including wall, glass, window-to-wall ratio, and shading, on energy consumption, daylight, and thermal comfort. This research was evaluated by parametric optimization using the Rhinoceroses' Grasshopper tool [16]. Although exploring all the previous literature reviews, the authors identified a lack of research available that extensively examines the effect of various building forms on daylight and energy consumption. Therefore, this work focused on the effects of various building forms that are typically used in architectural design and their significant impact on daylight and energy consumption. Visual comfort and cooling energy demand might have a contradictory relationship in tropical climates. However, enhancing the daylight by envelope, opening, orientation, and building geometry does not give a guarantee of thermal performance because of the penetration of heat inside the building space. To maintain the indoor thermal environment occupant required to run the air-conditioning. Meanwhile, it increases the cooling energy demand. Therefore, this research focused on identifying the optimal building form that is suitable to maintain the trade-off between daylight and cooling consumption in education buildings. The novelty of this study is to investigate the impact of building geometry on various daylight matrices along with cooling energy demand for education building. Moreover, the methodology of this research was applied to the existing allocated site of a school building. In this research, the authors developed nine different building forms such as single I, double I, L, U, square, hexagonal, rectangle, H, and circle shapes, with equal buildup area and volume in a Rhinoceroses tool. Grasshopper was used to investigate the performance objectives such as daylight and energy demand. Useful Daylight Illuminance (UDI), Daylight Autonomy (DA), Uniformity Ratio, and Average Lux were used as performance indices for daylight, and for the determination of energy demand, Cooling Energy Demand (CED), and Heating Energy Demand (HED) were taken into account. This research demonstrates that optimal building form enhances the daylight and reduces the energy demand.

2. Methodology

This section presents the methodological approach used for this research. It comprises into three sequential approaches, as shown in Fig. 1. Step 1 shows the development of different building forms; the second step illustrates the assign the building performance objectives as daylight and energy consumption; and finally, the third step reveals the results and outcomes.

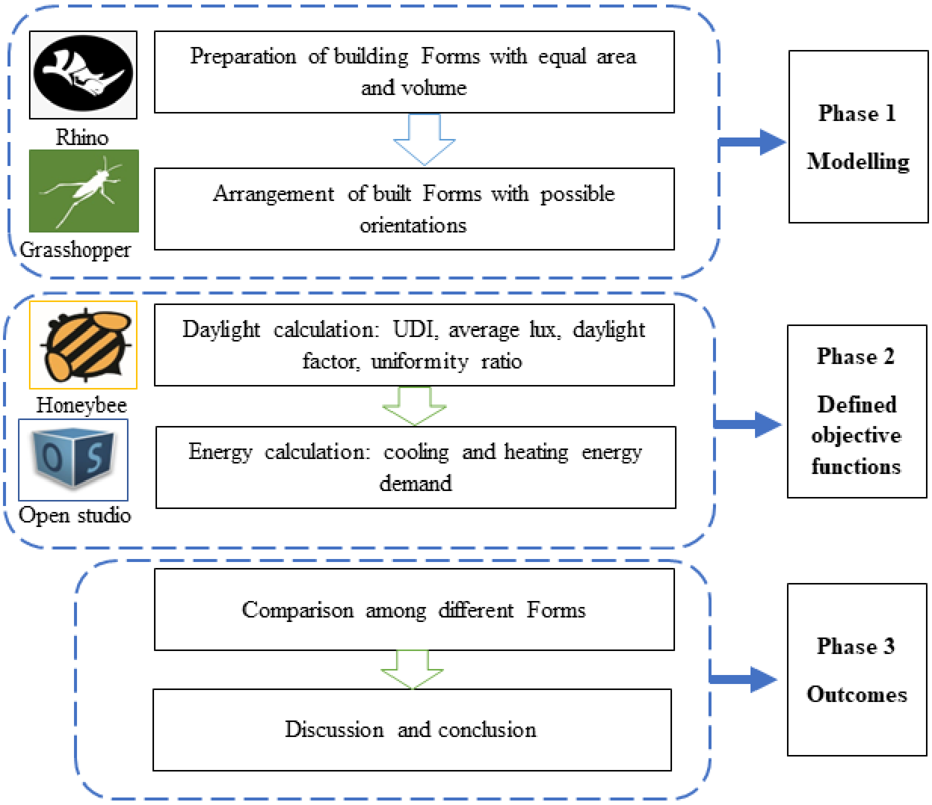

Fig. 1: Methodological hierarchy for simulation

3. Building model

A 3D Rhinoceroses software was used for the modeling. A working site allotted for a school building was assumed for the analysis, which is shown in Fig. 2. It is situated in the composite semi-arid (Köppen climate classification: Bsh) climate zone of Jaipur, India. Jaipur has extremely hot summer (45°C) and cold winter (4°C) temperatures [17]. Therefore, building form has a very crucial role in thermal comfort and energy consumption. In this work, different building forms were created with equal area and volume. Fig. 3 shows the possible building forms created in the Rhino tool. Furthermore, the Grasshopper plugin was used coupled with Rhino for simulation. The created building form was arranged in the possible building orientations as depicted in Fig. 4.

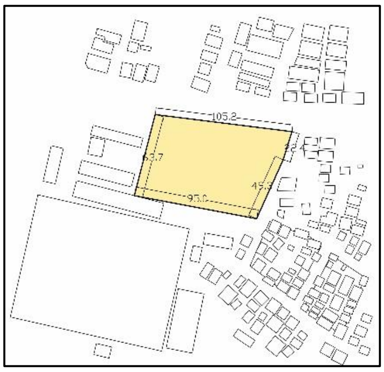

Fig. 2: Site plan for school building

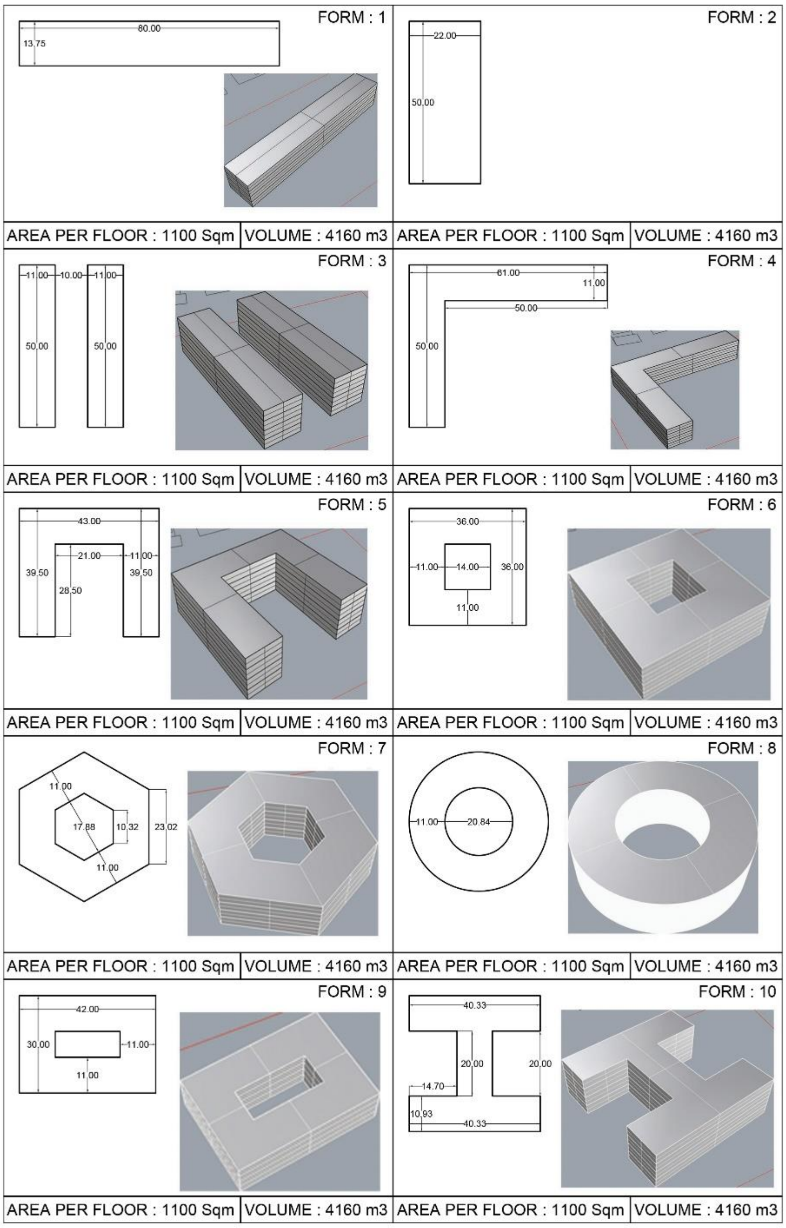

Fig. 3: Different building forms with area and volume

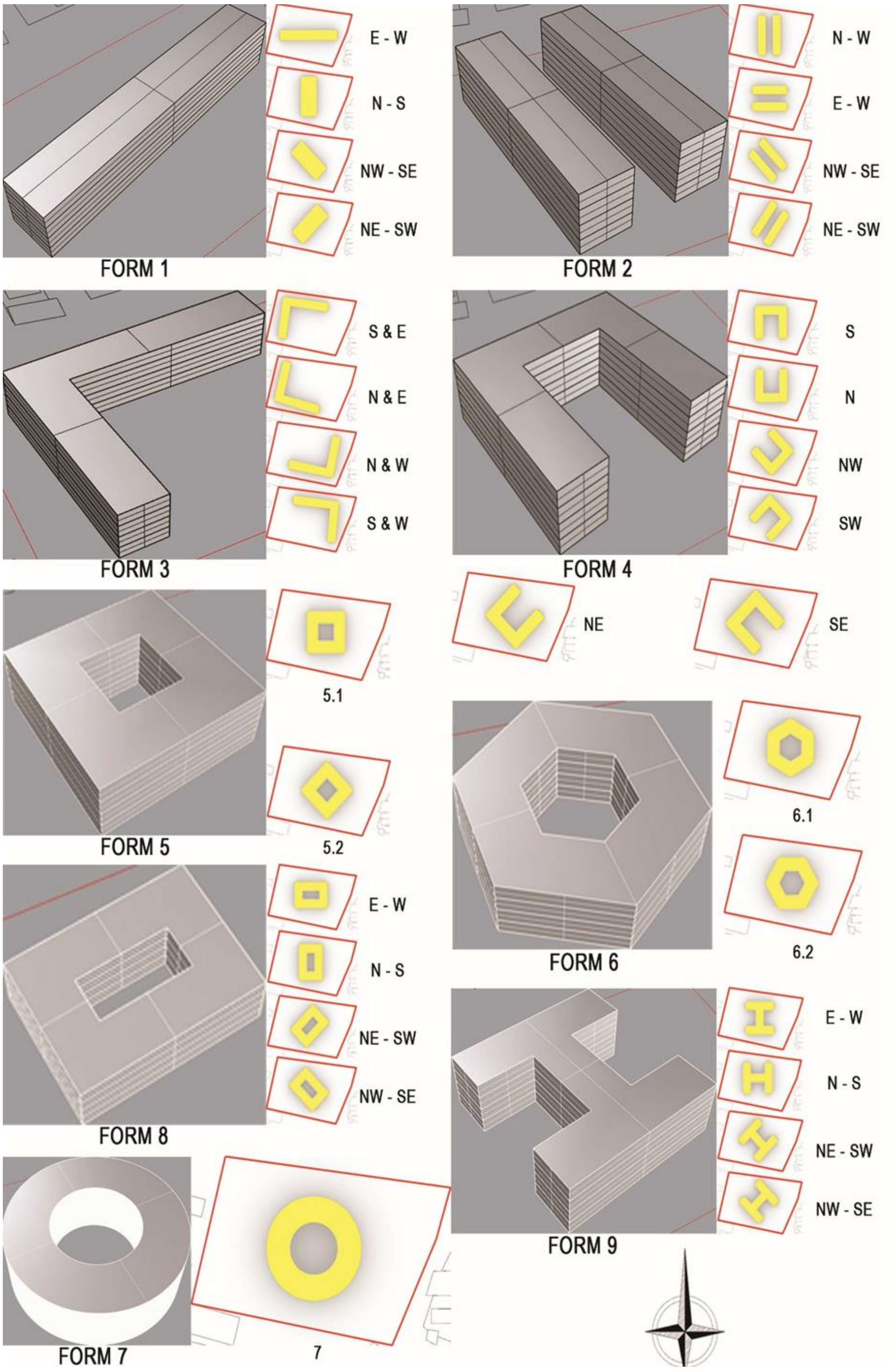

Fig. 4: Different possible orientations for simulation

4. Performance Objectives

In this research, two objectives with different indices were used for simulation. Assessing the quantity of daylight, average lux, useful daylight illuminance (UDI), daylight autonomy (DA), and uniformity ratio were calculated. For the energy calculation, cooling and heating were taken into account.

4.1. Lux

It is the unit of illuminance; it is defined as the amount of light falling on the surface called illuminance. It is used to create a local and short-term metric that evaluates the amount of light using a one-tailed criterion. [18]. Different illuminance threshold was defined for different types of buildings and kinds of use of spaces. In this research minimum 500 average lux level at a work plane height of 0.8 meter was taken into account as a threshold criterion.

4.2. Useful daylight illuminance (UDI)

It is defined as the fraction of time during which horizontal illuminance falls in the indoor space within a defined range. The lower and upper thresholds of illuminance are split into three bins to analyze the period of daylight availability. Upper bins (<2000 lux) show the overflow of daylight, which might be the cause of glare and visual discomfort. Lower bins illustrate the time period when the illuminance range (>100 lux) that is too dark. And intermediate bins (100–2000 lux) show the appropriate amount of daylight that comes into indoor space for the defined time period. [19].

4.3. Daylight autonomy (DA)

It is a long-term, one-tailed, and local index that measures the quantity of daylight that is present at a specific location during times when the area is inhabited. It is described as the proportion of occupied hours during the year when the lone daylight source meets a minimal illuminance threshold. [20].

4.4. Uniformity ratio

Visual comfort is related to both the amount and distribution of light in an area. The ratio of the minimal illuminance value to the average illuminance on the specified plane at the specified time moment is known as the illuminance uniformity (U_0) of the specified plane. Eq. 1 was used to calculate the uniformity ratio [21]. Many studies show that the range of uniformity ratio is between 0.30-0.70 as per space and building typology.

$$U_0 = \frac{E_{min}}{E_{average}} \qquad \text{(eq.1)}$$

4.5. Energy demand

Energy demand defined as the amount of operational energy (kWh) is required for an entire period of a year. In this research, the energy performance index (EPI) was calculated for cooling and heating energy [22]. It is the ratio of total annual energy demand and the built-up are of buildings in sq.m. as shown in Eq. 2.

$$EPI\ (kWh/\ sq.m./\ yr.)\ = \frac{Annual\ energy\ consumption\ (kWh)}{Total\ build\!-\!up\ area\ (sq.m.)} \qquad \text{(eq. 2)}$$

5. Result and discussion

After modeling in Grasshopper, the Radiance and Open Studio simulation engines were used to perform the daylight and energy simulations, respectively. Daylight was calculated at a work plane (table) height of 0.8 m, and lighting sensors were placed in a 2x2 meter grid matrix. An EPW format of the weather file for Jaipur city was imported into Grasshopper to investigate the defined performance objectives. The weather file contains the weather data including dry bulb temperature, wet bulb temperature, due point temperature, humidity, solar radiation (direct and diffused), global horizontal illuminance, wind velocity, and wind direction. Fig. 5 shows the most important weather data profile that has a significant impact on daylight and cooling energy demand. Fig 5 (a) illustrates the day bulb and wet bulb temperature, 5 (b) shows the humidity and 5 (c) shows the global horizontal illuminance (GHR), direct normal radiation (DNR), and direct radiation (DR).

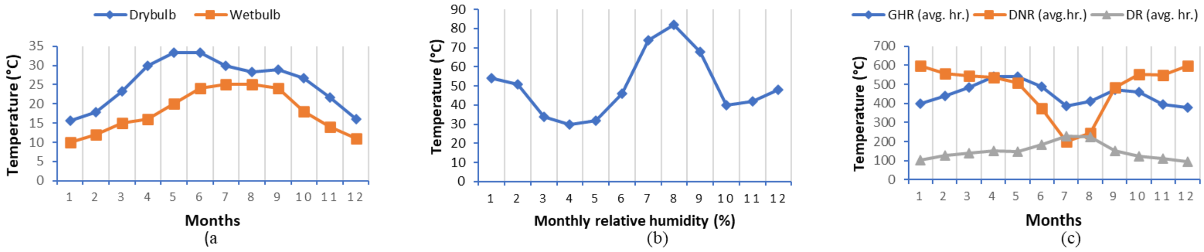

Fig. 5: Typical weather data profile of Jaipur city

The reflectance of the wall, ceiling, and floor was taken as 50%, 70%, and 20%, respectively, as per the energy conservation building code (ECBC) [23]. The calculation of energy demand (cooling or heating) and daylight was conducted for building operational time between 9 a.m. to 5 p.m. as per ECBC. A standard HVAC system type was used as the system configuration. It is an air-load HVAC system in EnergyPlus, which is most suitable in the early design stage considering the calculation time and cost [24]. The cooling set point of 26 °C and heating set point of 18 °C were the most suitable HVAC set point for energy efficiency point of view in tropical climates. The cooling and heating set points are taken as 26 °C and 18 °C, respectively [25]. The occupancy rate and their schedule, infiltration, and other constraints were set as per Indian standards. The ECBC and NBC standards were taken for choosing the setting of schedules during the simulation. Thermal conductivity of wall material 2.41 W/m^{2}K (burnt clay brick) and 3.62 W/m^{2}K (RCC slab) for roofing was taken into account for simulation. Table 1 presents the simulation results of daylight and energy consumption for each building form in different possible orientations. The result demonstrates that the I-shaped building in east-west orientation has higher lux and UDI levels. Because maximum daylight penetration comes from this side. Therefore, in this orientation, the uniform distribution of daylight is also enhanced compared to other orientations. L-shape building form in southwest facing was responsible for higher cooling energy demand. However, in peak summer, the sun's position between 12 p.m. and 3 p.m. is at the top of the building. Therefore, maximum heat comes from the building envelope through conduction and convection. Meanwhile, it enhances the building's cooling energy demand to maintain the indoor thermal environment. H-shaped and hexagonal building forms perform moderately in daylight and energy demand due to their compact building forms.

Table 1 Simulated results for daylight and energy demand

Form	Orientation	UDI	DA	Average Lux	Uniformity Ratio	Cooling Energy Demand	Heating Energy Demand
Single line I-shape	E - W	80.82	94.96	1734.26	22.62	113	18.26
	N - S	75.79	65.67	2254.97	6.86	113.22	18.26
	NE - SW	76.15	65.73	2273.86	9.77	109.4	18.13
	NW - SE	74.88	64.49	1549.37	11.67	111.04	18.71
Double line- I shape	E - W	80.02	86.26	1848.4	29.25	122.65	22.18
	N - S	68.63	96.83	4435.2	10.61	124.55	21.49
	NE - SW	77.51	95.85	3968.27	16.80	126.53	21.85
	NW - SE	78.22	95.36	1981.31	27.02	120.43	22.81
L- shape	S & E Elongation	62.96	98.16	4121.79	15.13	130.34	21.9
	N & W Elongation	59.13	98.51	4410.54	14.21	132.87	21.5
	N & E Elongation	66.26	97.8	4039.66	14.12	134.22	21.56
	S & W Elongation	63.2	97.74	4151.92	14.23	134.77	21.39
U- Shape	South	63.89	97.46	4742.38	10.72	132.72	21.25
	North	64.42	97.5	4516.95	10.59	132.29	21.35
	NW	67.6	97.41	3367.31	14.98	132.03	21.6
	SW	66.59	97.35	3533.33	13.74	132.17	21.48
	NE	68.47	94.98	4231.82	12.04	132.36	21.12
	SE	68.19	94.96	3265.83	14.60	132.14	21.5
Square Shape	1	79.97	83.31	2529.51	18.32	124.78	20.76
	2	79.39	84.12	2663.9	16.95	122.34	20.55
Hexagonal shape	1	68.45	96.7	3931.5	12.02	117.82	21.69
	2	70.94	90.4	3702.55	13.67	118.36	22.47
Rectangle shape	1	68.53	85.24	1862.25	22.75	120.59	20.98
H-Shape	E - W	79.77	94.01	2286.23	17.46	123.14	19.54
	N - S	79.78	94.41	2658.98	15.86	121.74	19.78
	NE - SW	80.3	82.39	2540.95	17.37	120.49	19.64
	NW - SE	79.44	81.85	2363.1	18.19	119.54	19.46
Circle Shape	E - W	70.42	96.63	3384.4	11.48	121.97	21.37
	N - S	73.22	91.09	3608.68	10.21	120.6	20.66
	NW - SE	70.09	96.64	3158.009	12.65	121.84	20.78
	NE - SW	66.34	96.83	4085.9	9.23	122.36	21.35

6. Conclusion

This research purposes is a decision-making approach for building form design in the composite climate of Jaipur, India. An education building site was taken into account for the analysis, and different possible building forms were created and simulated in different directions. A Rhinoceros tool coupled with Grasshopper was used to investigate daylight (average lux, UDI, DA, and uniformity ratio) and energy consumption (cooling and heating). The results reveal that single and double I-shaped buildings situated in east-west orientation were found to be the most suitable for daylight, and northwest-to-southeast longitude buildings had good performance in energy consumption. U and L-shaped buildings had the worst performance in daylight and energy consumption. It also demonstrates that optimum building form design can enhance the UDI and uniformity ratio by 35.83% and 293%, respectively, and reduce cooling and heating energy demand by 22.82% and 23.93%, respectively. The future work can be extended by optimizing the visual comfort, thermal comfort along energy consumption in the realistic education building and investigating the effectiveness of optimal solutions on occupant productivity.

7. References

1. Fazidah Hanim, H., Zafuan, H., & Amani, F. (2015). Environmental psychology: an analy-sis on lighting efficiency of the architecture studio in UiTM Perak/Fazidah Hanim Husain, Zafuan Husri and Farhah Amani.
2. De Luca F, Sepúlveda A, Varjas T. Multi-performance optimization of static shading devices for glare, daylight, view and energy consideration. Building and Environment. 2022 Jun 1;217:109110.
3. Edwards L, Torcellini P. Literature review of the effects of natural light on building occupants.
4. Küller R, Lindsten C. Health and behavior of children in classrooms with and without windows. Journal of environmental psychology. 1992 Dec 1;12(4):305-17.
5. Costanzo, V., Evola, G., & Marletta, L. (2017). A review of daylighting strategies in schools: state of the art and expected future trends. Buildings, 7(2), 41.
6. Cabeza LF, Chàfer M. Technological options and strategies towards zero energy buildings contributing to climate change mitigation: A systematic review. Energy and Buildings. 2020 Jul 15;219:110009.
7. Lan L, Wood KL, Yuen C. A holistic design approach for residential net-zero energy buildings: A case study in Singapore. Sustainable Cities and Society. 2019 Oct 1;50:101672.
8. Yoon Y, Moon JW, Kim S. Development of annual daylight simulation algorithms for prediction of indoor daylight illuminance. Energy and Buildings. 2016 Apr 15;118:1-7.
9. Kontadakis A, Tsangrassoulis A, Doulos L, Zerefos S. A review of light shelf designs for daylit environments. Sustainability. 2017 Dec 29;10(1):71.
10. Carlucci S, Causone F, De Rosa F, Pagliano L. A review of indices for assessing visual comfort with a view to their use in optimization processes to support building integrated design. Renewable and sustainable energy reviews. 2015 Jul 1;47:1016-33.

11. Szentesi-Nejur S, De Luca F, Flamand K. Simulation based daylight uniformity optimizations for elementary school projects in Quebec province. InProceedings of the 40th eCAADe Conference 2022 Sep (pp. 13-16).
12. Mushtaha E, Eiz H, Janbih L, Rifai RE. Analyzing and Improving Natural Daylight in Educational Buildings Using Skylights, Victoria International School of Sharjah as a Case Study. InIOP Conference Series: Earth and Environmental Science 2019 Nov 1 (Vol. 385, No. 1, p. 012013). IOP Publishing.
13. Moazzeni MH, Ghiabaklou Z. Investigating the influence of light shelf geometry parameters on daylight performance and visual comfort, a case study of educational space in Tehran, Iran. Buildings. 2016 Jul 13;6(3):26.
14. Kaminska A. Impact of Building Orientation on Daylight Availability and Energy Savings Potential in an Academic Classroom. Energies. 2020 Sep 19;13(18):4916.
15. Mahmoud RM, Abdallah AS. Assessment of outdoor shading strategies to improve outdoor thermal comfort in school courtyards in hot and arid climates. Sustainable Cities and Society. 2022 Nov 1;86:104147.
16. Lakhdari K, Sriti L, Painter B. Parametric optimization of daylight, thermal and energy performance of middle school classrooms, case of hot and dry regions. Building and Environment. 2021 Oct 15;204:108173.
17. Tewari P, Mathur S, Mathur J, Kumar S, Loftness V. Field study on indoor thermal comfort of office buildings using evaporative cooling in the composite climate of India. Energy and Buildings. 2019 Sep 15;199:145-63.
18. Bardhan R, Debnath R. Towards daylight inclusive bye-law: Daylight as an energy saving route for affordable housing in India. Energy for sustainable development. 2016 Oct 1;34:1-9.
19. Fang Y, Cho S. Design optimization of building geometry and fenestration for daylighting and energy performance. Solar Energy. 2019 Oct 1;191:7-18.
20. Costanzo V, Evola G, Marletta L. A review of daylighting strategies in schools: state of the art and expected future trends. Buildings. 2017 May 13;7(2):41.
21. British Standards Institution. Light and Lighting-Lighting of Work Places: Indoor Work Places. BSI; 2011.
22. Gupta G, Mathur S, Mathur J, Nayak BK. Comparison of energy-efficiency benchmarking methodologies for residential buildings. Energy and Buildings. 2023 Apr 15;285:112920.
23. Energy Conservation Building Code FAQs ECBC 2017: Bureau of Energy Efficiency (beeindia.gov.in).
24. Zhang A, Bokel R, van den Dobbelsteen A, Sun Y, Huang Q, Zhang Q. Optimization of thermal and daylight performance of school buildings based on a multi-objective genetic algorithm in the cold climate of China. Energy and Buildings. 2017 Mar 15;139:371-84.
25. Wu H, Zhang T. Multi-objective optimization of energy, visual, and thermal performance for building envelopes in China's hot summer and cold winter climate zone. Journal of Building Engineering. 2022 Nov 1;59:105034.