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SIMULATION-BASED RETROFITTING OF AN EDUCATIONAL BUILDING IN TERMS OF OPTIMUM SHADING DEVICE AND ENERGY EFFICIENT ARTIFICIAL LIGHTING CRITERIA

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ABSTRACT

The high level of daylight performance is crucial to increase academic and work performance of students and staff in educational buildings which are mostly used during the daytime. New design solutions have potential to reach optimum lighting conditions and minimum energy consumption. So, the purpose of this study is to evaluate and propose an energy efficient lighting design for an educational building. The aim is to find the optimum type of shading device with appropriate slat angles, transmittance of glazing, and the luminaire type/layout as well. Utilizing DIALux simulations, scenarios for combinations of these inputs are tested for classrooms, offices and a laboratory, which are non-identical due to their orientation, size, window characterization and facade organization. The procedure covers all significant days (winter/summer solstice and equinoxes) during one year. Such an integrated approach would be proposed for lighting design and retrofit applications.

Keywords: retrofitting, shading device, energy, daylighting, artificial lighting, simulation

1. INTRODUCTION

The physical environment has significant impacts on academic performance and alertness of students in educational buildings which are occupied mostly during daytime [1, 2]. The utmost concern is to benefit from daylight efficiently, to avoid visually uncomfortable conditions (i.e. glare occurred by excessive illuminance) and to apply energy efficient lighting strategies simultaneously. A special attention is necessary in their design and in retrofitting process afterwards.

Though energy efficient artificial lighting fixtures and light sources are selected and located in their right positions and layout, improperly designed educational buildings, which do not meet the necessary illuminance and uniformity requirements, allow the use of artificial lighting unreasonably. To illustrate proper requirements, work plane horizontal illuminance range from 300 to 500 lx in classrooms and offices. Higher illuminance varying from 500 to 750 lx is necessary in laboratories [3]. Uniformity is recommended to be above 0.67 according to DIN5034 [4]. To exemplify such an improper design, uncontrolled direct sunlight passing through the glazing in a facade without any sun protection components can only be avoided using curtains, which also block daylight completely inside the room. On the contrary, excessive amount of daylight in the interior and unbalanced distribution lead to glare problems. In those cases, shading devices provide sun control to balance the illuminance levels.

Several studies figured out impacts of building orientation, shading devices on the daylight performance and energy efficiency [5, 6]. One study analysed users' responses to the visual comfort survey, percentage of facade glazing and the recommended daylight autonomy to reduce electrical lighting energy consumption in an office building

Table 1. Geometrical properties of selected rooms

DESCRIPTION		Room A	Room B	Room C	Room D	Room E	Room F
ORIENTATION		Southeast	Southwest	Northwest	Northeast	Southwest	Southeast
	Type	Class	Class	Office	Lab	Office	Lecture Hall
	Lighting Row No. & Total Lighting No.	3 & 9	3 & 9	6 & 18	3&30 - 3&24	3 & 3	4 & 24
	Width, m	6.40	6.40	6.50	22.90	3.10	13.00
	Depth, m	9.80	9.80	12.40	12.10	6.60	9.85
	Height, m	3.60	3.60	3.30	3.30	2.60	3.40
	Floor Area (m^2)	61.13	62.83	80.36	268.82	19.70	128.19
WINDOW	Width, m	2.90	2.90	2.90	2.90	0.95	0.95 & 1.40
	Height, m	2.55	2.55	1.80	1.80	2.50	2.35
	Height from Floor, m	1.05	1.05	1.05	1.05	0.10	1.05
	Total Glazed Area (m^2)	14.80	14.80	10.44	36.54	4.75	18.92
	Window-to-Wall Ratio (WWR %)	63	63	49	48	59	43

[7]. Another one focused on several lighting retrofit scenarios for a hall in the university campus. The study involved calculations of energy consumption relying on LEDs and different types of fluorescent lamps in each scenario [8]. One research proposed a simplified method to predict the energy savings of artificial lighting in relation to daylighting [9]; while others focused on the impact of external shading devices on daylight penetration and its performance [10].

The aim of this study is to retrofit an educational building in terms of lighting criteria by proposing the optimum slat angles and types of shading devices according to orientation. The other objective is to find the appropriate and energy efficient type and layout of luminaire to provide an adequate uniformity and support illuminance in deeper spaces and to attain minimum electricity consumption. So, both daylighting and artificial lighting are considered together as an integrated system. The values of parameters (slat angle and type of shading devices, transmittance of glazing, and type of lamp and luminaire layout/type) are evaluated comparatively and determined correspondingly under different design scenarios for an educational building's lighting retrofit.

2. THE PROCEDURE

2.1. Description of the case rooms and measurements

The case building is an educational building in Izmir Institute of Technology (38°N latitude, 26°E longitude). A total of six rooms in this building were selected to conduct DIALux simulations [11]. Their physical and geometrical properties, the layout and technical properties of the artificial lighting system were obtained from architectural and electrical/lighting system drawings and field observation, Table 1, Fig. 1.

Measurements of horizontal work plane daylight illuminance were taken using a digital illumi-

Fig. 1. Interior and exterior views of windows in Room B

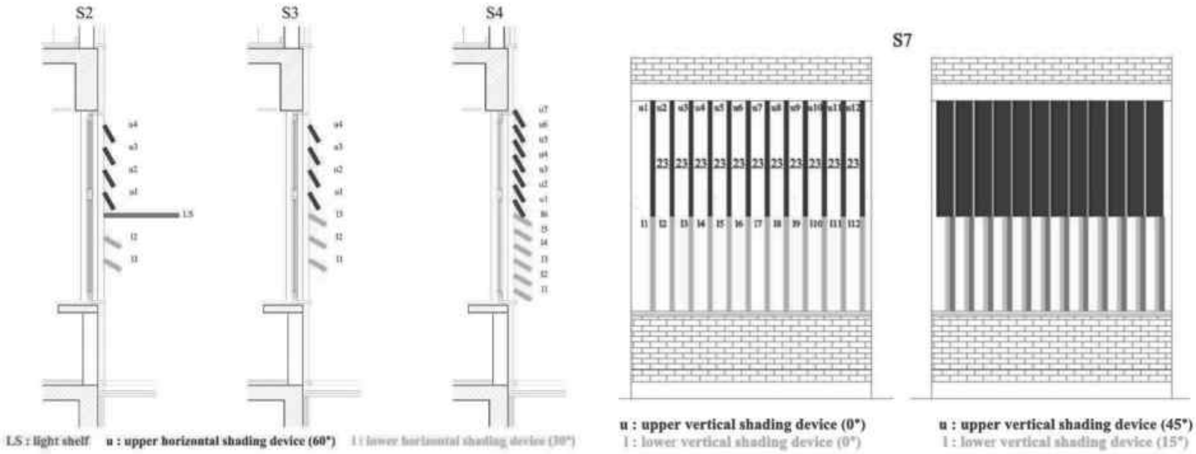

Fig. 2. Examples of options for shading devices

nance meter with an attached silicon photo diode receptor head, at 2.30 PM on December 4th, 2014. Its measuring range is 0.01–299, 900 lx. The sky condition was partly-cloudy. The optical properties of the glazing and surface materials were measured and calculated using both the illuminance and the luminance meter according to the method used in a previous study [12]. The reflectance of surface materials for walls, floor and ceiling were determined according to the Lambertian reflectance formulation. The reflectance of wall, floor and ceiling were 68%, 25% and 87% respectively. The transmittance of glazing was measured as 36% accordingly. Measured values were employed in DIALux model to correspond to the actual case before proposing retrofit scenarios.

2.2. Alternative retrofit scenarios using DIALux

DIALux performs daylight illuminance calculations, taking into consideration external obstructions, artificial lighting illuminance and its energy consumption as well [11]. The simulation-based models involved variants of shading devices, luminaires and glazings of sample rooms. Alternative retrofit solutions were proposed in terms of energy efficient lighting criteria. There are a total of nine alternative retrofit scenarios (S1-S9), which are derived from combinations of input values. These inputs are transmittance of glazing, type of shading devices, slat angles, type of luminaires and their layout. Three alternatives of transmittance of glazing (GT) were determined in retrofit simulations. GT1, GT2 and GT3 display the high (90%), medium (70%) and low (50%) transmittance, respectively. A higher-reflected-wall surface (80%) rather than the actual one was attained as an input in retrofit proposals. The base case scenario (S0) was implemented using the actual measured values.

A shading device acts to balance the light distribution on the horizontal work plane, while prohibiting the excessive penetration of sunlight to prevents overheating. Three types of shading system, a light shelf, horizontal shading devices (HSD) and vertical shading devices (VSD) have been proposed for each window including variations of slat angles and slat distances (Fig. 2). Slats are movable from 0° to 90° with 15° intervals where 0° is accepted as open and 90° as closed. These slopes are valid for both HSD and VSD. The slat width is taken as 25 cm. Upper and lower slats move independently from each other. For example, scenario 3(S3) involves HSD with 30 cm distance between slats and all slopes (0°, 15°, 30°, 45°, 60°, 75°, 90°).

The actual luminaire used in this building is a recessed modular type holding 4 TL-D/18W fluorescent lamps. Its total power is 70W, total luminous flux is 3834 lm. The retrofit scenarios involved replacing existing type of luminaires with LEDs'. The total power of the new LED panel with a similar luminous flux (3400 lm) is 41W. As it is essential to minimize the lighting power density [13] for the energy efficiency, LED type of luminaire with a similar luminous flux was chosen in retrofit scenarios. Luminaire layout is defined according to the number of luminaire rows which are switched on. For example, one alternative of luminaire layout included one working row near to the rear wall and others were switched off, while another alternative represented two working rows.

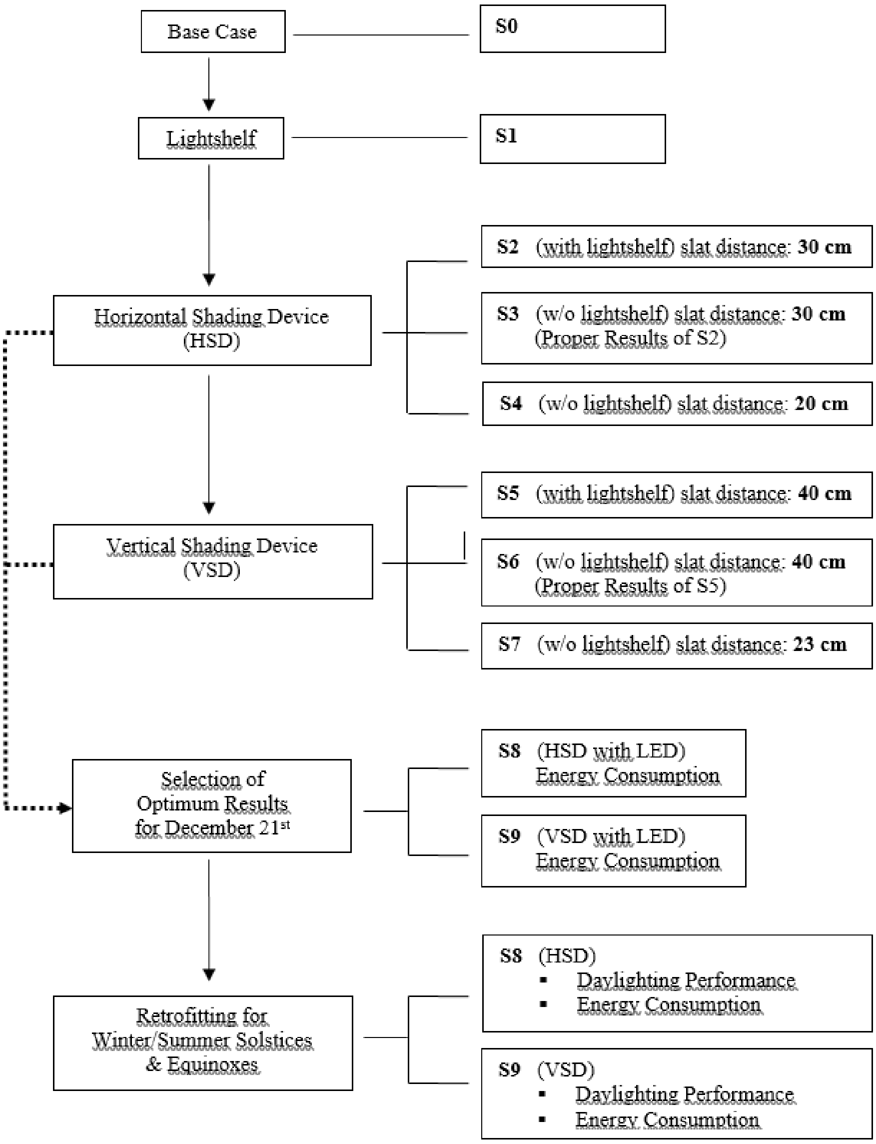

Fig. 3. Flowchart for scenario application steps (w/o: without).

The outputs are illuminance (lx), uniformity, LENI (Lighting Energy Numeric Indicator [kWh/yr.m^2] and the annual lighting electricity consumption [kWh/yr]. The European standard EN-15193 prescribes LENI values for educational buildings of (27–34.9) kWh/yr.m^2 with basic requirements [14].

As laboratories need higher illuminance (500–750) lx than classrooms and office rooms (300–500)lx [3], LENI are stated in a range of (41.8–51.9) kWh/yr.m^2 with comprehensive requirements [14]. Uniformity values should be above 0.67 according to DIN5034 [4]. In general, lighting consumes almost 10–50% of total electricity consumption in buildings; specifically 30–40% in office buildings. Recent studies search for new design/or technological strategies to reduce LENI below 10 kWh/yr.m^2 [13, 15]. To calculate lighting energy consumptions of buildings, Building Energy Performance Regulation (2008) and the Energy Calculation Method (BEP-TR) in Turkey have been adopted depending on the European Standard EN-15193[14], which defines the parameter of LENI. As it is known that LENI depends also on the daylight availability and is associated with the daylight climate; and climate in Izmir differs from the one in Europe, the recommended values may not fit the real situations in İzmir. Utilizing this kind of study, it is expected to provide useful information for developing such further standards and recommendations which are significant to our country's actual climatic conditions.

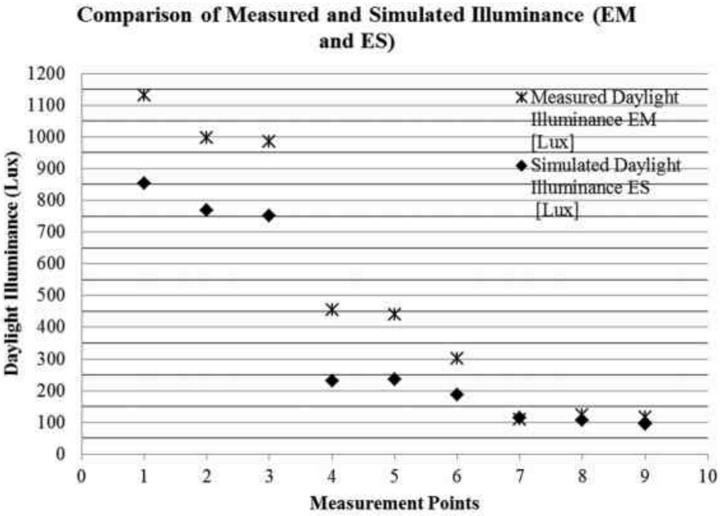

Fig. 4. Comparison of measured and simulated daylight illuminance for Room B

The electricity use was calculated for each single three-hour-periods (9:00 AM-12:00 PM; 12:00 PM-3:00 PM; 3:00 PM-6:00 PM) for winter/summer solstices and equinoxes. The whole year is subdivided into four periods due to seasons. The assumption here is that results for one significant day, i.e. winter solstice, are the same for other days in i.e. winter period. Each seasonal period identified by winter/summer solstices and equinoxes, covers 75 working days seperately. The annual electricity use corresponds to 300 days. Steps of scenario applications are given in Fig. 3.

In detail, retrofitting consists of a total of nine scenarios. First, DIALux performed the base case model for December 21st/June 21st and March 21st/September 21st. Second, simulations were run for a total of seven daylighting and energy efficiency improvement scenarios only for the day of December 21st. All simulations were produced under clear sky conditions. Third, one scenario including HSD, which resulted in the optimum illuminance and uniformity values; and another one including VSD were selected. Fourth, these two optimum scenarios were assigned as S8 and S9, respectively. They involved LED lighting fixtures, which replaced the existing fluorescent ones. So, it was possible to test their energy efficiency and to compare the results in terms of illuminance and uniformity. The calculation methodology for the annual lighting electricity consumption is simplified due to the standard EN15193. It takes into account the number of working luminaires and their working time i.e. for the winter solstice when S8 and S9 are the concern. For example, one row corresponds to three luminaires, which are switched on for only 3 hours, i.e. at noon.

daily energy consumption = luminaire power X number of working luminaires X working time (1)

seasonal energy consumption = Daily energy consumption X 75 days (2)

seasonal LENI = seasonal energy consumption / floor area (3)

Reduction and simplification of calculations, as above, make them flexible and available for short time stamp evaluations. The sum of seasonal electricity consumptions results in the annual one presently.

Fifth, the simulation generated outputs of the optimum case for HSD (S8) and the optimum case for VSD (S9) with fluorescent lighting fixtures for the equinoxes and the summer solstice over again. Sixth, models leading to unbalanced daylight distribution were retrofitted additionally by means of installing vertical and horizontal slats and of modifying the slat angles. Finally, the findings for the solstices and equinoxes showed us the improved scenarios containing the optimum shading device type, slat angle, lighting fixture layout and type. The calculations presented the electricity consumption of fluorescent and LED luminaires for all seasons. Seasonal LENI values (sLENI), which are identified here, are necessary to assess each scenario separately considering their response to seasonal conditions. According to this procedure

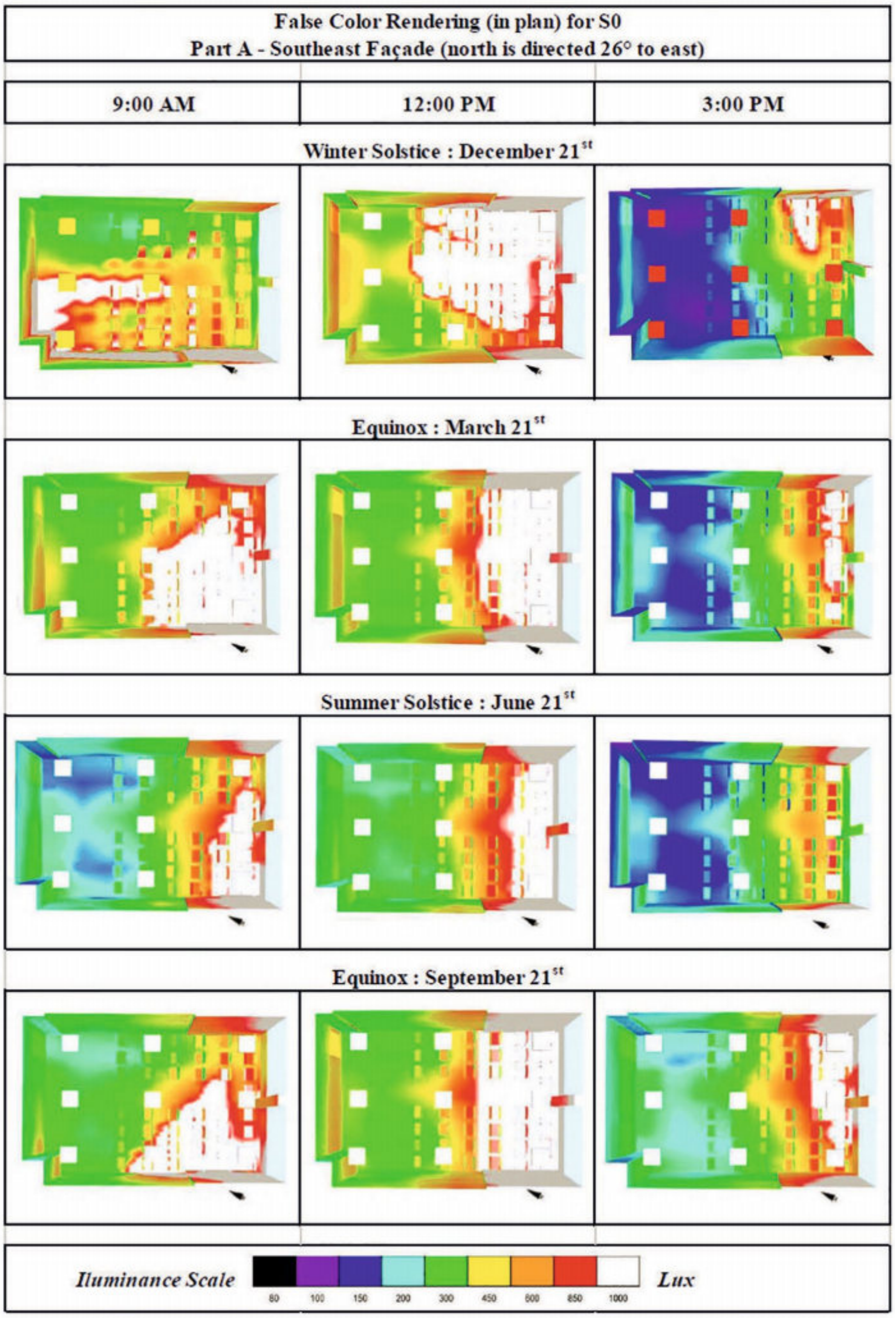

Fig. 5. Distribution of daylight illuminance for Room A in S0

the determination of the optimum HSD and VSD was based on the solstice and equinox conditions and LENI on the electricity consumption. The optimum application of HSD and/or VSD provides adequate conditions of daylight illuminance and uniformity while its role in the determination of the layout of working luminaires remains initially. The outcome designates the luminaires, which are counted in the energy consumption calculations and, by the way, in the LENI calculations. The subsequent step is to find out what would be the least consumed energy if the fluorescent type of lamp replaced to be the LED.

3. RESEARCH FINDINGS

Field measurements aimed to determine the actual daylight performance and to validate the base case scenario by comparing illuminance and uniformity. The target daylight illuminance was set as 500 lx and the uniformity as 0.6 according to recommendations [12–14] in evaluation of sun

Table 2. Retrofitting the Results for the HSD for Room A facing with Southeast

SD: Shading Device (length=25cm);
LL: Lighting Fixture Layout;
Panel length: 25 cm
Vertical; height: window height

Angle u: upper l: lower
n: Number of Lighting Row (on)

location: head of each side of window

Hour	W/S Solstices & Equinoxes	SD Angle	LL n	ILLUMINANCE (lx)			UNIFORMITY	
				E_{avg}	E_{min}	E_{max}	U1 E_{min}/E_{avg}	U2 E_{min}/E_{max}
9 AM	December 21st	u=30° l=75°	2	487	396	591	0.81	0.67
	March 21st	u=60° l=75°	2	513	459	605	0.89	0.76
	June 21st	u=0° l=90°	1	478	300	589	0.63	0.51
	September 21st	u=45° l=75°	2	504	442	597	0.88	0.74
12 PM	December 21st	u=75° l=75°	2	487	394	598	0.81	0.66
	March 21st			446	326	577	0.73	0.57
	June 21st	u=75° l=45°		547	500	657	0.91	0.76
	September 21st	u=75° l=75°		450	338	579	0.75	0.58
3 PM	December 21st	u=15° l=60°	2	507	439	602	0.87	0.63
	March 21st			566	520	642	0.92	0.81
	June 21st			508	438	612	0.86	0.72
	September 21st	u=45° l=90°		488	387	593	0.79	0.65

shading systems. It was observed that there was an unbalanced daylight distribution in this classroom. Its uniformity (almost 0.1–0.2) was very low and the illuminance at approx. half of the measurement points was below the recommendations (500 lx). The area close to the windows was very bright when compared to the rear area, Fig. 4. Thus, it was necessary to propose a shading system to achieve a uniform daylight distribution.

A lineer regression diagram was used to validate the DIALux model. The coefficient of determination (R^2) and the lineer regression equation were calculated by using Excel. Value R^2 was equal to 97% and confirmed the high accuracy of the model. This is an indicator for approx. 97 % chance of prediction power of the measured values by using the simulated values. Consequently, the simulation outputs fit the field measurements very well. Specifically, the measured illuminance was greater than the simulated ones (Fig. 4).

Retrofit simulations were conducted at 9:00 AM, 12:00 PM and 3:00 PM for winter/summer solstices and equinoxes under clear sky conditions. DIALux implemented every possible combination of slat angles, glazing and luminaire choices according to scenarios as mentioned in previous section. So, the analysis tool was run for almost 250 simulations for each case room. As this process was repeated for each six room, a total of 1500 simulation results were evaluated all together.

Regarding simulation results, which represent base case conditions for Room A, there was an unbalanced daylight distribution during the day due to the direct sunlight inside the room on December 21st. This day corresponds to the worst scenario; since, the sun elevation gets lowest inci-

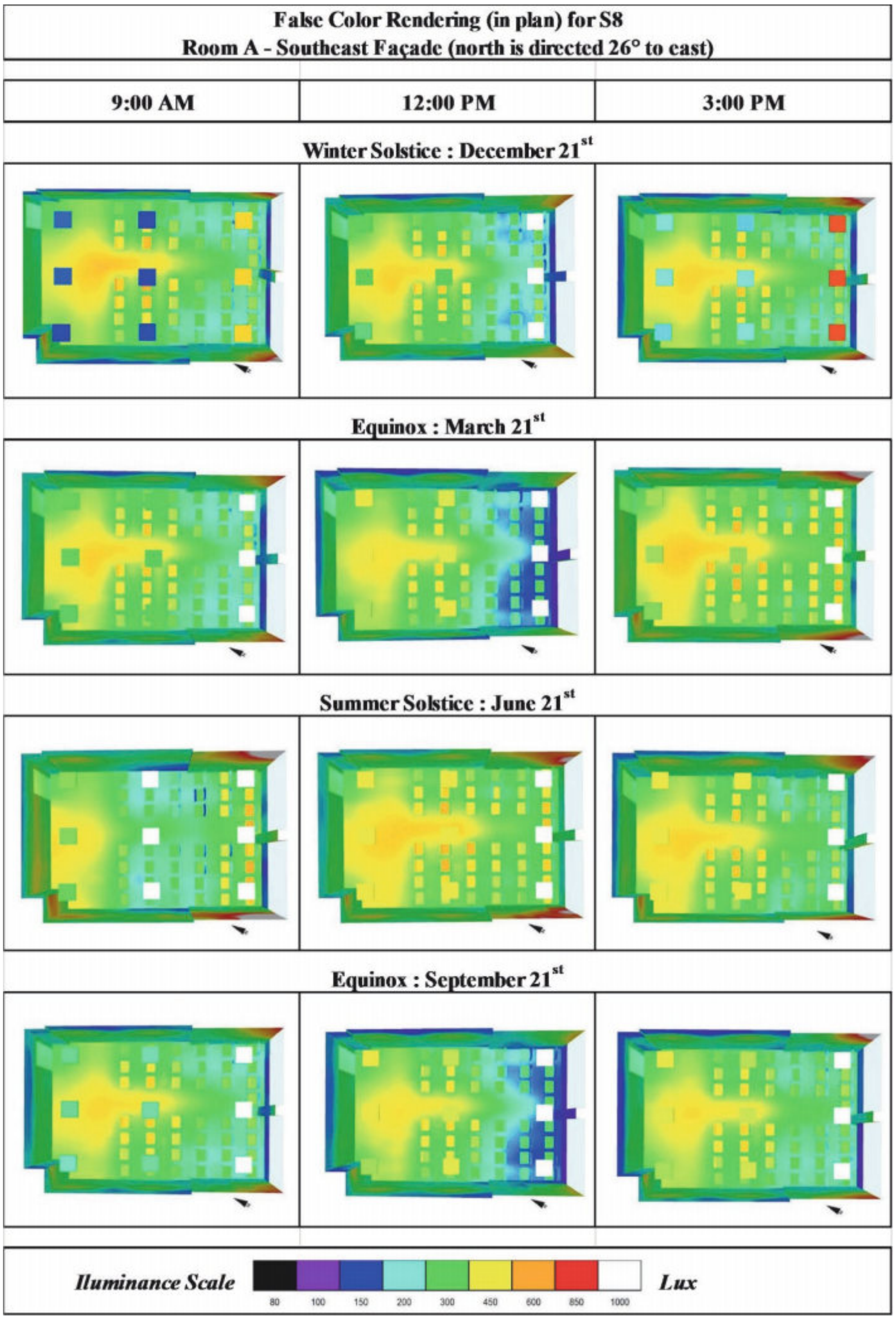

Fig. 6. Room A-False colour rendering (in plan) for retrofitted S8

dent values. The direct sunlight can reach at the rear wall during the morning hours; in the middle of the room at noon, Fig. 5. Daylight illuminance exceeds approximately 1000 lx mostly during the day. Even in summer period, disturbing bright area is almost one third of the whole floor area during the morning and at noon. The darkest region in this room received a very low level of daylight in the afternoon annually. Curtains are indispensable for such existing situations in the classroom to prevent direct sunlight. However, they cause the use of artificial lighting system during the day.

To improve its uncomfortable lighting conditions, Scenario-S4 (Table 2) contained HSDs whose slat distances were 20 cm. They controlled the penetration of sunlight and daylight; thus, uniformity varied from 0.46 to 0.89. This led to a comfortable and stimulating visual environment. Using all glazing transmittance values (GT1, GT2 and GT3), daylight illuminance was within the range of recommended values (300–500) lx. S4-FT1 was

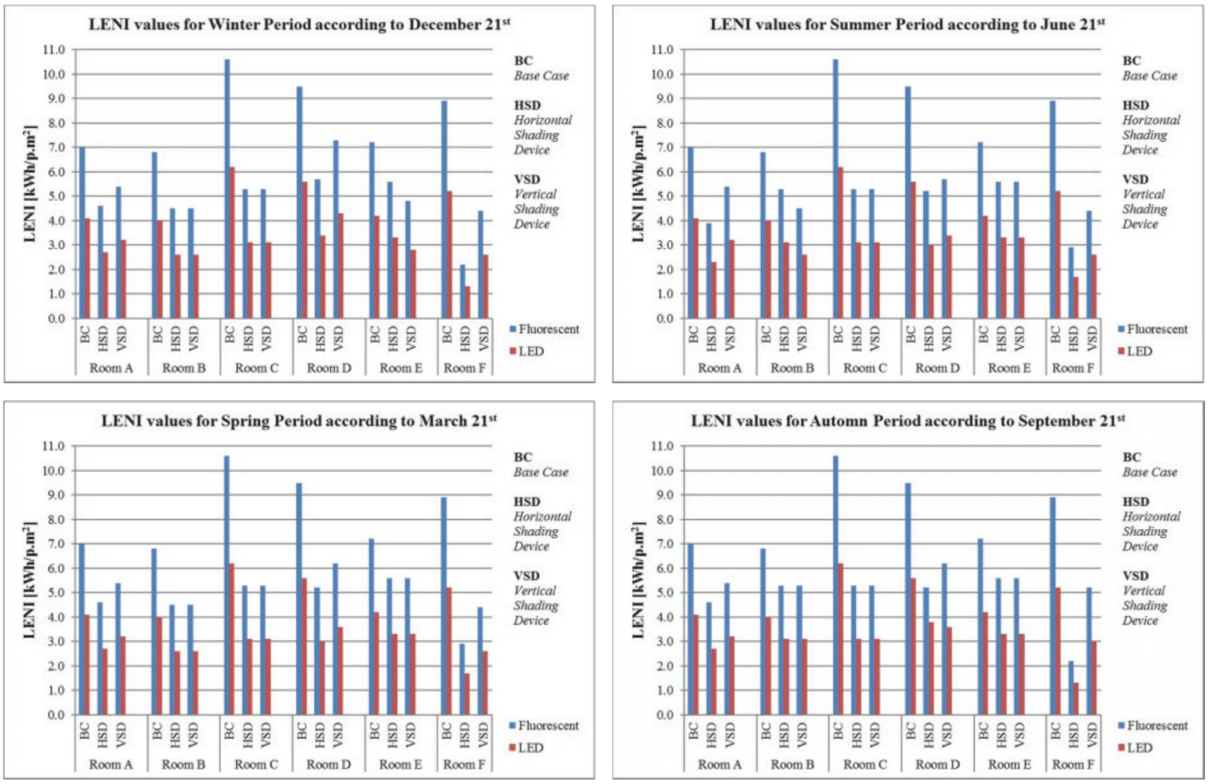

Fig. 7. sLENI values in winter/summer solstice and equinoxes for all case rooms.

found to be the most appropriate solution among the HSD scenarios in terms of uniformity. Upper and lower slat angles were 30° and 75° respectively in the morning, in this scenario. At noon, all the slat angles were 75° and two rows of luminaires are turned on. In the afternoon, upper and lower slat angles were 15° and 60° respectively and two rows of lighting fixtures are switched on.

S7-FT3 was proposed as the optimum one among the VSD scenarios. In S7-FT3, upper and lower slat angles were 45° and 30° respectively and two rows of lighting fixtures were in the working condition in the morning. At noon, upper and lower slat angles were 45° and 75° respectively. Only one row of luminaire was able to support the lighting level near the back wall. As all slat angles of the shading system were 75°in the afternoon, very low illuminance values were merely raised utilizing all artificial lighting system.

LED luminaires were integrated in S4-FT1 and S7-FT3 at this time. We named the former S8 and the latter S9. The photometric characterization of LED fixtures resulted in higher uniformity values. At noon, uniformity was increased from 0.79 (S4-FT1) to 0.92 (S8). It was rised up to 0.82 (S9) in the morning. Room A-False colour rendering (in plan) for retrofitted S8 is presented in Fig. 6.

Fig. 7 displays the sLENI values for all optimum HSD and VSD scenarios which initially fulfill the requirements of illuminance and uniformity. To discuss these scenarios furthermore due to desired energy consumptions, the proceeding step is to check which solution (HSD versus VSD) has the lower sLENI value; since both HSD-and VSD-retrofits are successful due to comfort levels. This process is accomplished for winter solstice; then, it covers the whole year to fig. out whether the optimum retrofit option for the worst time in a year would be additionally successful due to change in seasonal periods or not. Thus, the optimum solutions are obtained for HSD as S4-FT3 and for VSD as S7-FT3 on December 21st in Room B; for HSD as S4-FT1 and for VSD as S7-FT2 in Room C; for HSD as S4-FT1 and for VSD as S7-FT3 in Room D; for HSD as S4-FT3 and for VSD as S7-FT3 in Room E; for HSD as S4-FT2 and for VSD as S7-FT3 in Room F. A general conclusion depicts the dependency of sLENI on room orientation. Common retrofits are, conversely, valid in the whole year for each room. Specifically, HSD scenarios are found to be energy efficient solutions for Southeast and Southwest façade in relation to the geometric attributes (depth, width) of the room in this study.

4. DISCUSSIONS AND CONCLUSION

Reasons, which cause deficiencies in lighting conditions are stated as below:

- Facade configurations are independent of orientation and size in actual case. While there are large overhangs on North facade, preventing the penetration of diffuse daylight; there is no shading device on South facade resulting in the penetration of excessive direct sunlight.
- Despite the window-to-wall ratio is enough due to standards, room depth is higher than the required value. This caused insufficient amount of daylight in large rooms.
- The coated glazing, which is against high solar gain (the transmittance of glazing was almost 36%) minimizes the passage of daylight through the glass as well.

To improve above conditions, this study revealed scenarios bouncing design variants of shading devices and energy efficient lighting system relying on solstices and equinoxes.

Findings of illuminance derived from optimum solutions (S4-FT1 and S7-FT3) ranged from 480 to 532 lx on December 21th; similarly, that illuminance interval was kept similar in the whole year including a few exceptions observed at noon. Lower illuminance values were read at noon. The reason behind these exceptions may be the high protection of sun shading due to the higher slat angles. The uniformity varied between 0.46 and 0.89 during the year. Replacement of LEDs caused higher values of uniformity (0.63–0.92), but not significant change in illuminance.

The evaluation of the electricity use for periods was based on sLENI. Although Room E and Room B were two rooms facing Southwest (i.e. the same orientation), the installation of VSD in Room E was more energy efficient (4.8 kWh/p.m^2) than the use of HSD (5.5 kWh/p.m^2) in the same room on Dec 21st. Either the use of VSD or HDS did not make any difference in sLENI (5.5 kWh/p.m^2/flourescent) in the summer solstice and equinoxes. This condition was just the opposite when Room B was the concern. The application of VSD in Room B was more efficient (4.5 kWh/p.m^2/flourescent) than the use of HSD (5.2 kWh/p.m^2/flourescent) in the same room on June 21st. Their use did not influence sLENI either in winter solstice (4.5 kWh/p.m^2/flourescent) or equinoxes (4.5 kWh/p.m^2; 5.2 kWh/p.m^2/flourescent). The reason behind this situation is related to the sun elevation and the depth of the room. In winter, when sun elevations are low, the use of VSD in the least depth rooms becomes the energy efficient solution. In summer, its installation in the rooms with the highest depth results in the lowest energy consumption. Consequently, findings are in accordance to literature. The HSDs remained as optimum solutions for Room A, D and F facing Southeast and Northeast.

The best options for Room B and Room E facing Southwest were the VSDs. Room C facing Northwest may involve either HSDs or VSDs and neither of them affect the energy consumption among solstices and equinoxes. The electricity consumption became constant throughout the year.

The sum of sLENI values using fluorecent lighting for each room were within the limiting benchmark values (27–34.9 kWh/yr.m^2) of energy efficient lighting design criteria defined in EN-15193–1. Input parameters concerned in this study do not match all strategies to reduce the electrical energy consumption in retrofitting [15], but there are many others related to electric lighting installation and daylight harvesting. Still the reduction in electricity use was almost in the range 56–83% with the contribution of LED luminaire, layout, transmittance of glazing and shading devices. There would be more reduction when sensors/dimming control systems are installed and the design criteria maintain room depth, ceiling height and window area satisfactorily.

Optimum scenarios lead to a high level of visual comfort conditions and a low level of energy consumption by positioning the slats with high angles (60° or 75°). That blocks the view mostly. It is obviously crucial to achieve visual comfort conditions and less energy consumption without ignoring the outdoor visual contact. The depth of slats may be decreased and their geometry may be re-shaped in this context.

It is best to set the slat angles by the control of an automation system containing intelligent sensors, which makes adjustments according to the daylight illuminance. The application steps for retrofitting scenarios would be an infrastructure for further researches. Yet, this study implied feedback information about deficiencies in the actual case and optimum solutions to satisfy energy efficient lighting criteria. Such a preceding study was considered and its methodology was built to provide foreknowledge for such a system design.

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