

Article

An Evaluation of the Luminous Performance of a School Environment Integrating Artificial Lighting and Daylight

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Abstract: The energy performance of buildings has been extensively studied at the Federal University of São Carlos, Brazil in order to achieve energy conservation and reduce environmental impacts. Artificial lighting is one of the systems that consume the most electricity in educational buildings; therefore, by adopting measures to improve energy performance, the luminous performance can also be improved. Artificial lighting allows for visual tasks to be accurately and safely carried out by means of lamps of varied temperatures, color rendering index, and luminous performance. Providing adequate lighting in school environments can influence both the health and well-being of school members, contributing positively to productivity. The present study aimed to evaluate the luminous performance of the existing artificial lighting system in a classroom by considering the minimum requirements recommended by the Brazilian standard NBR ISO/CIE 8995-1/2013. Through computer simulations using the DIALux evo program, it was possible to propose actions to improve the existing lighting system in order to offer better visual comfort to users and ensure electricity savings. The artificial lighting system consisted of LED luminaires integrated with daylight and the use of a manual control device, thus generating electricity savings of almost 65% when compared with the existing artificial lighting system in the room.

Keywords: artificial lighting; natural lighting; luminous performance; energy efficiency; university classrooms



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1. Introduction

After the oil crisis that occurred in the 1970s, concerns about environmental preservation and energy efficiency have been present worldwide since the increase in energy production leads to environmental impacts, such as flooded areas due to hydropower generation and pollution from coal or gas electricity plants, causing a scenario which requires large investments from the government [1].

In Brazil, national programs were developed in order to promote the efficient use of energy resources and the preservation of the environment, such as the National Program for the Conservation of Electric Energy (PROCEL), established in 1985 through Law no. 10.295/2001 [2], and the Energy Efficiency Program (PEE), established by Law no. 9.991/2000 [3]. In 2021, these initiatives ensured a total of 4.54% in energy savings regarding the total consumption of electricity, mainly due to the actions suggested by the programs, which prevented the emission of 2.87 million tons of CO₂ [4].

The International Energy Agency (IEA) [5] points out several benefits, both in the economic and social fields, provided by investments in energy efficiency, such as the decrease in local air pollution, in addition to positive impacts to the macroeconomy, health, and well-being fields. It is also possible to observe that reductions in energy demand and

greenhouse gas (GHG) emissions, for example, has been an important goal for political representatives around the world, mainly considering the improvement in the efficiency of products and processes that consume energy.

The use of natural lighting has been studied through non-conventional systems, such as heliostats, light ducts, and light shelves, with the aim of considering the usage of natural lighting (sunlight) from conventional systems (windows and zenith openings). Unfortunately, these non-conventional systems often provide insufficient lighting [6,7].

Light shelves are considered non-conventional systems that are capable of redirecting natural lighting into the internal parts of a building and may reduce the heating of areas close to openings by avoiding direct sunrays and the direct glare of sunlight. Some studies have shown that, when properly dimensioned, these devices improve the ambient illuminance index and reduce the electricity consumption used by artificial lighting and air conditioning systems [8–10].

Another method that may improve the use of natural lighting inside buildings and ensure energy savings is considering the natural lighting complemented by artificial lighting (electrical lamps) through an electrical lighting control system. As daylight varies throughout the day due to solar trajectory and sky conditions, the electrical control system may supply more or less artificial lighting to the area [11] according to users' needs. Thus, the environment may become more pleasant, and the internal luminance may guarantee the minimum lighting conditions according to the parameters specified by the NBR ISO/CIE 8995-1 [12].

Artificial lighting control systems can include manual on/off switches, presence and absence detectors, and daylight-related controls [13]. The type of system that needs to be installed depends on the occupation and use of the room, in addition to specific characteristics such as the room size, volume and orientation, surface colors and reflectance, and window geometry. The system should attend to several requirements in order to ensure sufficient internal illuminance in the room. Thus, considering the necessary adjustments of the artificial lighting system to natural lighting usage, this is a complex scenario [14].

It is possible to adjust artificial and natural lighting usage by means of automatic lighting control, but this system does not consider human aspects, such as age or the activity being performed, and these elements are important to ensure the comfort that is needed in the room. Considering this scenario, the control system may not achieve the users' needs, but a manually operated control system can improve visual comfort with little or no cost in terms of energy savings [15].

In order to save electricity and improve the quality of indoor and outdoor lighting, Light Emitting Diode (LED) lamps have stood out when compared to other types of lamps. Among other advantages in relation to fluorescent lamps, for example, LED lamps have lower electricity power (Watts), cause fewer environmental impacts (no pollutant components), provide greater luminous efficiency (more lumens), present greater durability and mechanical resistance (no glass bulb), and have the possibility of dimming and a low heat emission [16], ensuring more comfort to users.

Applying simulation software allows for the analysis of large amounts of data to calculate the lighting performance of indoor rooms in buildings. One of these software, available for free use, is the DIALux evo [17], developed by the German company DIAL GmbH, which is used worldwide for designing, calculating, and visualizing artificial and natural lighting systems for both indoor and outdoor environments.

Currently, the company provides a free-access validated version of the software according to technical reports from the Commission Internationale de l'Eclairage (CIE)—the International Lighting Commission [18,19]. This software uses the photon-mapping algorithm to perform calculations. In previous versions, DIALux used the radiosity method in its calculations, which was useful for individual rooms only. However, to perform a more complex analysis, the software considers that the new photon shooting method brings faster and more accurate results [20].

Although it is currently possible to design the lighting of an area in compliance with its internal lighting standards and to apply sophisticated control technologies, the problem persists in existing buildings, where lighting systems are not designed to integrate natural and artificial lighting. Considering this scenario, implementing a new lighting system with control technologies may result in costs and time-consuming retrofits. As this process depends on budget forecasts and does not materialize in the short term, the existing system continues to consume energy without optimization [21].

Currently, the Sustainable Development Goals proposed by the United Nations (UN) have been elaborating many actions regarding the energy field. SDG 7—affordable and clean energy—highlighting the target of 7.3, states that “By 2030, (it is necessary to) double the global rate of improvement in energy efficiency” [22]. In this manner, any effort in this direction must be considered as a contribution to achieve the goal.

In this sense, this article aims to present the evaluation results of an improvement performed in a classroom. An artificial lighting system was retrofitted with LED lamps, in addition to an increase in the use rate of natural lighting with the simple routine procedure of an artificial lighting control that would be executed by the users, neither demanding complex nor expansive control systems, legitimating its implementation.

The classroom is inside a building at the Federal University of São Carlos—UFSCar, São Carlos and São Paulo State, Brazil. The evaluation was performed by means of the DIALux evo software (Version 5.8.2.41968), and based on the simulation results, a new lighting system associated with manual lighting control was proposed in order to improve the luminous performance and the quality of lighting with less electrical energy consumption.

2. Materials and Methods

The Federal University of São Carlos has 126 buildings for academic purposes. These buildings are categorized by function as management buildings, academic departments, libraries, auditoriums, restaurants, and classrooms. There are specifically 7 buildings that are used as classrooms for an average of 10,000 students, denominated AT1 (built in 1997), AT2 (built in 1994), AT4 (built in 1994), AT5 (built in 1998), AT7 (built in 2009), AT8 (built in 2010), and AT9 (built in 2012), with a total of 14,526.26 m² of built area and 136 classrooms.

A case study was carried out in one of the classrooms at AT5, in which the windows are oriented to the north, allowing for the entry of natural lighting. In the south hemisphere, facades facing the geographic north receive the greatest amount of sunlight. Figure 1 presents a picture of the building and the selected classroom, which has total capacity of 60 students.



Figure 1. Building (left) and case study classroom (right).

The DIALux evo [17] software allows for the simulation and analysis of the performance of virtual models with artificial lighting systems through the following steps: (I) construction, (II) lighting, (III) calculation objects, (IV) export, and (V) documentation.

Steps (I), (II), and (III) are the processes of construction and feedback of the data related to the object of study and the lighting project. Steps (IV) and (V) refer to the manipulation of the simulation output data and the presentation of reports.

In the construction step (I), the indoor and outdoor environments are modeled with one or several floors, the surface characteristics such as colors and materials are defined,

and furniture can be inserted. All of these data are available on internal software catalogs and, if they do not exist, it is possible to create the desired texture based on the type of material and degree of surface reflectance. Furthermore, it is possible to import models built in other parametric programs that interface with DIALux evo, such as ArchiCAD, AutoCAD, Revit, and SketchUp. In the construction stage, the user defines the activities carried out in each environment and the minimum required illuminance parameter, as well as the artificial lighting performance metrics and visual performance benchmarks.

The study object was previously modeled using the ArchiCAD program and then imported to DIALux evo. For the construction phase, the following data were taken into account:

- Dimensions of 6.80 m in width and 9.80 m in length, totaling 66.64 m²;
- Ceiling height of 3.40 m;
- Openings facing north;
- Windows measuring 9.80 m in length and 1.90 m in height, totaling a glazed area of 18.62 m²;
- Building alignment, specifically a longitude of -47.88° and latitude of -21.98° ;
- Time zone range, namely UTC/GMT -3 h.

In the lighting step (II), three parameters were defined: artificial lighting systems, scenarios of simulations, and the energy consumption of the lighting systems.

In the first parameter, luminaires, lamps, and daylight control systems were included, and either the online search tool (LUMsearch), available on the program, or imported photometric file formats, such as *.ldt or *.ies, from luminaires and lamp manufacturers, could be used.

From luminaires or lamp data files, the parameters related to luminous flux (lm), luminous efficiency (lm/W), color temperature (K), and Color Rate Index (CRI) were transferred automatically into the luminaire or lighting system. In addition, some adjustments could be performed manually according to the project's needs.

At this step, the characteristics of the existing lighting system were also inserted and, subsequently, characteristics of potentially more efficient luminaires were considered. The following characteristics were defined:

- Artificial lighting comprising 12 (twelve) luminaires, each with 2 (two) fluorescent lamps of 32 W each and 3.5 W for the ballast, totaling 71 W per luminaire;
- Direct light distribution type;
- Luminaire dimensions of 1.520 m $\times$ 0.167 m $\times$ 0.076 m each;
- Lighting activation system comprising 3 switches activating the front row of the board, one row in the middle of the room, and two rows at the back;
- Height of 2.35 m between the luminaire and the work surface;
- Common hours of use from 08:00 a.m. to 12:00 p.m., and from 02:00 p.m. to 06:00 p.m., from Monday to Friday for 10 months a year, totaling an average usage of 1760 h per year.

The 22nd of June was considered as a sample, during the winter solstice, of a period with low solar incidence. For this simulation, the least favorable scenario in relation to daylight was considered, because if the natural lighting inside the classroom met the standardized levels proposed by this research in this condition, it would also meet the standardized levels in a scenario with a greater solar incidence, that is, the summer solstice, for example.

In addition, the electric power consumption of artificial lighting was considered the actual usage behavior; this was simulated by manually turning the lights “on” during the common hours of use.

The luminaires and lamps in the classroom were installed more than 20 years ago, and no technical data were found. In order to perform the simulation, technical data from similar luminaires were taken into account, with a luminous flux of 6500 lm. The total power of each luminaire was 71 W (2×32 W for each lamp, plus 7 W for ballast) according to

the catalog available in the DIALux evo software. Tree switches (“on and off”) operated the luminaires: S1 commanded Line1, S2 commanded Line2, and S3 commanded Line 3). Figure 2 presents a 3D plan of the classroom.

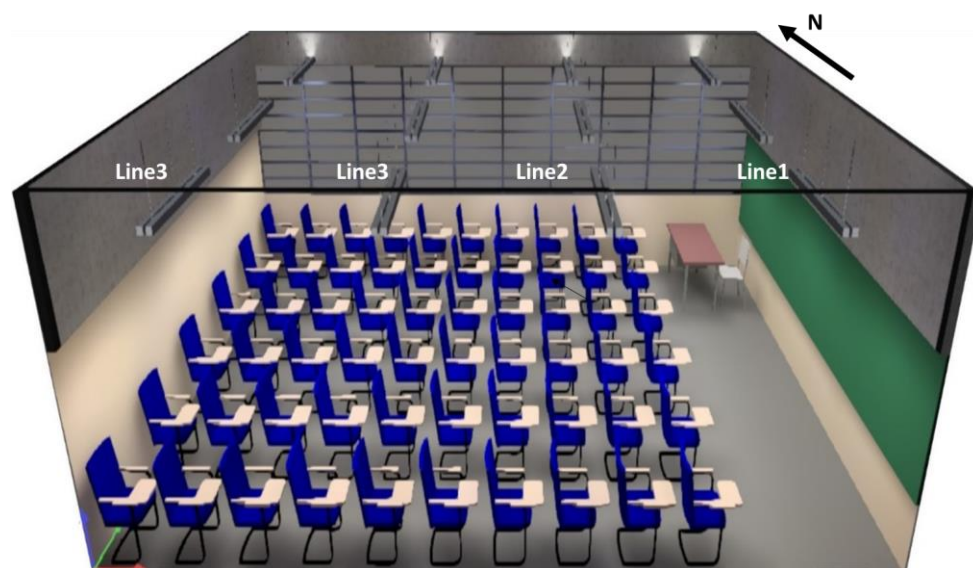


Figure 2. Classroom distribution lines of luminaires.

Simulations were performed using the DIALux evo [17] software, and the result analysis considered the following parameters recommended by the Brazilian standard NBR ISO/CIE 8995-1 [12]:

- **Maintained Illuminance (E_m):** On the reference surface of classrooms, the maintained illuminance suggested is not less than 300 lx.
- **Uniformity (U):** Since it is a classroom and, therefore, students' arrangements are flexible, the work area considered was the total room area, discounting a range of 0.5 m from the walls, and thus presenting the planned illuminance uniformity of ≥ 0.60 (ratio between the minimum value and the average value).
- **Color Aspects:** This refers to the qualities of lamp colors, which influence the visual performance and the well-being of users. The appearance of a color can be represented by its correlated color temperature, which can be classified as warm (below 3300 K), intermediate (3300 K to 5300 K), or cool (above 5300 K). The CRI (Color Rate Index) defines the color reproduction, and the quality increases as it approaches the maximum value of 100. Because the object of study is an environment where users remain for long periods, the CRI recommended is greater than or equal to 80.
- **Reflectance:** All elements inside the classroom were considered (concrete beam: 0.40; walls: 0.81; blackboard: 0.22; door: 0.48; teacher's desk: 0.15; teacher's desk structure: 0.31; teacher's chair: 0.50; student's chair clipboard: 0.65; student's chair upholstery: 0.02; student's chair structure: 0.00; floor: 0.20; roof: 0.40).

The technical information considered in the simulation was that available in an IES file compatible with the DIALux evo software, which was available on the Brazilian market at the time the study was carried out. The color aspects of the lamps were previously evaluated in order to meet the recommendations of the NBR ISO/CIE 8995-1 standard [12].

Suspended luminaires were maintained, since this type of mounting avoided the need to lower the ceiling, affecting the ventilation and the aesthetics of the classroom. In order to establish the optimum mounting height, three height mountings (2.40 m, 2.60 m, and 2.80 m) were considered.

In addition, two relative luminaire positions were considered. One was at 0° , related to the orientation of the building to the north, and one was at 90° . The two positions were used to verify their influence on the results to find out the best position for the luminaires.

From the characterization of the lighting systems, it was possible to organize the systems in groups and define scenarios using natural lighting, artificial lighting, or the integration of lighting systems by using the “light scenarios” tool available on the DIALux evo software.

For scenarios containing natural lighting, the clear sky model was considered. In addition, scenarios that presented only natural or artificial lighting were simulated. The integration of both lighting systems throughout the classroom’s operating hours was also performed.

The third parameter, called “energy consumption”, displays the system’s consumption in kWh per year; the consumption in kWh per year per square meter of the Lighting Energy Numerical Indicator (LENI), as prescribed in BS EN 15192-1:2017+A1:2021 [23]; and the annual costs in any currency. Additionally, it allows for the addition of a manual and/or automatic dimmer and a presence sensor.

In the calculation object (III), parameters related to the lighting calculation were assigned, such as the definition of the use plan and marginal zones, for example. In this case, the use plan considered was 0.75 m from the ground, and the marginal zone was 0.50 m from the ground. Diagrams were also configured, and they represent the illuminance obtained in the model in relation to the plans defined through value graphics, isographic lines, and color scales (in lux or in candela per m²).

Then, after defining these three steps (construction, lighting, and calculation objects), the user selected the calculation option and the program returned the overview of the results obtained on all calculation surfaces.

The export option (IV) step allows users to generate images of their projects from different perspectives and to save them.

The documentation stage (V) presents reports containing the results obtained in the simulation and information about the lighting systems. It can find values for the total number of luminaires, the mounting height of the lighting system and lighting power density (expressed in W/m² and W/m²/100 lx), luminous performance (in lm/W), and uniformity in the usage plan, for example.

Therefore, from the simulation, it was possible to state the best arrangement for the artificial lighting and natural lighting usage; it was also possible to integrate and suggest improvements for the lighting systems.

3. Results

The simulations considered the winter solstice day since it represents a less powerful natural lighting source; as a result, a greater usage of artificial lighting is requested, consequently indicating an increase in power consumption.

The results were organized into two sub-sections. The first one refers to the analysis of the use of daylight during common use hours, and the second relates to the evaluation of the existing artificial lighting system and potential new artificial lighting arrangements considering luminaires with LED lamps and classroom luminary control.

3.1. Daylight

To measure the daylight contribution, hourly simulations were performed while considering the classroom’s windows being oriented to the north and the winter solstice. Figures 3 and 4 point to the graphical representation of the false colors presenting the scale used to show the daylight variations in illuminance in the work plan at 08:00 a.m. and 04:00 p.m.

It is possible to perceive, from Figures 3 and 4, the low level of illuminance provided by natural lighting inside the classroom. In both hours, the average illuminance level range varied from 22.9 to 214 lx, and only the area closest to the windows received illuminance greater than or equal to 300 lx. The further away from the windows, the lower the illuminance in the work plan.

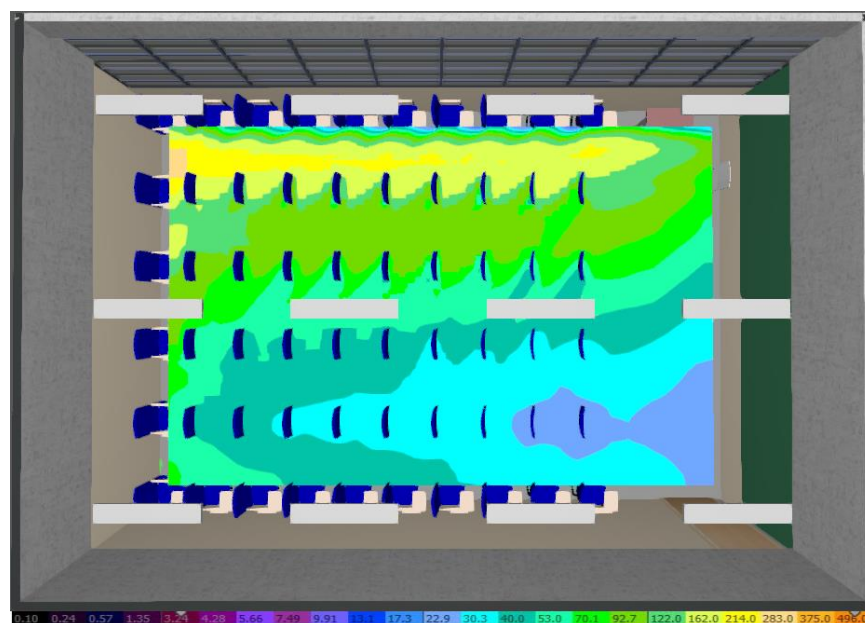


Figure 3. False color representation of natural lighting variation of illuminance in the work plan at 08:00 a.m. (scale color legend varying from black 0.10 lx to orange 496.0 lx).

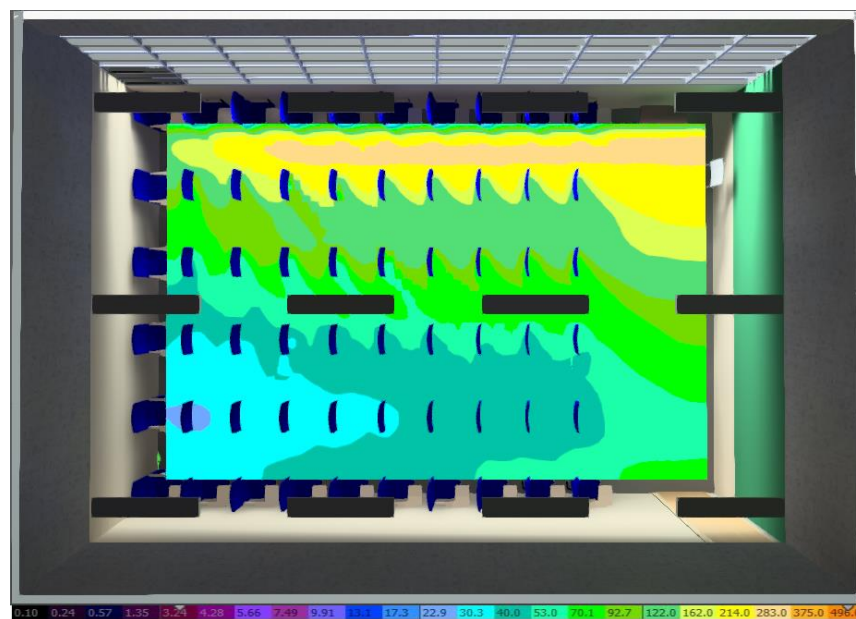


Figure 4. False color representation of natural lighting variation of illuminance in the work plan at 04:00 p.m. (scale color legend varying from black 0.10 lx to orange 496.0 lx).

The same occurred for the uniformity of the work plan, which did not reach the level of 0.60. All of the parameters attend to the NBR ISO/CIE 8995-1 standard [12].

3.2. Artificial Lighting System

The first-round simulation was performed based on the existing lighting arrangement in the classroom. Table 1 summarizes the results obtained.

As observed in Table 1, the uniformity in the work plan is greater than 0.60, and the average illuminance is greater than 300 lx. Thus, the room conditions comply with the NBR ISO/CIE 8995-1 standards [12].

In terms of illuminance distribution, the results presented by the simulation are in Figure 5, which shows the graphical representation of the false colors, presenting the color scale to show the variation of illuminance in the work plan.

Table 1. Main results obtained for the existing arrangement of luminaires.

Simulation	Luminaire Power P_{lum} (W)	Quantity of Luminaires	Mounting Height of Luminaires h_{mount} (m)	Uniformity at Work Plan U	Lighting Power Density LPD (W/m^2)	Luminous Performance (lm/W)
Existing lighting arrangement	71	12	3.10	0.64	12.79	65.0

Elaborated by authors.

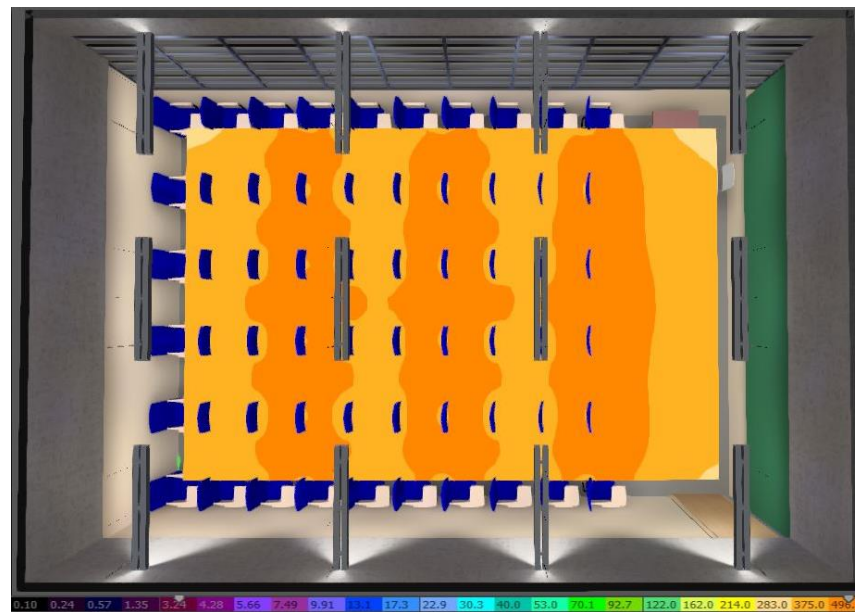


Figure 5. False color representation of the existing lighting system (scale color legend varying from black 0.10 Lux to orange 496.0 Lux).

The next simulation round tried out a new arrangement with LED luminaires from two different manufacturers. According to the manufacturer's technical data sheets, all luminaires have a CRI greater than 80 and, in terms of color appearance, they all have a correlated color temperature of 4000 K, achieving the intermediate level according to the NBR ISO/CIE 8995-1 standard [12]. All luminaires contain only one LED lamp, and the type of light distribution is direct. Table 2 shows the technical information about the luminaires.

Table 2. Main technical information of the LED luminaires used in the simulations.

	Luminaire	Dimension (L × W × H) in m	Power (Including LED Driver) (W)	Luminous Flux (lm)	Luminous Performance (lm/W)
Manufacturer I	A	$1.676 \times 0.060 \times 0.090$	28	2385	85.2
	B	$1.119 \times 0.060 \times 0.090$	37	3180	85.9
	C	$1.676 \times 0.060 \times 0.090$	56	4770	85.2
Manufacturer II	D	$1.340 \times 0.240 \times 0.049$	30	3500	116.7
	E	$1.332 \times 0.232 \times 0.100$	33	4000	121.2
	F	$1.340 \times 0.240 \times 0.049$	35	4100	117.1

Elaborated by authors.

For the simulation, all six luminaires from the two manufacturers had three mounting heights, and the position was determined in relation to the north. Table 3 presents the results observed in 18 simulations.

Table 3. Results for LED luminaires.

	Luminaire	P _{lum} (W)	Quantity of Luminaires	h _{mount} (m)	Uniformity at Work Plan U	LPD (W/m ²)
Manufacturer I	A	28	20	2.40	0.58	8.40
				2.60	0.63	
				2.80	0.66	
	B	37	16	2.40	0.51	8.88
				2.60	0.55	
				2.80	0.57	
	C	56	12	2.40	0.57	10.08
				2.60	0.60	
				2.80	0.60	
Manufacturer II	D	30	12	2.40	0.53	5.40
				2.60	0.59	
				2.80	0.76	
	E	33	12	2.40	0.57	5.94
				2.60	0.75	
				2.80	0.74	
	F	35	12	2.40	0.57	6.30
				2.60	0.76	
				2.80	0.76	

Elaborated by authors.

The criteria used to choose the best lighting arrangement for the lighting system from the 18 simulations performed took into account ($U \geq 0.60$ and the lower LPD (W/m^2)). As it is possible to observe in Table 3, some reached the minimum uniformity of 0.60, and the luminaire (D), Manufacturer II, with a mounting height of 2.80 m, presented the lowest lighting power density ($5.40 W/m^2$) with 0.76 in uniformity (U). The relative positions of the luminaires at 90° in relation to the north indicate that the longest sides of the luminaires were parallel to the longest sides of the room.

The luminaires positioned at 90° to the north presented the best values of luminous performance. The dimensions of the luminaires and of the classroom were relevant since they were coincident with the room's longest side and, therefore, were better distributed. Figure 6 shows the new arrangement of LED luminaires, and Figure 7 presents the results of the illuminance level.

In all simulations performed, the mounting heights of the luminaires were influenced only by the uniformity of the illuminance. In most simulations, the recommended minimum uniformity of 0.60 was reached when considering the mounting height of 2.80 m for luminaires.

In addition, the luminous performance of the existing system (fluorescent lamps) is $65.0 (lm/W)$, while that of the LED luminaire is $116.7 (lm/W)$, representing an increase of 79.5% in the luminous performance with less energy consumption.

In the next section, the simulations carried out and their results are discussed, considering improvements to detect the best solution to artificial lighting systems, and an optimized option to integrate artificial and natural lighting in the classroom is proposed.

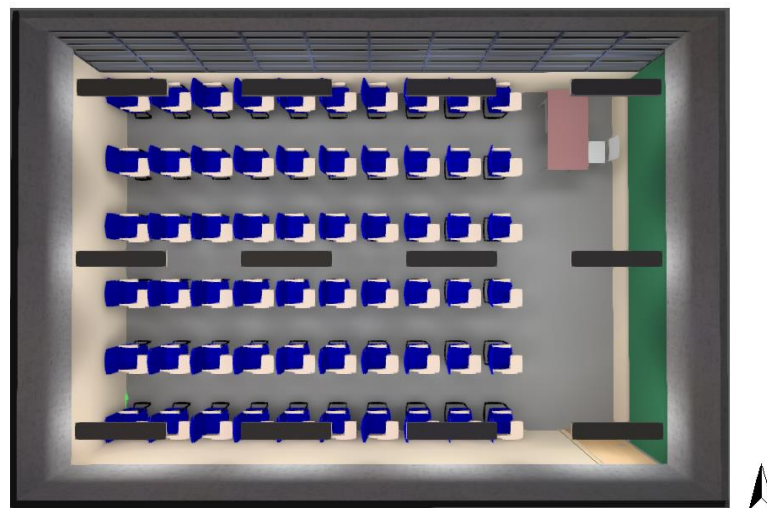


Figure 6. LED luminaires positioned at 90° to the north.

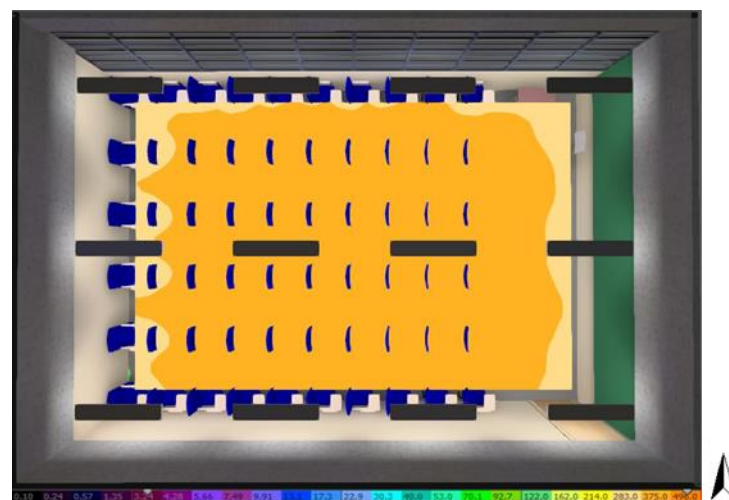


Figure 7. The false color representation of illuminance level at the work plan for LED luminaires (scale color legend varying from black 0.10 lx to orange 496.0 lx).

4. Discussion

The discussion considers the possibility of integrating artificial lighting and daylight to ensure savings in annual energy consumption by adopting the best option presented by the simulations.

4.1. Integration of Artificial Lighting and Daylight

The illuminance level contribution of daylight is lower than 300 lx in most hours of the day (Section 3, Results, Figures 3 and 4). This condition leads to a low illuminance standardized level, which requests supplement with artificial lighting systems.

In the case study, a new luminaire arrangement was proposed, positioning the luminaires parallel to the windows in the room with three electric circuits.

Considering this luminaire arrangement, depending on the incidence of natural lighting, the users, following a timetable schedule, can manually activate each row of luminaires in order to adjust the lighting level in the work plan (student desks) while the classroom is being used. Figure 8 shows the proposed arrangement of the circuits and operating switches.

According to the simulation results, artificial lighting and daylight can be integrated, and to guarantee the minimum illuminance in the usage plan, operating switches are scheduled as shown in the timetable in Table 4.

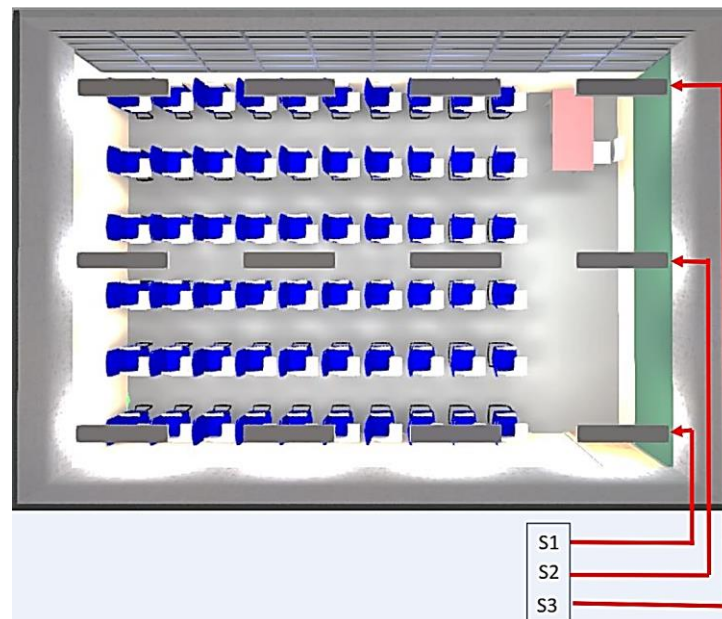


Figure 8. Proposed arrangement of circuits and operating switches for LED luminaires.

Table 4. Schedule timetable for artificial lighting system operation time.

Daytime	Switch 1	Switch 2	Switch 3	Operation Time (%)
08:00 a.m. to 09:00 a.m.	ON	ON	ON	100
09:00 a.m. to 12:00 p.m.	ON	ON	OFF	67
12:00 p.m. to 02:00 p.m.	OFF	OFF	OFF	0
02:00 p.m. to 03:00 p.m.	ON	OFF	OFF	33
03:00 p.m. to 06:00 p.m.	ON	ON	ON	100
06:00 p.m. onwards	ON	ON	ON	100

Elaborated by authors.

Simulations were performed to verify the classroom illuminance level on an hourly basis, and in Figures 9 and 10, the results for 09:00 a.m. and 02:00 p.m. are presented, indicating the hours of the day that required less artificial lighting.

It is possible to observe in Figures 9 and 10 that in both hours (09:00 a.m. and 02:00 p.m.), the illuminance level consisted of the integration of natural and artificial lighting, turning switches 2 and 3 off, and reaching the standard required level of 300 lx along the work plan level.

The new luminaire alignment and electrical circuits for switching the luminaires can provide a better performance in the classroom lighting system when compared to the current operational system, where all luminaires are switched “on” during the entire day. Each luminaire row can be switched “on” individually to adjust the luminance level according to the external natural lighting. Adopting a schedule to “turn off” the switches when possible ensures efficient energy savings.

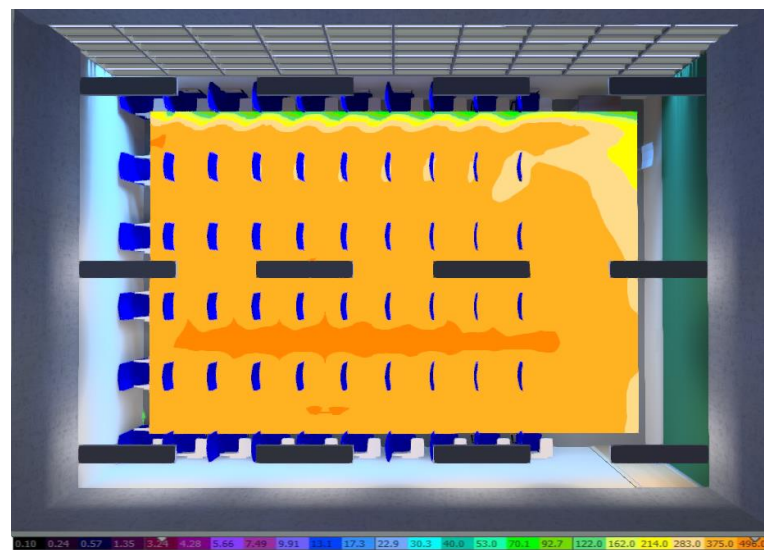


Figure 9. False color representation of illuminance level in the work plan for integrated lighting system at 09:00 a.m. (scale color legend varying from black 0.10 lx to orange 496.0 lx).

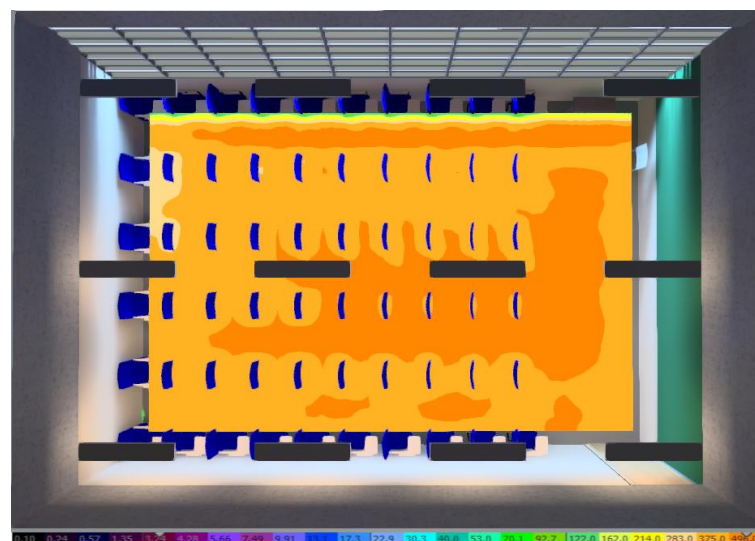


Figure 10. The false color representation of the illuminance level in the work plan for integrated lighting system at 02:00 p.m. (scale color legend varying from black 0.10 lx to orange 496.0 lx).

4.2. Annual Energy Consumption Savings

In order to find out the electricity savings, it was considered that the classroom was used from 08:00 a.m. to 12:00 p.m. and from 02:00 p.m. to 06:00 p.m., from Monday to Friday, 22 days a month and 10 months a year on average, totaling 1760 h of use.

From those data, the amount of electric demand for artificial lighting was calculated by considering the following: I—the existing arrangement; II—the improved arrangement with LED lamps; and III—the optimized arrangement with users operating the luminaries' switches. Table 5 shows the results.

From the data in Table 5, it can be seen that the replacement of the existing fluorescent lamps (71 W) with LED luminaires (30 W) while maintaining the quality of the room lighting achieved an obvious 58% reduction in power usage and estimated annual energy savings.

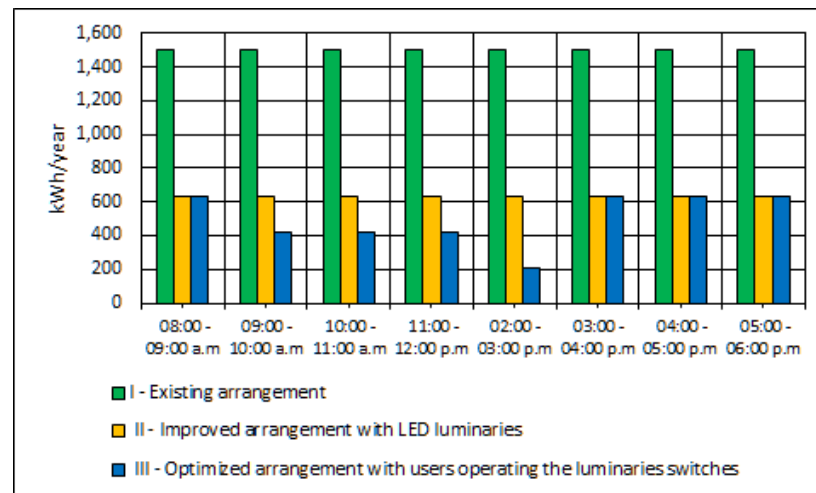
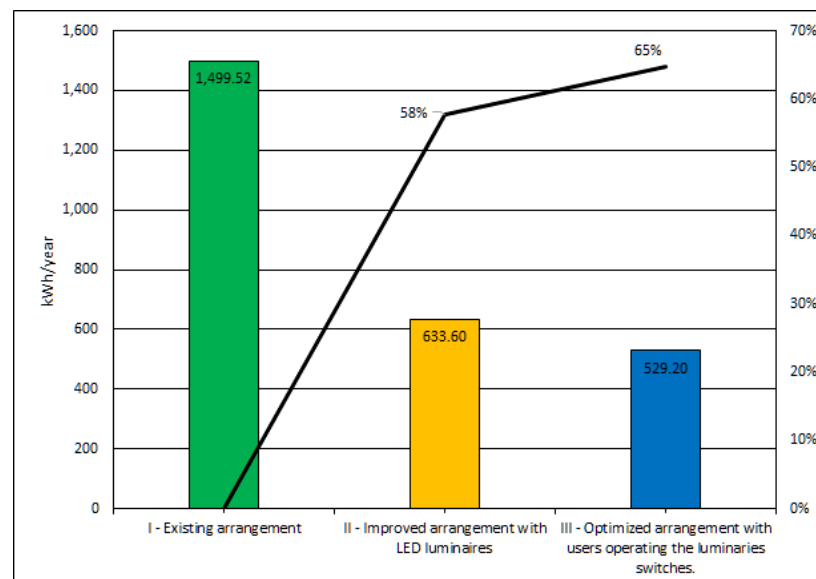
In addition, by adopting a timetable (Table 4) for the manual control of luminaries, the power reduction remained at the same level (58%), but the estimated annual energy savings increased to 65%, due to switching “off” S2 and S3 at certain hours (02:00 p.m. to 03:00 p.m.) of classroom use.

Table 5. Annual electricity consumption and savings.

Classroom Lighting Conditions	Luminaries' Power (W)	Reduction in Power (%)	Quantity (Units)	Use Time (Hours/Year)	Electricity Consumption (kWh/Year)	Estimated Annual Energy Savings (%)
I—Existing arrangement	71	0	12	1760	1499.52	0
II—Improved arrangement with LED luminaires	30	58	12	1760	633.60	58
III—Optimized arrangement with users operating the luminaries' switches	30	58	12	1470	529.20	65

Elaborated by authors.

Figure 11 shows a graph of the electricity consumption per hour in simulated systems for the three scenarios: I—existing arrangement; II—improved arrangement with LED luminaires; III—optimized with users operating the luminaries' switches. Figure 12 illustrates the annual consumption and potential savings that can be obtained in scenarios II and III.

**Figure 11.** Electricity power consumption per day based on time of classroom use.**Figure 12.** Annual electricity consumption and relative savings.

Considering the graphics in Figures 11 and 12, it is possible to observe the advantages of adopting a classroom condition (III) using a manual lighting control, because even with manual operation, great savings in energy consumption can be reached. It is also possible to automatize manual operation in the future with lighting sensors available on the market.

5. Conclusions

The results of the DIALux evo simulations demonstrated that the classroom does not receive enough natural lighting throughout the area of the work plan during the day, considering the time of usage, thus requiring supplementation with artificial lighting to maintain a minimum illuminance of 300 lx during hours of use.

The simulation results also pointed out a new optimized artificial lighting arrangement; therefore, the best solution consists of six luminaires, 30 W LED luminaires, positioned at 90 degrees to the north and mounted at a height of 2.80 m, which achieved the required illuminance level inside the classroom.

When considering the replacement (retrofit) of the existing system of luminaires of 71 W (two fluorescent lamps with ballasts) with a new system with 30 W LED luminaires (including driver), the luminous performance of the system increased by 79.5%.

In terms of electric energy consumption, electricity savings of around 58% were obtained when comparing the existing artificial lighting system with the artificial lighting system of LED luminaires.

Annual savings of 64% were achieved when comparing the existing artificial lighting system with the artificial lighting system of LED luminaires integrating daylight usage and the manual control device according to a timetable.

In addition to the complexity of artificial lighting control, implementations to equalize the internal classroom luminance that may require sensors, wiring, and electronic devices may lead to expensive investments, which are often not available in a university's budget.

On the other hand, the luminaires' retrofit and new arrangement (positioning to the north) and the proposed manual lighting control may be feasible to implement due to the low cost of the components and services for its implementation, considering that the resources are available as routine maintenance items on universities' budgets.

Furthermore, the adoption of manual operation by classroom users (teachers and students) may be a result of a pedagogical regard to the need for balanced lighting, as well as a way to increase awareness about the importance of saving energy, which can be expanded beyond the classroom. This is a simple measure that can contribute, even in a small scale, to achieve SDG 7.

It is possible to emphasize that research should consider automatic control lighting systems, based on year-long simulations, incorporating sensors and devices with Wi-Fi communication more persistently to automatic lighting control. In addition, an incorporation of the IoT (Internet of Things) and correlated matters that are currently available on the market can be expected.

Meanwhile, it can be a good practice to encourage research to be conducted on electricity savings by mapping similar classrooms in university buildings, resulting in large scales of annual electricity consumption savings, and of course, promoting less harmful effects to the environment.

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