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Energy efficiency of commercial offices by luminous retrofit

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ABSTRACT. Lighting is one of the systems that mostly consume electricity in commercial buildings. Therefore, improving its efficiency has the potential to reduce electricity consumption and emission of polluting gases. The objective of the present study was to assess an office lighting system retrofit of an existing building from the 1990s, verify the light levels in relation to standards of the Brazilian requirements, and to explore new systems with potential for luminous and energy improvement. The analyzes were carried out through computer simulations using the DIALux evo software, which allows the evaluation of artificial and natural illuminations simultaneously. The results indicated that the existing lighting system does not meet the average illuminance standard value for office environment. From simulations with new arrangements and types of luminaires and lamps, two more efficient lighting systems were designed. The first presented savings of 15.5% in lighting energy when replacing T12 fluorescent lamps with LED luminaires. The second system considered the use of natural light and was complemented by artificial lighting with the aid of a dimming system linked to the availability of daylight, and presented up to 67% less electric energy consumption when compared to the existing lighting system in the environments. Therefore, it was possible to propose actions to the existing lighting system retrofit and, thus, offer better visual comfort to users and at the same time save energy.

Keywords: Luminous performance; natural lighting; artificial lighting; benchmarking; computational simulation.

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Introduction

Buildings energetic behavior is determined by several factors, such as climatic conditions, characteristics of the openings, type of occupation and operation of the systems (Borgstein, Lamberts, & Hensen, 2016). Artificial lighting is one of the systems that significantly contributes to the consumption of electricity in commercial buildings and, therefore, has great potential for savings in both new and existing buildings. Especially in existing buildings, lighting systems retrofit is one of the most propitious means of achieving a reduction in electricity demand, since most of these buildings did not follow energy efficiency standards and/or principles at the time of project design (Michael, Gregoriou, & Kalogirou, 2018). In addition to the energy benefit, the reformulation of the lighting system can provide improvements in the comfort, performance, and visual safety for users.

Energy policies in buildings aim to reduce electricity consumption without losses for the consumers, that is, they aim to be energy efficient. The evaluation of the energy management system makes it possible to indicate a series of specific recommendations based on energy criteria and targets. For such evaluation, the benchmarking process allows to compare energy performance indexes between buildings with similar technical features. It basically consists of four steps: elaboration of a database with information on the reference buildings; selection of relevant information regarding energy performance; comparison of the index between the buildings in the sample and the reference, and; recommendations for efficient measures both technically and economically (Pérez-Lombard, Ortiz, González, & Maestre, 2009).

In the index-comparison step, buildings with similar technical features, such as the same type of construction and occupation, should be considered. Alternatively, a self-reference can be used, whose comparison is done with a reference building derived from the real building, and the energy performance is compared based on an index that shows the percentage of savings in relation to the self-reference (Pérez-Lombard et al., 2009).

Several researchers have contributed to studies involving strategies to reduce energy consumption and improve building lighting systems. According to Dubois and Blomsterberg (2011), one should invest in improving the technologies of lamps, ballasts and luminaires and in the use of occupancy sensors and/or manual or automatic artificial lighting control devices. Haq et al. (2014) commented that, in addition to using more efficient lamps with better luminous efficiencies, the consumption of electrical energy can be reduced by decreasing the time of use with the aid of devices for switching off the artificial lighting system.

Lamps and luminaires with LED technology have been widely used in homes, industries and businesses due to advantages such as, greater luminous efficiency, greater durability, the possibility of dimming and low heat emission (Kumar, Kuppusamy, Holuszko, Song, & Loschiavo, 2019; Nardelli, Deuschle, Azevedo, Pessoa, & Ghisi, 2017).

The factors that influence the performance of energy consumption of buildings are also analyzed. Bodart and De Herde (2002) indicated some parameters that are high related to the potential for saving electricity, such as the light transmission coefficient of the glass, the facade configuration, the opening orientation and the reflectance of the walls. Yun, Kim, and Kim (2012) showed that urban factors, such as orientation and angle of obstruction, also significantly influence the incidence of sunlight and, thus, interfere with the consumption of lighting energy. Susorova, Tabibzadeh, Rahman, Clack, and Elnimeiri (2013) evaluated the influence of geometric factors in commercial offices considering six climatic zones in the United States. Among the results obtained, the authors concluded that rooms oriented to the north with large windows and rooms with small openings oriented to the south tend to consume less energy in regions of warm and temperate climates compared to those oriented to the north with small windows and those oriented to the south with large openings.

Considering that natural and artificial lighting influence the health, well-being, and performance of human beings (Burattini et al., 2019; Van Bommel, 2006), it is essential that lighting systems be adequately designed in the necessary quantity and quality.

The use of natural light in indoor environments as a measure to reduce electricity consumption has been widely studied in conjunction with artificial lighting control devices. In addition to saving electricity and reducing greenhouse gases, it is possible to provide more pleasant environments for users (Shishegar & Boubekri, 2017).

The reduction in electricity consumption is achieved by using artificial lighting to complement the natural light available in the environment, as it varies throughout the day due to the rotation movement of the earth and sky conditions (Shishegar & Boubekri, 2017).

The evaluation of the performance of natural light in an indoor environment is influenced by several factors, such as geographic location, obstructions, characteristics of the openings and reflectance of the internal surfaces. According to Lou, Li, and Lam (2017), the luminance distribution of the sky is one of the most relevant aspects, which varies according to the sun position, climate, turbidity and cloud coverage.

The integration of artificial and natural lighting combined with control strategies allows the reduction of electricity consumption by reducing the luminous flux and, consequently, the power of the lamps according to the solar incidence in the plan of use and also when detecting the presence of the occupants and turning off the lamps when the place is vacated (Haq et al., 2014). In addition to the device linked to natural light and the occupancy sensor, electronic timers allow the control of artificial lighting according to pre-set schedules.

The choice of the control system depends, basically, on the occupation patterns and the tasks performed in the environment. For example, presence sensors are more recommended in places where occupation is less frequent and/or irregular, such as entrance halls and corridors (Gentile, Laike, & Dubois, 2016). In spaces that are constantly occupied without significant interruptions during the activity period, timers are suggested for allowing the lighting system to be switched on and off according to pre-established times (Haq et al., 2014).

Xu et al. (2017) evaluated the energy performance of lighting systems combined with control strategies in open-plan offices in China. With the aid of the Ecotect and Daysim simulation software, the authors concluded that the manually powered and automatically turned off system was more energy efficient. In addition, the isolated use of occupancy sensors and devices linked to natural light can result in energy savings of 30 and 23% respectively.

Shishegar and Boubekri (2017) analyzed the impacts of control systems linked to natural light in a virtual office building considering hot and arid climates in three American cities. Through the E-Quest software, lighting control through switches, automatic on/off device and dimming system was considered. The results indicated that the use of switches that completely or partially turn off the luminaire groups is more efficient (savings of up to 79% annually) in regions with a predominance of clear sky conditions. That is, in places under cloudy conditions and low availability of natural light, these systems turn the lighting on and off frequently and can disturb the occupants, in addition to reducing the lamp life. In this case, dimming systems that decrease the luminous flux of the lamps according to the availability of natural light can reduce lighting energy consumption by between 55 and 65%.

Byun and Shin (2018) evaluated the proposal for a lighting system considering the use of occupancy and lighting sensors and user satisfaction in a real work environment. The results indicated that the system can reduce electricity consumption by 43%, with 27.6% referring to the replacement of fluorescent lamps with LEDs, 6% due to the adjustment of the maximum illuminance according to the brightness values, and 9.4% due to the use of occupancy sensors.

Although there are a variety of lighting control systems, quantifying the potential for energy savings is an important task, given the various factors that can influence the results, such as the particularities of the climate, the building and the natural lighting system (Bodart & De Herde, 2002).

The objective of the present study was to assess the office lighting system retrofit of an existent building to verify the light levels in relation to the standard requirements recommended and to explore new systems with potential for light improvement and energy saving.

Material and methods

Initially, some requirements and general aspects necessary for the development of the research were outlined. The object of study refers to the office rooms of a building built more than 25 years ago and, as there have been no changes in the lighting system since then, the benchmarking process has been carried out, which allows the comparison of a performance index and later assessment of the current condition of the system.

The self-reference approach was performed, and the energy performance index used for comparison purposes was the limit lighting power density (LLPD). This index allows the evaluation of performance taking into account the type of activity performed in the environment and is given in W/m² per 100 lux.

In the benchmarking process, computer simulations were performed using the DIALux evo software that allows the design, calculation and visualization of artificial and natural lighting systems for both indoor environments (Chiradejaa, Ngaopitakkul, & Jettanasen, 2015; Soori & Vishwas, 2013) as for external (Sawicki & Wolska, 2019; Yoomak, Jettanasen, Ngaopitakkul, Bunjongjit, & Leelajindakrairerk, 2018). The two versions offered by the German company DIAL GmbH are free and have been validated according to the CIE technical report (Acosta, Muñoz, Esquivias, Moreno, & Navarro, 2015; Commission Internationale de L'eclairage [CIE], 2006). The evo version used in this study uses the photon mapping algorithm in its calculations.

After defining general parameters, the method was divided into three stages:

a) Characterization of the object of study by means of data collection based on original architectural projects and information collection on site. Some relevant characteristics in this stage were: geographic location, dimensions of the rooms and reflectance of the surfaces, characteristics of the openings, elements of the existing lighting system and layout of the work areas. All this information allowed the architectural modeling of the studied rooms and the construction similar to the current lighting system for later computational simulations.

b) The simulations and analysis of the results followed parameters recommended by Brazilian standards. Those involving artificial lighting were based on requirements in accordance with the standard NBR ISO/CIE 8995-1 (Associação Brasileira de Normas Técnicas [ABNT], 2013) and those that addressed natural light followed some recommendations from the standard NBR 15215-4 (Associação Brasileira de Normas Técnicas [ABNT], 2005). The following scenarios were simulated: existing lighting system, potentially more efficient lighting systems and lighting system integrated with natural light and a lighting control device. In all simulations, the luminous and energetic performances were evaluated for further comparisons.

c) The simulated lighting systems were compared with each other considering aspects such as average illuminance in the work plane, luminous efficiency and, mainly, the limit lighting power density, which allowed to indicate the most efficient system among them.

The flowchart in Figure 1 briefly presents the method used in the present study.

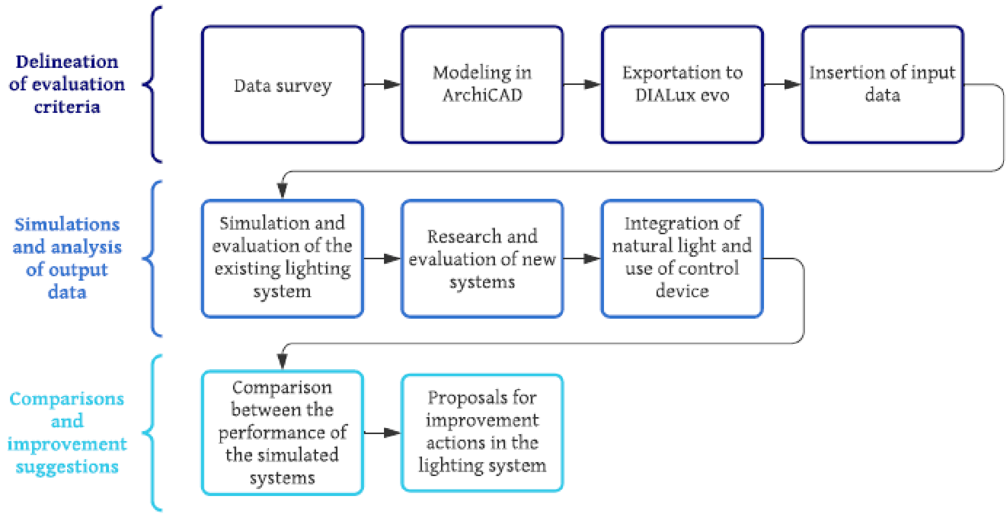


Figure 1. Flowchart of the main steps of the proposed methodology.

The steps mentioned are detailed in the next chapters.

Characterization of the object of study

The present study referred to office environments in an existing building located in the municipality of Paranavaí, northwest of Paraná, Brazil. The climate of the region is classified as humid temperate according to the Köppen-Geiger classification and holds an estimated population of 88,922 inhabitants in 2020.

The building was built between the years 1990 and 1993, has 3 floors (ground floor + 2 floors) and its main facade is oriented to the northwest. Among the 10 commercial rooms with different configurations, the present study evaluated the luminous and energetic performance of 8 of them, which are symmetrical and are distributed equally on the first and second floors of the building (Figure 2). The surroundings are mainly characterized by commercial buildings with heights of around 6 meters, in addition to single-story houses and several vacant lots, with a radius of up to 130 meters being considered as an obstacle to natural light in the simulations.

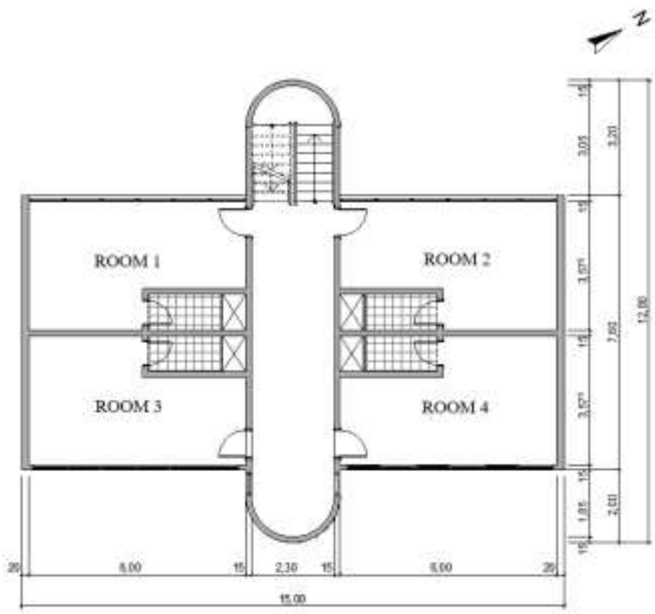


Figure 2. Floor-type plan of the building (dimensions in meters).

Each room has a ceiling height of 2.95 m and consists of a working environment and a toilet, with areas of 18.17 and 2.00 m² respectively. Rooms 1 and 2, whose openings are oriented to the main façade (northwest), have 6 tilting windows of dimensions 1.00 x 1.60 m and sill of 0.50 m, that is, the window-to-wall ratio is 54%. Rooms 3 and 4, whose openings are oriented to the southeast, have 6 tilting windows of dimensions 0.95 x 0.60 m and sill of 1.50 m, that is, the window-to-wall ratio is 19%.

The modeling of the building and the studied rooms were created with the aid of the ArchiCAD architecture software and, later, exported to DIALux evo 9.2 through an IFC format file. Data such as reflectance of surfaces, positioning of the lighting system and reference values related to illuminance and uniformity were entered directly into the simulation software.

Simulation and evaluation criteria

The first stage of the simulations considered the characteristics of the lighting system in the rooms and evaluated the performance of the system based on the minimum values recommended by standards as described in the following item.

Based on this analysis, different types of LED luminaires available in online catalogs from Brazilian manufacturers were considered, including only those whose technology is known to have the best cost-benefit ratio at the time of this study. Due to the 2.95 m ceiling height, it was decided to use overlapping luminaires in the lighting systems simulations that are potentially more efficient than the existing one. In addition to the type of installation, characteristics such as power, luminous efficiency and color aspects of the luminaires were also essential in this process.

After obtaining an optimized system, the use of an artificial lighting control device linked to natural light was simulated.

Artificial lighting

The simulations and analyzes regarding artificial lighting followed values recommended by the standard NBR ISO/CIE 8995-1 (ABNT, 2013) as shown below.

- Surface reflectance: the standard suggests reflectance ranges for the most relevant internal surfaces, such as ceilings (0.6 - 0.9), walls (0.3 - 0.8), work planes (0.2 - 0, 6) and floor (0.1 - 0.5).

- Maintained illuminance ($\overline{E_m}$): for each type of environment, task or activity, a minimum illuminance value on the reference surface is recommended. Regarding offices, this value varies between 200 and 700 lx. In this study, the minimum value of 500 lx was considered for calculation purposes.

- Uniformity (U): it is recommended that uniformity, the ratio between the minimum value and the average value of the illuminance, is not less than 0.7 and that the task area is illuminated as consistently as possible. As the environments do not have a known workplace arrangement, the standard allows the entire environment to be considered as the work area minus the marginal range of 0.5 m wide from the wall and the reference height for illuminance to be 0.75 m above the floor.

- Light characteristics: appearance and color reproduction are characteristics related to the quality of the light produced by the lamp and influence the visual performance and the well-being of the user. The color appearance, represented by its correlated color temperature, is classified as hot (below 3,300 K), intermediate (3,300 K to 5,300 K) and cold (above 5,300 K). Color reproduction is defined by the overall color rendering index (R_a) which indicates that the closer to 100, the better the lamp's ability to reproduce the colors of the environment and objects in a natural and correct way. The aforementioned standard also recommends that, in hot climates and indoors where people stay for long periods, the color temperature is preferably cold, and the R_a is greater than 80.

In addition to these characteristics, the power and luminous efficiency were also analyzed: the choice of the luminaire from the power (W) in isolation is not appropriate. An indicator of energy performance commonly available in product catalogs is the consumption of electricity by luminous flux (W/lm). From that, the user and/or designer can instantly verify if that product tends to satisfy their needs even before making any luminotechnical calculations. Therefore, when analyzing and comparing the power and luminous efficiency of the LED luminaires simultaneously, it was possible to select the most suitable ones for the appropriate objectives.

Daylight

The parameters followed for natural light considered the recommendations of the standard NBR 15215-4 (ABNT, 2005) as described below.

- In cases where it is not possible to monitor the natural lighting throughout the year, it is suggested that the illuminance survey be carried out under the sky conditions of the summer and winter solstice periods, and every 2 hours from the beginning office hours. In this study, the 2019 solstices of the year available in the DIALux evo database were considered with an interval of 1 h during the working period (from 8 am to 6 pm).

- Building facade alignment: 29.00°.

- Geographic coordinates: latitude -23.08° and longitude -52.45°.
- Type of sky: the overcast model was chosen, as it is possible to establish minimum lighting conditions as it represents the worst situation in terms of availability of natural light.

The observation of the illuminance distribution in the environment was carried out from four points arranged linearly, at a height of 0.75 m from the floor (

) and helped to define the groups of luminaires that would light simultaneously. The arrangement of these points considered the minimum distance of 0.50 m from the walls in order to avoid the influence of the light reflected by them.

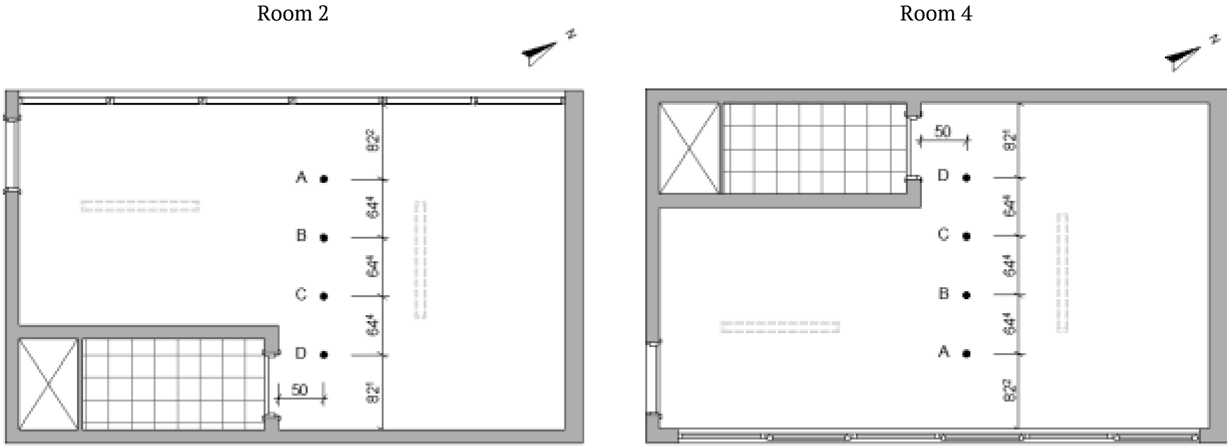


Figure 3. Positioning of the evaluated points in the illuminance distribution (dimensions in meters).

The distribution of illuminance in the environment was analyzed for the following scenarios: natural light; natural light + 100% artificial lighting; natural light + artificial lighting + control device linked to natural light (dimmer).

Integration of artificial lighting and natural light

The luminaires were divided into two power circuits parallel to the room openings. Thus, according to the incidence of natural light in the plan of use, the luminous flux of the circuits can be reduced asynchronously and, consequently, the consumption of electrical energy can be reduced. To perform this alternation in the luminous flux of the luminaires, the use of a lighting control device linked to natural light, also known as a dimmer, was considered. The variation in luminous flux occurred every 25% so that the system met the requirements of average illuminance (⩾ 500 lx) and uniformity (⩾ 0.6) over the entire working day (8 am - 6 pm) simultaneously.

In this stage, a room of each orientation was selected to represent the worst case in terms of solar incidence due to the influence of the surroundings. Therefore, the simulations in this stage considered the environments of rooms 2 and 4 located on the first floor.

Results and discussion

The results obtained were organized in four stages: (1) simulation and performance evaluation of the existing lighting system; (2) research and evaluation of systems with new types of lamps and the lamps arrangements; (3) integration of the most efficient artificial lighting system and natural light, associated with the use of an artificial lighting control device, and; (4) comparison of the simulated systems and improvement proposal.

In all stages, lighting levels and electricity consumption of lighting systems were evaluated to comply with the minimum levels in accordance with the standard NBR ISO/CIE 8995-1 (ABNT, 2013) and obtain greater energy efficiency in lighting simultaneously.

Evaluation of the existing lighting system

The lighting system in the work environments consists of two luminaires with two T12 fluorescent lamps each, which is activated by means of a switch for each luminaire-lamp assembly located near the entrance door. Each lamp has a power of 40 W and a luminous flux of 2,800 lumens.

As all rooms have the same artificial lighting system and this is not influenced by the orientation of the openings, the computer simulation was performed only for one representative room and considered for the others subsequently.

The three-dimensional view and the isographic lines considering the existing lighting system were presented in Figure 4, while the main simulation output data were shown in Table 1.

(a) 3D view

(b) Isographic curves (in lx)

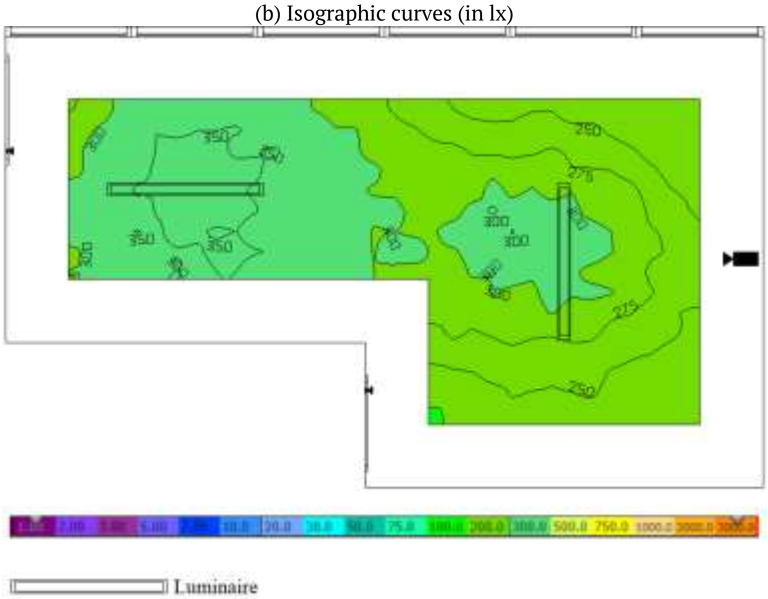


Figure 4. Representation of the existing lighting system.

Table 1. Summary of the simulation results of the existing lighting system.

Characteristic	Description
$E_{average}$	292 lx
Uniformity	0.7
Number of luminaires	2
Luminous performance	63.0 lm/W
LPD	8.80 W/m²
LLPD	3.01 W/m² per 100 lx

As noted in the Table 1, the average illuminance ($E_{average}$) in the usage plan reaches 292 lx, a value 42% lower than the standard recommended and, although the illuminance distribution is greater than 0.6, the existing system does not offer lighting conditions suitable for performing visual tasks. The low efficiency of the existing lighting system can be justified using fluorescent lamps with low luminous efficiency, which were the most efficient available on the market at the time of the building's design.

Based on the verification of the luminous and energetic performance of the existing lighting system, the next stage of the study comprised the research and simulation of new arrangements and types of luminaires to obtain more efficient potential lighting systems.

Analysis of potential more efficient artificial lighting systems

In this stage, a brief search was carried out for LED overlay luminaires in online catalogs of the main Brazilian manufacturers. After several simulations varying the positioning, orientation, and number of luminaires, three artificial lighting systems with luminaires from two different manufacturers were selected. The output data were presented in Table 2.

The quantity and arrangement of the luminaires in the environment were calculated by the simulation software itself according to criteria inserted in the input data, such as minimum luminance and uniformity in the work plan.

All simulated luminaires have a maintenance factor of 0.80, an intermediate color temperature (between 3,300 and 5,300 K) and a color rendering index > 80 according to data from the manufacturers. As they are overlapping luminaires, the installation height is 2.95 m.

Table 2. Summary of the simulation results of the proposed lighting systems.

Characteristic	Description		
	Proposal A	Proposal B	Proposal C
$E_{average}$	655 lx	646 lx	660 lx
Uniformity	0.8	0.6	0.7
Number of luminaires	4	3	4
Luminous performance	119.2 lm/W	130.4 lm/W	130.2 lm/W
LPD	8.03 W/m²	7.59 W/m²	7.44 W/m²
LLPD	1.23 W/m² per 100 lx	1.18 W/m² per 100 lx	1.13 W/m² per 100 lx

The choice of artificial lighting systems considered mainly those that demanded the smallest possible number of luminaires to meet the minimum recommended light levels (illuminance and uniformity), even though the present study did not include the cost of acquiring the luminaires. From the limit lighting power density (LLPD), the proposed system C was the one best suited to the objective of the study, that is, it would consume less electrical energy given the minimum illuminance required for the work area office environments.

Figure 5 presents the three-dimensional view and the isographic lines of the selected system.

Integration of artificial lighting and daylight

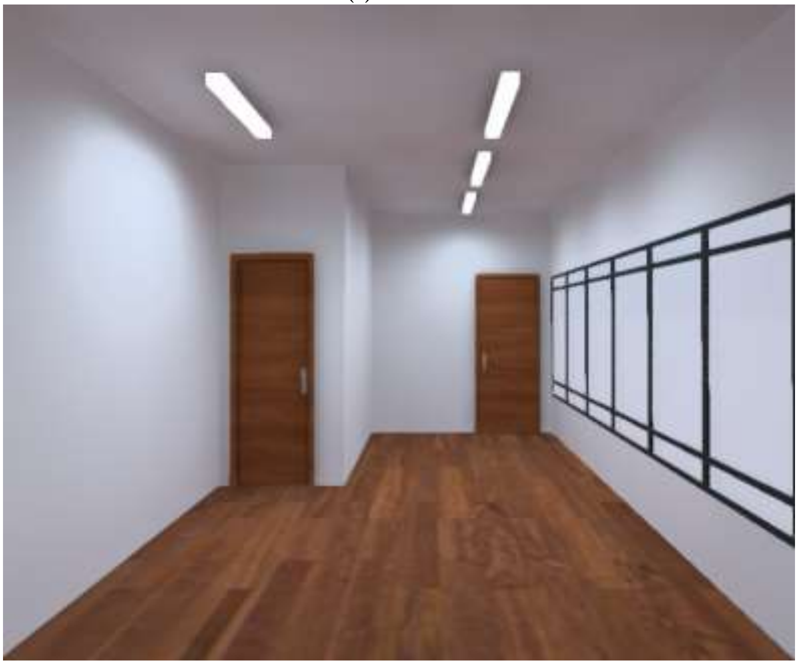
The analysis of the distribution of light in the environment considering the three scenarios indicated that when considering only the contribution of natural light in the environments, the median points receive illuminance below 500 lx during most of the working hours. That is, there is a need for complementation with artificial lighting. When the artificial system is activated in its entirety, the illuminance exceeds 500 lx at all points, reaching up to 1,600 lx at the summer solstice depending on the orientation and the window-to-wall ratio. When using a dimming device linked to natural light, it is observed that the luminous flux of output is only what is necessary to complement the illuminance from natural light. The output power of the luminaires is also reduced, which can lead to possible energy savings throughout the day.

This analysis allowed the luminaires to be divided into two groups with independent activations, one composed by the row of luminaires closest to the openings and the other by the most distant row. Thus, several light scenarios were simulated, varying the luminous flux of the luminaires asynchronously.

From Table 3, the performances of all systems simulated in this study are briefly observed.

Considering the existing artificial lighting system and the proposed system C, it was noted that the replacement of fluorescent lamps by LED luminaires and the rearrangement of their positioning allowed the system to meet the average illuminance in accordance with the standard NBR ISO/CIE 8995-1 (ABNT, 2013) and improved the limit lighting power density (LLPD) by more than 60%. That is, in addition to offering better visual conditions, the replacement of the type of lamp also resulted in energy benefits, with electricity savings reaching 15.5%. This savings could have been even greater if the existing lighting system met at least 500 lx of average illuminance, which would result in a greater quantity of fluorescent lamps and, consequently, greater total power of the system. Byun and Shin (2018), who also evaluated the influence of replacing fluorescent lamps with LEDs in office environments, obtained savings of 27.6% in electricity consumption.

(a) 3D view



(b) Isographic curves (in lx)

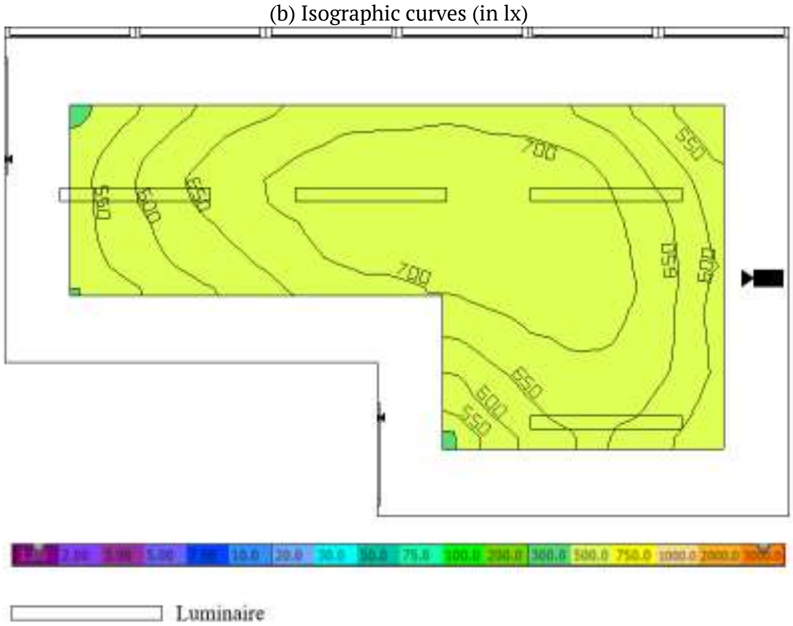


Figure 5. Representation of the proposed lighting system C.

Table 3. Comparison between the performance of the evaluated systems.

	Existing artificial lighting system	Proposed artificial lighting system C	Proposed artificial lighting system C + daylight + dimming system	
			Orientation: northwest	Orientation: southeast
$E_{average}$	292 lx	660 lx	⩾ 500 lx	⩾ 500 lx
Uniformity	0.7	0.7	⩾ 0.6	⩾ 0.6
LLPD	3.01 W/m² per 100 lx	1.13 W/m² per 100 lx	⩽1.13 W/m² per 100 lx	⩽1.13 W/m² per 100 lx
Power [(1)]	1,600.0 W	1,352.0 W	532.4 to 621.1 W	714.0 to 840.8 W

Note: [(1)] Total power per working day (8 am - 6 pm).

Another comparison made was between the artificial lighting system and the system that included natural light and the dimmer, both considering the proposed system C. The use of this control device causes LLPD to vary according to the availability of natural light, but not exceed the value of 1.13 W/m² per 100 lx. Thus, the energy savings achieved were between 38 and 61% depending on the orientation and size of the openings. It is worth mentioning that the simulations considered overcast conditions and, therefore, electricity savings may vary since the solar incidence fluctuates throughout the day.

Susorova et al. (2013), who also studied offices in warm and temperate climates, concluded that the rooms facing north with large windows consume less electricity than those facing south with small windows. Also, regarding the dimensions of the openings, the authors analyzed that, the greater the window-to-wall ratio, the greater the savings in lighting energy and the lower the savings in cooling energy due to the greater exposure to sunlight. These situations are like the results obtained in the present study when verifying the difference in the economy of the rooms with orientations similar to those of Susorova et al. (2013).

Finally, the last comparison considered the existing lighting system and the proposed artificial lighting system C integrated with natural light and the dimming system. In that case, the savings in lighting energy reached around 67%, in addition to the evident improvement in the quality of lighting in terms of uniformity and illuminance in the work area.

The present study addressed the luminous and energetic performance of the lighting systems without considering costs with products and equipment involved. Therefore, a more comprehensive approach to the most cost-effective system verification is recommended. It is also suggested to consider the influence of users on the final consumption of electricity, given the stochastic nature of human behavior.

Conclusion

The output data of the existing artificial lighting system showed that the average illuminance in the usage plan is 42% lower than that recommended by the Brazilian standard. After several simulations, the proposal C was select for the final simulations because it presented the lowest density of limit lighting power. Thus, it was concluded that this optimized lighting system would save up to 61% of electricity per working day in rooms with openings oriented to the northwest (window-to-wall ratio of 54%) and up to 47% in those with windows facing southeast (window-to-wall ratio of 19%).

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