INTEGRATION OF NATURAL AND ARTIFICIAL LIGHT: POTENTIAL ENERGY SAVINGS ESTIMATION USING THE CLEARNESS INDEX, MEASUREMENT AND SIMULATION

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ABSTRACT

The increase of energy consumption in the building sector has been studied intensively in order to improve the scenario before the population growth and urbanisation. The lighting systems, largely used in any kind of building, are responsible for most of the energy consumption in the sector. To estimate the potential energy savings associated with strategies that explore the use of daylight, several methods can be used. The field evaluation is the one with the most precise results, however, in developing countries it may not be the best option due to the limited technologies and high costs. Given the importance of energy efficiency in the building sector, this paper aims to develop a framework based on field measurements and simulations to evaluate the potential for energy savings associated with the utilisation of natural lighting and dimming the artificial system. Days for analysis were selected based on the Clearness Index and data collection following the Brazilian regulations. The software eQUEST and DIALux were used to estimate the energy savings. Compared to the base case, the use of natural lighting and dimming the artificial lighting system allowed a reduction of 15.9% in the annual energy consumption.

Key words: Energy savings, natural lighting, Clearness Index, simulation.

RESUMO

O aumento do consumo de energia nas edificações tem sido estudado intensivamente a fim de melhorar o cenário diante do crescimento populacional e da urbanização. Os sistemas de iluminação, amplamente utilizados em qualquer tipo de edificação, são responsáveis pela maior parte do consumo de energia do setor. Para estimar o potencial de economia de energia associado a estratégias que exploram o aproveitamento da luz natural, diversos métodos podem ser utilizados. A avaliação de campo é a que apresenta resultados mais precisos, porém, em países em desenvolvimento pode não ser a melhor opção devido às tecnologias limitadas e custos elevados. Dada a importância da eficiência energética no setor da construção, este trabalho tem como objetivo desenvolver um *framework* baseado em medições e simulações de campo para avaliar o potencial de economia de energia associado ao aproveitamento da iluminação natural e dimerização do sistema artificial. Os dias para análise foram selecionados com base no Índice de Transmissividade Atmosférica e a coleta de dados foi realizada seguindo as normas brasileiras. Os programas computacionais eQUEST e DIALux foram usados para estimar a economia de energia. Em comparação com o caso base, o uso da iluminação natural e a dimerização do sistema de iluminação artificial permitiram uma redução de 15,9% no consumo total anual de energia.

Palavras-chave: Economia de energia, iluminação natural, *Clearness Index*, simulação.

1. INTRODUCTION

Energy consumption in the building sector has increased due to the growth in population and its search for welfare (ASLANI; BAKHTIAR; AKBARZADEH, 2019; CAO *et al.*, 2016). In 2021, buildings were responsible for about 30% of the global final energy consumption (INTERNATIONAL ENERGY AGENCY, 2022). In Brazil, the residential, commercial and public sectors utilise, together, 41.7% of the total electricity produced in the country (EMPRESA DE PESQUISA ENERGÉTICA, 2022).

In this scenario, the necessity of adopting energy savings practices is evident. Lighting systems are responsible for the major part of energy consumption in buildings and, consequently, constitute a good opportunity to promote energy savings (XU *et al.*, 2017). An alternative to reduce the use of artificial lighting systems is the exploitation of daylight. Such a passive strategy allows to reduce energy consumption and improve visual comfort inside the buildings (ZHU; LI; LI, 2017).

The use of daylight was assessed in many studies. Zhen *et al.* (2019) concluded that the transmittance of the glass, the ceiling height and local latitude significantly affect the use of daylight in a residential building in China. However, Nicoletti *et al.* (2022) stated that latitude has little influence on the utilisation of daylight in Italy. To Aslanoglu *et al.* (2021), the satisfaction about daylight quality depends on its sufficiency, uniformity and sun hours.

Some studies have evaluated the potential for energy savings associated with the use of natural lighting. A review of methods used to estimate potential energy savings due to daylight was made by Yu and Su (2015a). According to them, the methods can be categorised as field measurement, computer simulation and hand calculation based on mathematical equations and algorithms. All things considered, it is necessary to evaluate the method more suitable for each situation, weighing up the cost, available technology and devices, duration of the experiments, etc.

Although there is a variety of methods, some authors prefer the field measurement method because of its accuracy (DEMIRBAŞ *et al.*, 2016; GENTILE; LAIKE; DUBOIS, 2016; KUNWAR *et al.*, 2020; YU; SU, 2015b) whether in real, scale or laboratory environments (ACOSTA *et al.*, 2018; SHACKELFORD *et al.*, 2020). Other authors have decided for modelling and simulation due to the possibility of evaluating and proposing different scenarios (CHOI *et al.*, 2016). Besides, there may be cases where some sensors and technologies are not available or are too expensive, which is common in developing countries – like Brazil. In order to achieve better results, an alternative is to collect field data as much as possible and then combine them with simulations, reducing the cost of the process.

2. OBJECTIVE

This paper presents a framework - based on field measurement and simulation - to estimate the potential for energy savings by integrating daylight and artificial lighting.

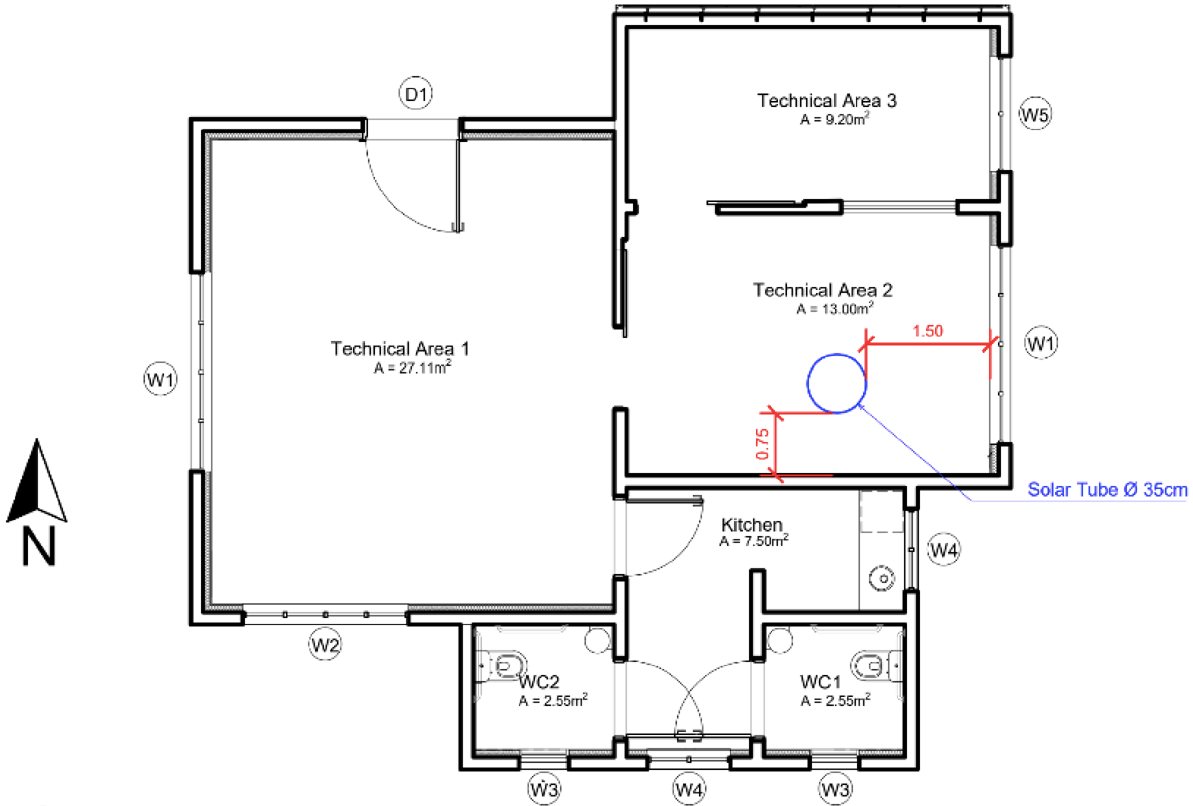
3. METHOD

3.1. Case study

The building under analysis is a bioclimatic building located in the city of Araranguá, in Southern Brazil, in the state of Santa Catarina. It belongs to the Federal University of Santa Catarina (UFSC) and it was built using bioclimatic strategies in order to achieve a good energy performance. In Figure 1 it is possible to see the building. More information about it can be found in (BILÉSIMO, 2019; BILÉSIMO; RAMPINELLI; MARCELINO, 2020; ESPÍNDOLA, 2016; GUERRA, 2016).

Figure 1 - Bioclimatic building under analysis (BILÉSIMO; RAMPINELLI; MARCELINO, 2020).

As shown in Figure 1, there are shading devices in the East and West facades. There are seven rooms. Figure 2 shows the seven rooms and indicates the position of each type of windows and door listed in Table 1. In Technical Area (TA) 2 there is a solar tube. Its location improves the use of natural light on a desk next to the wall in the room.



Scale 1:50

Figure 2 - Floor plan of the building.

Table 1 - Size of door (D) and windows (W)

External opening	Width x Height (m)	Window-sill height (m)
D1	1.20 x 2.60	-
W1	2.40 x 1.40	1.20
W2	2.00 x 1.40	1.20
W3	0.60 x 0.60	1.50
W4	1.00 x 1.40	1.20
W5	1.40 x 1.40	1.20

3.2. Measurement of natural lighting

According to NBR ISO/CIE 8995-1 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2013), good conditions of lighting provide the visualisation of the surroundings, allowing people to see, move safely and accomplish visual tasks with efficiency, precision and safety, without causing visual fatigue and discomfort. In this context, such a regulation establishes levels of illuminance that must be provided in order to assure visual comfort and guarantee the good execution of the tasks.

The procedure to verify experimentally the situation of natural lighting in indoor environments is established, in Brazil, by the regulation NBR 15215-4 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2005). It establishes, among other parameters, where data must be collected, the distance between the measurements and the most adequate days to perform the analysis.

Technical Areas 1 and 2 were chosen for the analysis because such areas are frequently occupied by professors and students. Technical Area 3 is where the equipment (such as the servers and the weather station's control panel) is kept, so it is seldom occupied. Attending to the regulation, measurements were performed from 8 am to 6 pm, with breaks of two hours. This is the operating period of the building. Over the winter, the sunset occurs before 6 pm; therefore the last measurement was taken at 5 pm, even though the building remains open until 6 pm. Data were collected in the points indicated in Figure 3. That kind of information is useful for analysing the moments in which natural lighting is not enough according to the regulations.

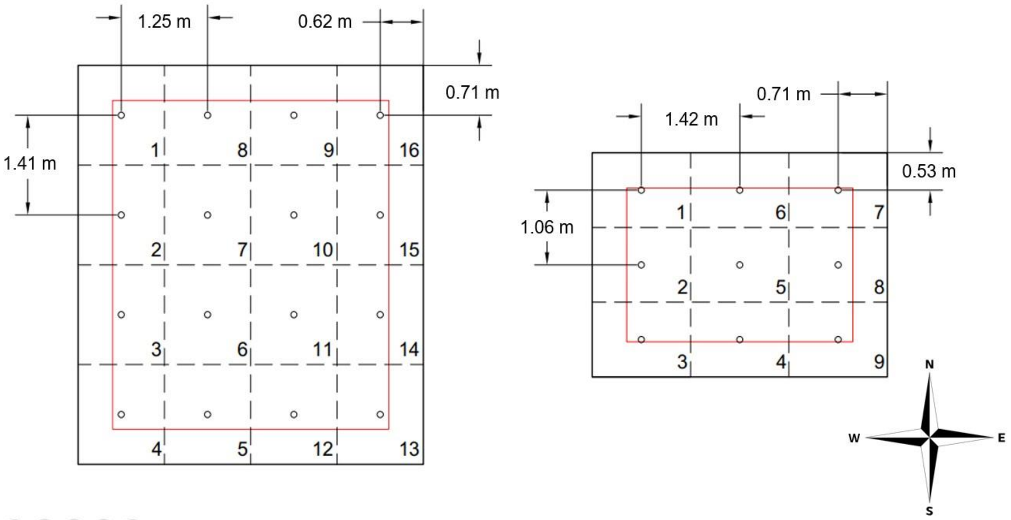


Figure 3 - Points used to collect data in Technical Area 1 (on the left) and 2 (on the right), indicated by NBR 15215-4

Data were collected on the work surface, which is 0.80 m from the ground, and the measurement procedure happened with all lights off, rooms and curtains opened. In Technical Area 2, the contribution of the solar tube was also verified by repeating the procedure with room and curtains closed.

Directives of the regulation say that the procedure must be carried out in a representative day, which is a day that can be considered "typical" according to the local climate. In this paper, multiple representative days were tested in order to have a bigger sample and consequently achieve accurate results.

3.3. Selection of representative days

Solar irradiance was measured by the meteorological station installed in the building. The measurements were repeated during days close to the summer solstice of 2017 and winter solstice of 2018. This happened until the sample had a sunny, cloudy and an intermediate day for both seasons in each area.

To choose the representative days, the Clearness Index (K_T) was used. It consists of the ratio between solar irradiation in the terrestrial surface and solar irradiation at the top of the atmosphere (extraterrestrial) (DUFFIE; BECKMAN, 2013a). On a daily basis, K_T allows to classify the days in sunny, intermediate (partially sunny) and cloudy. By calculating the daily mean of an entire month $K_{T,average}$, it is possible to estimate the frequency of each type of day along that month. The relationship between the two indexes is indicated in Figure 4.

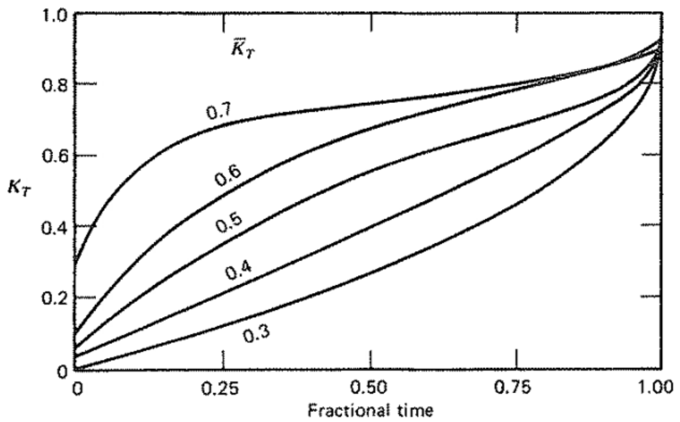


Figure 4 - Distribution of days with various values of K_T as a function of $K_{T,average}$ (DUFFIE; BECKMAN, 2013b)

3.4. Data measurement

The solar irradiance in the terrestrial surface was obtained from the Weather Station of the building and illuminance data were measured using lux meters. The main specifications of the measurement devices are presented in Table 2.

Besides this information, the position of the sun in the sky at the time of each measurement was recorded.

It allowed the creation of maps showing the temporal distribution of illuminance, which is useful to estimate the amount of light at any time of any day of the year, just by knowing the position of the sun at the moment.

Table 2 - Specifications of measurement devices.

Device	**Range**	**Nominal precision (+/-)**
Vantage Pro2 Weather Station/ Davis Instruments	0 - 1800 W/m²	5%
MLM-1020 Digital Lux meter/ Minipa	0 – 20000 lx	20 lx

As the measurements were taken over summer and winter, the illuminance of the points in spring and autumn were estimated based on interpolation (an example of the maps used for this aim is in Section 4.2). Both measured and estimated illuminances were used to evaluate the necessity of artificial lighting and the energy savings associated with the use of natural lighting.

3.5. Simulations in DIALux and eQUEST

DIALux is a freeware software that allows designing, calculating and visualising, among other functions, the distribution of natural and artificial lighting inside and outside environments. The programme has a large database containing selected luminaires and lamps (DIAL GMBH, 2017).

Compared to more complex software as DAYSIM, which makes dynamic simulations, the use of DIALux is relatively easier. The latter is limited to static simulations, but this is not a problem when data from the simulation is analysed together with measurement results.

The software was used in order to simulate only artificial lighting inside the building in moments that natural lighting was not enough to provide the minimum illuminance requested by the regulation. This is possible due to the additivity law associated with the illuminance. That was useful to estimate the fraction of the artificial lighting system that would be necessary to achieve adequate illuminance levels. To estimate the fraction of the artificial lighting system that would be used if there was no solar tube, the illuminance provided by the solar tube was subtracted from the total illuminance of TA 2 and the simulations were repeated.

In the simulations, the authors tried to reproduce internal characteristics with precision using colours, furniture and luminaires similar to the ones used in the building, except for the solar tube, which was not included in the simulation (its contribution in lighting was considered, though). Furniture and colours were selected from the catalogue of the software, while the luminaires were selected from the Philips catalogue, which can be also found in the software. The main characteristics of the luminaires selected are shown in Table 3.

Table 3 - Characteristics of the luminaires used in the simulation

Luminaire	**TCS640**	**TCS460**
Room	Technical Area 1	Technical Area 2
Number and type of lamps	2 x TL5 – 25 W	2 x TL5 – 13 W
Power (lamps + ballast)	105 W	57 W
Luminous efficiency	38.3 lm/W	31.1 lm/W
Colour Rendering Index	100	100
Light source colour	840	840
Correlated Colour Temperature	4000 K	4000 K

Measurements were taken every two hours and, considering that the necessity of artificial lighting would change during this period, hourly consumption was estimated. This estimate was found by averaging the consumption of two subsequent measurement times, e.g. the necessity of artificial lighting at 9 am is the average of what is necessary at 8 am and 10 am. This procedure was repeated for every hour that the measurement was not taken, in both rooms, with and without the contribution of the solar tube. After finding the hourly need of the artificial lighting system in each case, four profiles of artificial lighting consumption were created (one for each season of the year) and used as inputs in eQUEST v. 3.65 in order to estimate the potential energy savings.

Besides that, three scenarios were considered in order to estimate the energy savings associated with the integration of artificial and natural lighting:

- Case A: the base case represents the use of artificial system without any dimming, which means every time that more light is necessary the whole system needs to be turned on;
- Case B: it uses natural light and a dimmer associated with the artificial system;

- Case C: it is equal to case B plus the use of the solar tube, that increases the amount of natural light in Technical Area 2.

The authors decided for this software because its use is relatively simple and intuitive when compared to other software. More details about the model of the building in eQUEST (occupation, energy consumption for equipment and HVAC system, etc.) can be found in Bilésimo, Rampinelli and Marcelino (2020).

4. RESULTS AND DISCUSSION

4.1. Characteristics of representative days

Typically, $K_T > 0.7$ characterises sunny days while cloudy days present $K_T < 0.3$. Values between this range imply intermediate days. However, based on empirical observations we considered:

- $K_T < 0.35$ – cloudy;
- $0.35 \leq K_T \leq 0.60$ – intermediate;
- $K_T > 0.6$ – sunny.

The days selected were predominantly sunny and cloudy, whose K_T are listed in Table 4 (DUFFIE; BECKMAN, 2013b). Due to some inconsistent data at some points, the procedure sometimes had to be repeated for other days. That is why three sunny days and five cloudy days were needed to conclude the analysis. Figure 5 shows the solar radiation for sunny days and Figure 6 for cloudy days, obtained from the analysis described in subsection 3.4. It is possible to see the differences in the level of solar radiation and also in its behaviour along the days.

Table 4 – K_T of the days selected for the analysis of each room in each season.

Analysis	**Season**	**Typical day**	**K_T**
TA 1	Summer	Sunny	0.68
		Cloudy	0.17
	Winter	Sunny	0.62
		Cloudy	0.25
TA 2	Summer	Sunny	0.69
		Cloudy	0.24
	Winter	Sunny	0.62
		Cloudy	0.09
Solar tube	Summer	Sunny	0.69
		Cloudy	0.33
	Winter	Sunny	0.62
		Cloudy	0.09

Source: (DUFFIE; BECKMAN, 2013b).

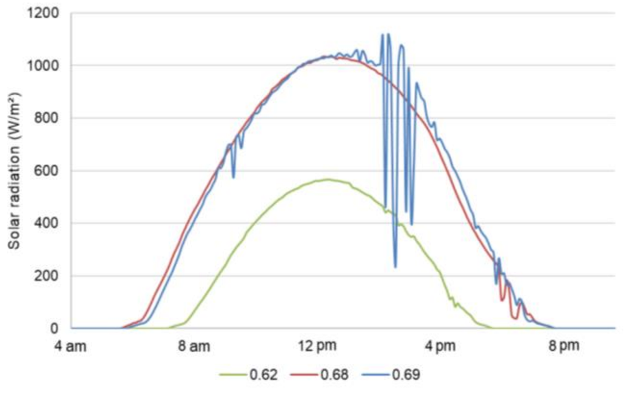


Figure 5 - Solar radiation in selected sunny days

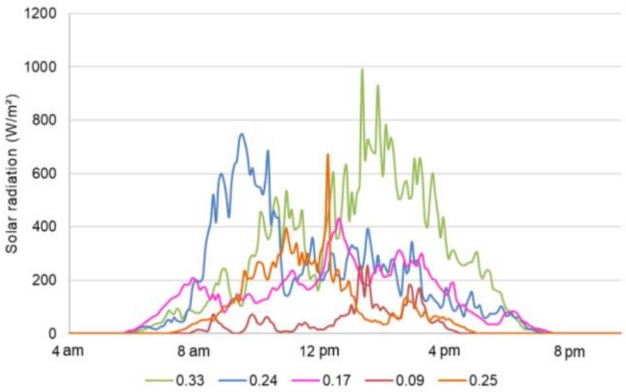


Figure 6 - Solar radiation in selected cloudy days.

Zhen *et al.* (2019) also evaluated the representative days to daylight analysis in buildings in China. The authors concluded that the Chinese winter solstice (December 22nd) is the most unfavourable day for daylight. This paper corroborates with theirs, confirming the necessity of considering the sky conditions of representative days in the evaluation of artificial lighting.

4.2. Distribution of illuminance

This section contains only some maps of each kind of distribution of illuminance, for demonstration, although the same procedure was applicable to any kind of day, at all points.

Figure 8 presents the spatial distribution of illuminance in TA 1 for days with a predominantly clear sky during summer. In general, in TA 1, the illuminance on sunny days remains above the minimum required by regulation, i.e. 500 lx, in all seasons. However, Figure 8 shows just one of the maps used to verify the points in the room where the use of artificial lighting was required. In TA 2 is possible to see that, in this case (the end of a sunny day of winter), the artificial lighting system would have to be turned on in the whole room but not with full power, once the natural light provides almost half of the required illuminance (500 lx) in most of the room as shown in Figure 7.

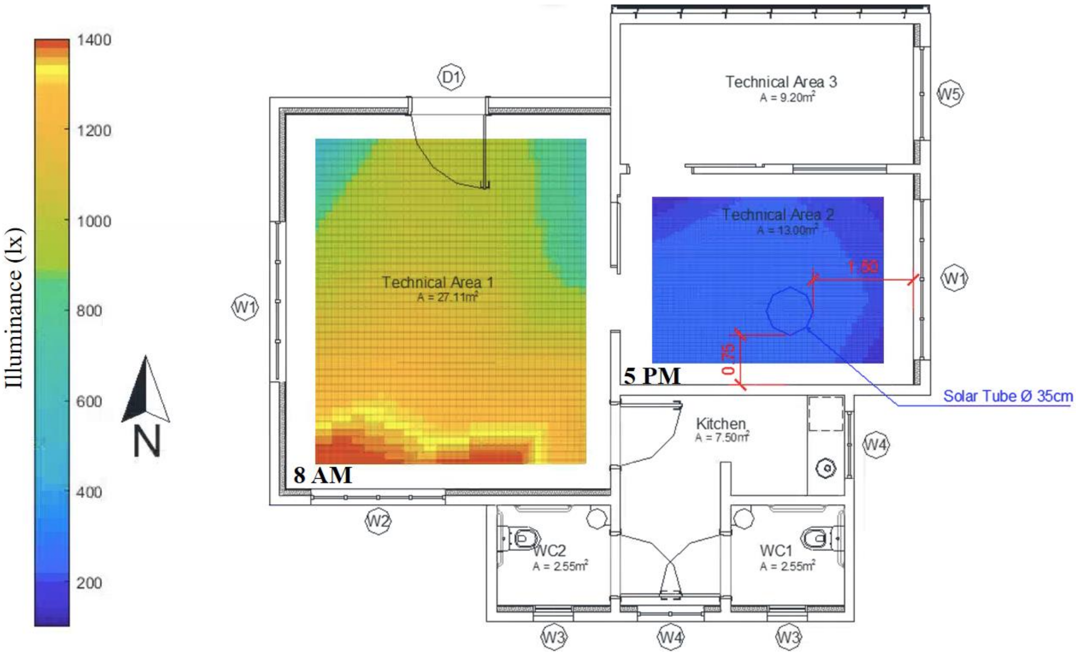


Figure 7 - Illuminance distribution (in lx) for TA 1, in a day with K_T equal to 0.68 (summer) at 8am and for TA 2, in a day with K_T equal to 0.62 (winter) at 5pm.

As explained before, illuminance data were associated with the sun position at the moment of measurement, represented by the elevation and azimuth angles. This kind of map allows an estimation of the level of illuminance throughout spring and autumn days.

Figure 8 shows the variation of illuminance during sunny days as a function of the solar azimuth and elevation angle at point 2 in TA 1 and point 5 of TA 2 (right under the solar tube). At point 2 (TA 1), higher azimuth angles (meaning the afternoon) cause intensification in the level of illuminance, that did not suffer a significant influence of the elevation angle, because this point is close to the western window. In point 5 (TA 2), both angles had significant influence on the illuminance, except for azimuth angles from 100° to 200°, where the elevation angle did not affect it significantly. This happens mostly because of the position of the current point.

The needed percentage of the artificial lighting system to achieve 500 lx on the working surface was simulated in DIALux based on the information given by the maps and its results are shown in Table 5.

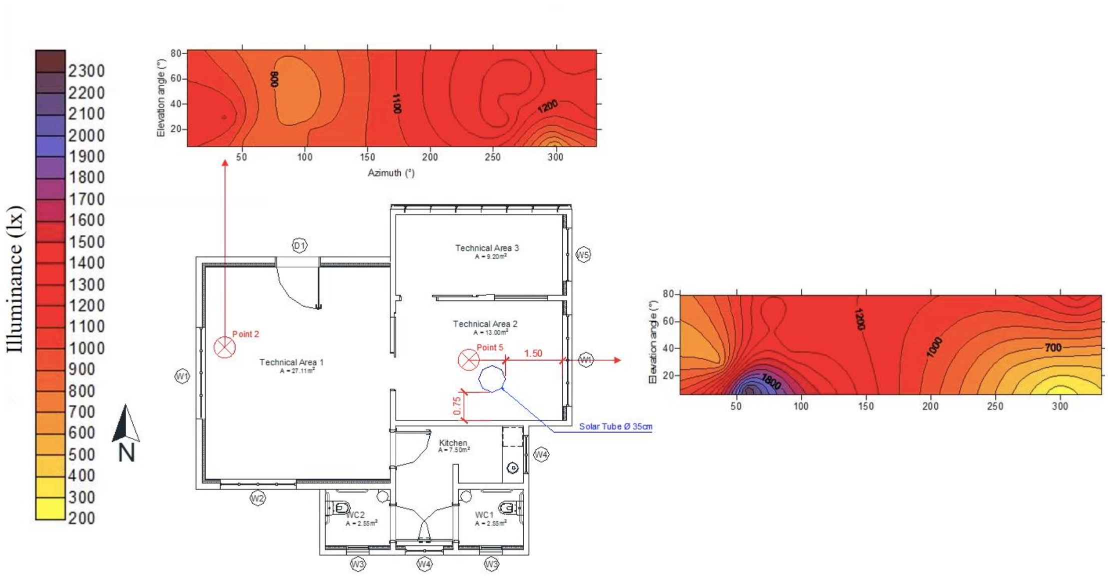


Figure 8 - Temporal distribution of illuminance (for sunny days) at Points 2 in TA 1 and 5 in TA 2.

It is important to underline that the building operates from 8 am to 6 pm and these averages are on a daily basis. Although, by using natural lighting it is possible to see that the artificial lighting system would not be not fully required during all operating hours, once the percentages just reach over 90% in cloudy days if no strategy is used (Case A).

Table 5 - Average percentage of the artificial lighting system required to achieve 500 lx on a daily basis.

Case	**Condition of the sky**	**Spring**	**Summer**	**Autumn**	**Winter**
A –Base case	Sunny	25.0	33.3	25.0	41.7
	Intermediate (Partially Sunny)	50.0	33.3	41.7	75.0
	Cloudy	91.7	100.0	91.7	91.7
B – Dimming	Sunny	9.0	11.2	9.0	14.6
	Intermediate	27.6	13.5	23.9	33.8
	Cloudy	55.6	52.8	55.9	68.6
C - Dimming and solar tube	Sunny	6.0	2.7	6.0	10.2
	Intermediate	26.8	11.1	23.4	30.2
	Cloudy	51.8	45.9	52.4	67.8

With the hourly percentage, four different patterns of use of the artificial lighting system were created, according to the season and the number of typical days in each one of them. Table 6 presents the percentage of sunny, intermediate and cloudy days of each season found after calculating the Clearness Index and its mean values.

Table 6 – Frequency of each type of day for each season.

Season	**Average K_T**	**Sunny (%)**	**Intermediate (%)**	**Cloudy (%)**
Summer	0.47	35	36	29
Autumn	0.42	28	36	36
Winter	0.46	34	35	31
Spring	0.41	27	35	38

The profiles inserted as inputs in eQUEST demonstrated, as expected, a higher energy consumption designated to lighting during winter months, in all cases. This had an impact in all other aspects except for equipment once its operation is scheduled (BILÉSIMO; RAMPINELLI; MARCELINO, 2020). Figure 9 presents energy consumption for the three cases (A, B and C, respectively). In general, comparing the annual energy consumption of cases B and C with case A, there was a reduction of 15.9% and 17.9%, respectively.

It is well known that light is associated with heat generation. This becomes clear by looking at the results generated by the software. On average, in case B, energy consumption for artificial lighting was 51.0% lower than in case A. This caused a reduction of 8.3% in the energy designated to cooling spaces. However, due to the lower heat generation, the energy consumption on heating increased. In case C, the energy consumption with artificial lighting was even lower. There was a reduction of 57.4% compared to case A, causing a decrease of 9.3% in cooling and an increase of 55.1% in heating spaces. Comparing it to case B, the use of solar tube caused an additional decrease of 13.2% in energy consumption designated to artificial lighting. Mesloub *et al.* (2023) evaluated the use of a daylight tubular system and concluded that they were capable of saving 21% of energy consumption in offices of Saudi Arabia. Nicoletti *et al.* (2022) simulated two offices in cities from South and North Italy and found that a daylight control system could save about 26% to 48% of energy consumption.

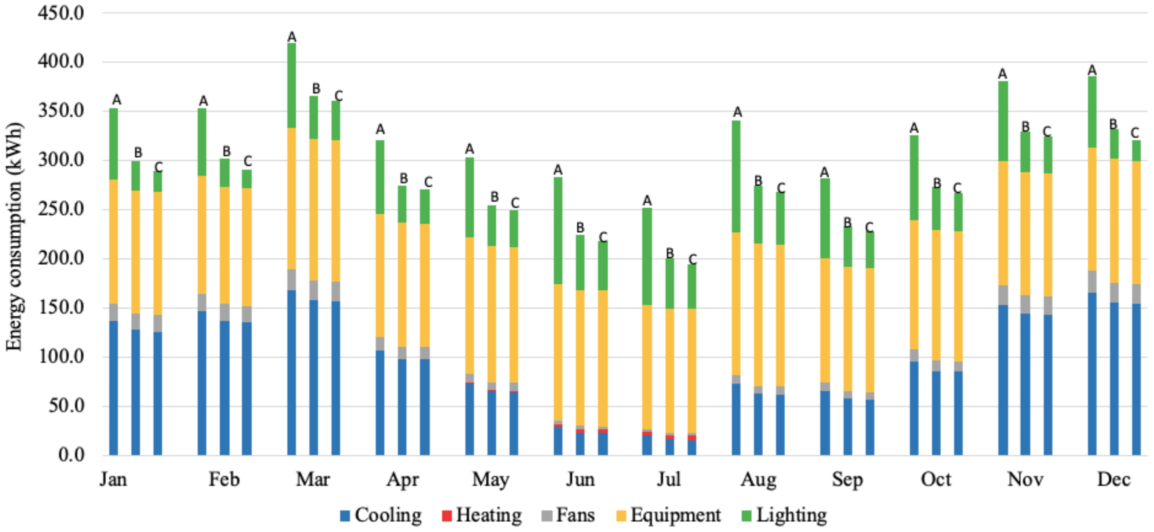


Figure 9 - Energy consumption in cases A, B and C.

5. CONCLUSIONS

This paper aimed to develop a methodology to estimate energy savings in a simplified way, with field measurement and without using complex software. Based on this, data were collected following Brazilian regulations and used relatively simple software (eQUEST and DIALux) in order to estimate the potential energy savings of a building in Araranguá, SC, Brazil.

The proposed framework was useful not only to show the energy savings associated with lighting but also its impact on heating and cooling needs. On annual balance, it was observed a reduction from 15.9% to 17.9%. In terms of lighting energy savings, the potential reduction varied from 51.0% to 57.4%, depending on the scenario. The maps containing the temporal distribution of illuminance are particularly useful because once they are replicated for a specific place, it is possible to have an idea of the illuminance levels at any time of the year.

The simulation of the artificial lighting system with a dimming control showed potential for energy savings around half of the energy consumption for lighting. However, it is important to mention that the simulation shows the “ideal case” and the performance of the dimming system can be a little different once it is installed (YU; SU, 2015b). The impacts of the solar tube were not very clear in this paper because the evaluation focused on the whole building.

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