

OPTIMIZATION OF LIGHTING SYSTEMS FOR INCREASING ENERGY EFFICIENCY OF PUBLIC BUILDINGS

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Due to the requirements of energy efficiency as well as the increasing importance of energy savings and efficiency improvements, it is essential to focus on the optimization of lighting in buildings. Lighting represents a significant part of energy consumption and therefore it is important to implement solutions that minimize its energy intensity. The use of daylight through efficient window and light pipe design, as well as adaptive shading, can significantly reduce the need for artificial lighting. The introduction of LED technology and intelligent control systems allows not only to reduce energy consumption but also to adapt lighting to actual needs. This paper presents the results of lighting intensity measurements and the subsequent design of a lighting system for power consumption. The performed analysis shows that lighting retrofitting can bring energy savings of more than 30%. In doing so, the proposed solutions combine daylight and artificial light to optimize the lighting according to the actual needs.

KEYWORDS

lighting optimization, energy efficiency, public buildings, lighting control systems, energy saving, lighting design, LED lighting

1 INTRODUCTION

Energy efficiency is a key factor in the design of modern lighting systems in buildings. The introduction of LED technology and intelligent control systems allows not only to reduce energy consumption, but also to adapt lighting to current needs. Energy expenditure on lighting has gained considerable attention in the last decade, mainly due to its approximately 19% share in global electricity consumption [IEA 2019]. In buildings, lighting is the fourth most important source of energy consumption after heating, cooling and hot water. However, its relative importance is increasing - improvements in thermal insulation and efficiency of HVAC systems are reducing other components of the building energy balance, while lighting remains necessary during operating hours regardless of outdoor climatic conditions [Reinhart 2001].

For this reason, strategies to reduce the need for electric lighting are coming to the fore, particularly through maximising the use of daylight. Efficient design of openings (windows, light conductors), building orientation, the lighting characteristics of surfaces and transparent structures as well as adaptive shading significantly influence the level of natural light utilisation indoors. Studies show that with properly designed daylighting, the need for electric lighting can be reduced by 30-60% [Li 2010], which also contributes to improved visual comfort and user productivity [Dubois 2011].

Other significant advances have been made in the field of electric lighting itself. The introduction of LED technology represents a revolutionary step - LED luminaires are 5 to 10 times more efficient than traditional incandescent bulbs and have a longer lifespan [Haas 2000]. This has made them economically viable and massively deployed. At the same time, they allow the implementation of advanced control systems (so-called smart lighting) that allow dimming, changing the colour temperature and dynamically adjusting the lighting according to the presence of people or the intensity of daylight [Tzempelikos 2007].

However, despite these advances, studies point to a rebound effect, i.e., a secondary increase in consumption due to savings - the more efficient and cheaper the technology, the more it is used. In lighting, this means that even though LED lighting consumes less energy per unit luminous flux (lm/W), the total amount of installed lamps, the illuminated area, and the length of time they are in operation increases [Hass 2000, Tzempelikos 2007]. This phenomenon has been observed especially in commercial buildings and public spaces, where lighting systems are often operated beyond the actual needs.

The same problem applies to user comfort requirements - modern working and living environments increasingly place emphasis on visual quality, lighting dynamics, colour variability and design, which can increase the number of luminaires and the complexity of the control system. The result is a more complex system that, without intelligent control, paradoxically consumes more energy than an initially inefficient system with a simple switch [Tzempelikos 2007].

The solution to these problems lies in an integrated approach that includes not only technical solutions, but also space design, user education and systematic management of the building operation. Studies show that maximum savings are achieved where the principles of daylighting-oriented design, energy efficient EL system, and automated control based on sensor data are applied simultaneously [Li 2010, Dubois 2011, Tzempelikos 2007].

The operation of older types of lighting systems is one of the most energy-intensive in terms of the overall energy balance of the building. These systems often do not meet the current requirements for lighting efficiency and quality. The modern approach to lighting design is based on legislative and normative frameworks, involving optimization of technical parameters to achieve energy savings without compromising visual comfort [Smola 2015]. High-quality lighting should be designed to provide visual comfort, i.e., a state in which the visual system functions efficiently and without overexertion [STN EN 16247 – 2 2022]. This well-being is dependent on the appropriate selection of light sources, proper placement of luminaires, and even distribution of brightness in the space [SIEA/ERDF 2013]. Deficiencies in lighting can lead to increased visual fatigue, symptoms of which include headaches, burning eyes or conjunctivitis [SIEA/ERDF 2013].

An important aspect of energy efficient design is to make the most of daylight. In spaces where natural lighting is effectively incorporated into the daylighting regime, there are significant savings in electrical lighting operating costs [SIEA/ERDF 2013][Darula 2015]. Daylighting provides high levels of illuminance that artificial lighting often does not achieve without energy-intensive solutions. Therefore, when designing artificial lighting, it is necessary to create a visually pleasing environment without unnecessarily increasing the lighting intensity, which can paradoxically lead to fatigue and higher energy consumption [SIEA/ERDF 2013]. Modern concepts such as pooled lighting, combination of daylight and artificial light allow for more efficient operation of interiors where natural

light is not available throughout the day [Lalt 2014]. Energy efficient design also includes graduated lighting, which amplifies light output only where it is functionally necessary, for example in workplaces [Lalt 2014].

The type of lighting fixtures plays a key role in energy optimization. Direct luminaires focus light on a specific work activity and are effective in high spaces such as production halls. Indirect luminaires, which reflect light from the ceiling, are suitable for offices and entrance areas where the emphasis is on glare reduction. Semi-direct and mixed luminaires provide uniform illumination throughout the space but can contribute to increased energy consumption and visual fatigue if used inappropriately [SIEA/ERDF 2013]. The choice of light sources should take into account the nature of the space and energy efficiency requirements. In terms of long-term sustainability and energy savings, the use of LED technology is most recommended as it offers higher efficiency and longer lifetime compared to traditional sources [Horak 2015].

2 METHODS AND RESULTS

CALCULATION OF ENERGY CONSUMPTION FOR LIGHTING

This method is used to calculate the electricity consumed in lighting.

Table 1. Annual daylight hours [Decree 364/2012]

Building type	t _D	t _N	t _O
B1 office buildings	3300	100	3400
B2 Schools and school establishments	2400	0	2400
B3 hospitals	4000	1000	5000
B4 hotels	4000	1000	5000
B5 restaurants	3000	1400	4400
B6 sports halls	4000	800	4800
B7 wholesale and retail	3700	300	4000

t_D - daylight hours (h/year), t_N - time of use without daylight (h/year), t_O - sum of the times, t_D and t_N (h/year) [Dahlsveen 2008]

Calculation of the annual energy consumption estimate

We calculate the energy consumption for lighting according to the relation:

$$W = 6 \cdot A \cdot P_n \cdot F_c \cdot F_o \cdot (t_D \cdot F_D + t_N) \text{ [kwh/year]} \quad (1)$$

A - floor area of lighting,

P_n - total installed power of luminaires,

F_c - constant illuminance factor,

F_o - occupancy factor F_D - daylight factor t_D - daylight hours t_N - time when daylight is not used [Decree 364/2012].

Constant illuminance factor F_c

It is determined depending on the building category and what control is used in the building. It is only considered if the installed power input is 60% of the type of control [Decree 364/2012].

Table 2. Daylight utilization F(D) [Decree 364/2012]

Building type	Control type		
	R1-R7	R8	R9
B1 Administrative buildings	0.92	0.85	0.92
B2 Schools and school establishments	0.92	0.85	0.92
B3 hospitals	0.92	0.9	0.92
B4 hotels	0.92	0.92	0.92
B5 restaurants	0.98	0.98	0.98
B6 sports halls	1.00	1.00	1.00
B7 wholesale and retail	1.00	1.00	1.00

Table 3. Occupancy factor F(o) [Decree 364/2012]

Building type	Control type			
	R1-R2	R3-R6	R7-R8	R9
B1 office buildings	0.7	0.5	0.7	0.6
B2 Schools and school establishments	0.5	0.4	0.5	0.5
B3 hospitals	0.9	0.9	0.9	0.9
B4 hotels	0.8	0.7	0.8	0.8
B5 restaurants	1.00	1.00	1.00	1.00
B6 sports halls	1.00	1.00	1.00	1.00
B7 wholesale and retail	1.00	1.00	1.00	1.00

Constant illuminance factor F_c

$$F_c = \frac{1+MF}{2} \quad (2)$$

MF - maintenance factor (specified in the project). If the control system is not installed F_c choose 1 [Decree 364/2012].

Table 4. Control factor values for constant illuminance F_c [Decree 364/2012]

Lighting system, environment and maintenance	F _c
Non-dimmable lighting system	1
Halogen point sources in dimmable recessed downlight luminaires in clean environment, individual source replacement	0.95
Linear fluorescent lamps in open pendant downlights with dimmable HF ballast in very clean environment, annual luminaire cleaning interval, individual source replacement after failure and group replacement after 20 000 h	0.9
LED sources (L ₈₀) in closed sealed beam luminaires with dimmable ballast, clean environment, annual cleaning interval for luminaires	0.85
Busbar-mounted open fluorescent luminaires with dimmable HF ballast, dirty environment, two-yearly group replacement interval for fluorescent lamps and cleaning of luminaires	0.8

Calculation of the lighting energy figure

This LENI lighting energy indicator refers to the energy consumption and usable area of the building.

$$\text{LENI} = \frac{W}{A} \quad [\text{kWh} / \text{m}^2 \cdot \text{year}] \quad (3)$$

W - energy consumption (kWh),

A - area (m²) [Sternova 2010].

Table 5. Lighting requirements - educational buildings (STN EN 12464-1:2023)

Type of accommodation	E(m) (lx)	Ru GL	R _a	Type of materiality	E(m) (lx)	Ru GL	R _a
Listening rooms, lecture halls	50 0	19	8 0	Staircases	15 0	25	8 0
Black, green and white boards	50 0	19	8 0	Communication spaces and corridors	10 0	25	8 0
Computer-only work	30 0	19	8 0	Teachers' rooms: classrooms, assembly rooms	30 0	19	8 0
Rooms for technical drawing	75 0	19	8 0	Sports halls, gymnasias, swimming pools	30 0	22	8 0
Practical training rooms and laboratories	50 0	19	8 0	School canteens	20 0	22	8 0
Preparatory rooms and workshops	50 0	22	8 0	Kitchens	50 0	22	8 0

Em- required maintained illuminance

RUGL- glare rating system limit values

Ra- minimum colour rendering index [STN EN 12464-1 2023]

Determination of the number of light sources for a room

The lighting of interior spaces shall provide illumination for the specified activity. The number of luminaires is calculated from the luminaire luminous parameters, distance from the work surface, the required illuminance according to EN 12464 - 1, correction factors related to losses and power reserve [Tkotz 2006].

Table 6. Coefficient p [Tkotz 2006]

Coefficient p for design of installed power		
Normal light power losses	p	1.25
increased light power losses	p	1.43
large losses of light output	p	1.67

The first step to calculate the illumination is to determine the characteristics of the space (dimensions, reflectance and colour of surfaces). height hm, width b, length l.

Table 7. Surface reflectance for daylight [Tkotz 2006]

Daylight reflectance of surfaces	
surface colour	reflectance p
white	0.70 – 0.80
yellow	0.65 – 0.85
pink	0.65 – 0.85
light blue	0.45 – 0.55
light brown	0.25 – 0.35
light green	0.25 – 0.35
medium grey	0.20 – 0.25

The next step is to find out what kind of room it is and what kind of lighting will be used. The spatial index k is calculated.

$$k = \frac{l \cdot b}{h \cdot (l + b)} \quad [\text{m}] \quad (4)$$

l - length of the room (m)

b - room width (m)

h is calculated as

h = hm- height of the work area from the ground [m] (5)

hm- height of the room

Determine the luminaire efficacy and the luminous flux ϕ of the luminaire (indicated on the luminaire).

Table 8. Luminaire efficiency [Tkotz 2006]

	η_{LB} in %
square bath	60
Reflective trough with large angle	60
reflector for multiple fluorescent tubes	75

Based on the finding of the spatial index k, the reflective efficiency of the space is determined.

Table 9. Reflectance of space [Tkotz 2006]

Reflectance of space η_R				
reflectance p				
Ceiling	0,8			
Walls	0.5	0.3		
Floor	0.3	0.1	0.3	0.1
Spatial index k	Reflectance of space η_R in %			
0.6	52	49	43	42
1	73	67	64	60
1.5	89	81	81	75
2	97	86	89	81
3	100	94	101	90

The overall lighting efficiency shall be determined.

$$\eta_B = \eta_{LB} \cdot \eta_R \quad (6)$$

The number of luminaires for the room:

$$n = \frac{E \cdot (l \cdot b) \cdot p}{\Phi \cdot \eta_B} \quad (7)$$

E - required illuminance (lx)
 l - length of the room (m)
 b - room width (m)
 p - coefficient for installed power (-)
 ϕ - luminous flux of the luminaire (lm)
 η_B - luminaire efficiency [Tkotz 2006].

Estimated electricity consumption for lighting

There are three floors in the analyzed building. Linear fluorescent lamps of 36 W are used in all rooms. The fluorescent lamp wattage is currently at 50%. The total wattage of fluorescent lamps can be seen in the individual tables.

Table 10. Information on the number and wattage of luminaires - 1st floor

1st floor						
Room	Number of luminaires	Number of luminaires	Wattage (W)	kW	Total input power	
Assembly room	12	12	432	0.432	0.864	kW
B101	12	24	864	0.864	0.864	kW
B102	3	6	216	0.216	0.216	kW
B103	3	6	216	0.216	0.216	kW
B107	3	6	216	0.216	0.216	kW
B108	3	6	216	0.216	0.216	kW
B109	3	6	216	0.216	0.216	kW
B110	3	6	216	0.216	0.216	kW
corridor	8	4	144	0.144	0.576	kW
School director	3	3	108	0.108	0.216	kW
Secretariat	1	2	72	0.072	0.072	kW
				2.916	3.888	kW

Table 11. Information on number and wattage of luminaires - 2nd floor

2nd floor						
Room	Number of luminaires	Number of luminaires	Wattage (W)	kW	Total input power	
B202	12	12	432	0.432	0.864	kW
B201	12	12	432	0.432	0.864	kW
B205	12	12	432	0.432	0.864	kW
B206	3	3	108	0.108	0.216	kW
B207	12	12	432	0.432	0.864	kW
B208	12	12	432	0.432	0.864	kW
B209	3	3	108	0.108	0.216	kW
B210	12	12	432	0.432	0.864	kW
B211	12	12	432	0.432	0.864	kW
B212	12	12	432	0.432	0.864	kW
B213	1	1	36	0.36	0.72	kW
B203	12	12	432	0.432	0.864	kW
B204	3	3	108	0.108	0.216	kW
Corridor	9	4	144	0.144	0.648	kW
				4.716	9.792	kW

Table 12. Information on number and wattage of luminaires - 3rd floor

3rd floor						
Room	Number of luminaires	Number of luminaires	Wattage (W)	kW	Total input power	
B310	15	15	540	0.54	1.08	kW
B306	12	12	432	0.432	0.864	kW
B307	3	3	108	0.108	0.216	kW
B308	12	12	432	0.432	0.864	kW
B312	15	8	288	0.288	1.08	kW
B311	9	9	324	0.324	0.648	kW
B303	3	3	108	0.108	0.216	kW
B302	15	15	540	0.54	1.08	kW
B304	12	12	432	0.432	0.864	kW
B305	3	3	108	0.108	0.216	kW
B301	3	3	108	0.108	0.216	kW
Corridor	9	4	144	0.144	0.648	kW
				3.564	7.992	kW

The area of each room where the individual data on the number of pieces and the power input of the luminaires were collected is 2270.1 m².

Building category: B2 Schools and educational establishments

Daylight factor F_D : 0.92

Occupancy factor F_o : 0.5

Constant illuminance factor F_c : 1

Annual daylight hours: 2400 h

Total luminaire power: 10.87 kW

Then, on the basis of relation (1), we determine the energy consumption for lighting

$$W = 6 \cdot 2270.1 + 10.87 \cdot 1 \cdot 0.5 \cdot (2400 \cdot 0.92 + 0) = 25621.08 \text{ kWh/year}$$

The total estimated electricity consumed by lighting from the obtained parameters for the theoretical teaching is 25621.08 kWh/year.

Control of the lighting intensity using a Luxmeter

To check the lighting intensity, we have taken measurements in two classrooms namely on the east side and on the west side. For school classrooms in general and according to STN EN 12 464 - 1, the required lighting intensity value is $E_m = 500 \text{ lux}$.

The measurement took place in March between 8:00 and 8:30. The first-class measurement performed was the east-facing class. It was bright sunny weather. Figure 2 shows the class and the individual points where the measurement was taken. The classroom is painted white. The data in the table were measured without the lights on.



Figure 1. Testo 440 Lux-Set luxmeter

Table 13. Measured values for the east side of the building

Measurement p. no.	Lighting intensity	Unit
1.	2200	lux
2.	1900	lux
3.	2000	lux
4.	1300	lux
5.	1600	lux
6.	1400	lux
7.	860	lux
8.	900	lux
9.	905	lux

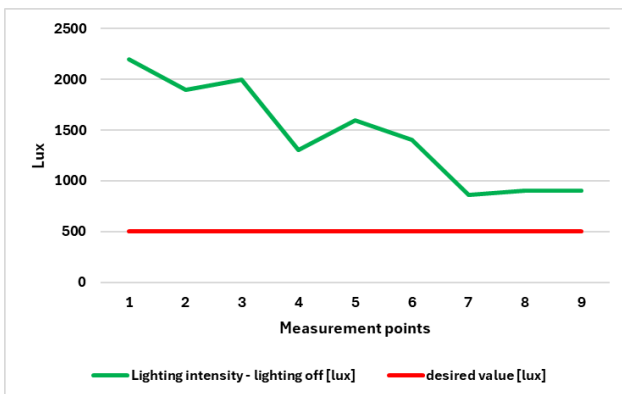


Figure 2. Illuminance of an east-facing room

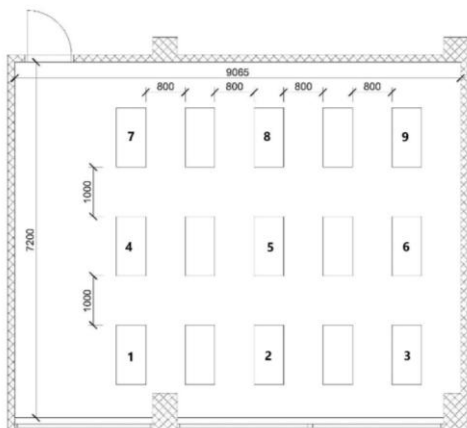


Figure 3. East-facing classroom

From the measurements that have been made the effect of daylight is very favourable on visual wellbeing. The values that have been measured are much higher than the 500 lux requirement. The measurement points 1. 2. 3. are close to the

window. The further the measurement is directed towards the wall the values decrease.

The second measurement was taken on the west side of the school. The data in the table is obtained first when the lighting is in the off state and the next measurement was taken when the lighting is on.

Table 14. Measured values for the west side of the building

Lighting off			Lighting on		
Measureme nt no.	Lightin g intensi ty	Uni t	Measureme nt no.	Lightin g intensi ty	Uni t
1.	545	lux	1.	860	lux
2.	385	lux	2.	711	lux
3.	52	lux	3.	400	lux
4.	243	lux	4.	690	lux
5.	260	lux	5.	700	lux
6.	90	lux	6.	502	lux
7.	103	lux	7.	440	Lux
8.	108	lux	8.	490	lux
9.	78	lux	8.	370	lux

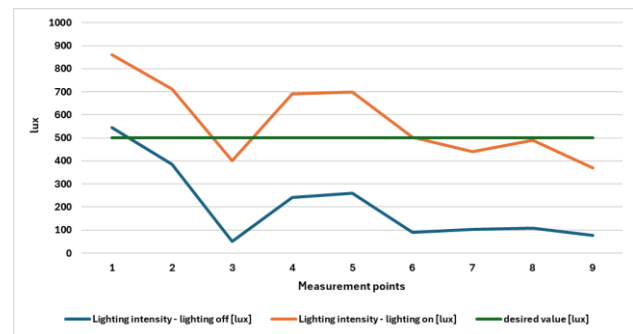


Figure 4. Illuminance of an west-facing room

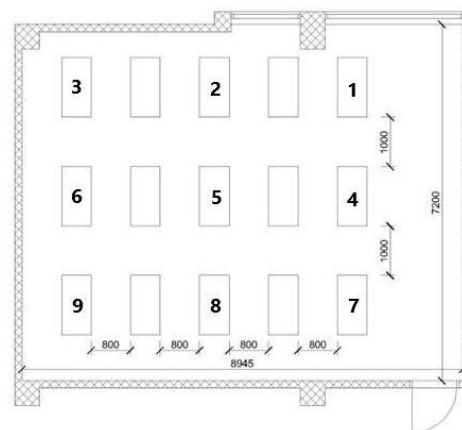


Figure 5. West-facing classroom

In clear weather, the values were measured and are shown in Table 20. In this case, daylight enters the room through one large window and one small window. Near the window, a value was measured that meets the illuminance value. At points 2 to 9 the illuminance values were non-compliant at 500 lux. The measurement was also taken with the lighting on. The measurement that was taken further away from the window closer to the wall, the illuminance was noncompliant despite the lighting being on - it does not meet the requirement set out in EN 12 464-1.

Modelling of the lighting system

In order to ensure optimal lighting conditions and at the same time to achieve energy savings, a reconfiguration of the lighting system was proposed in the analysis using the Dialux simulation software. This tool allows accurate modelling of the interior luminaire layout based on real room parameters such as dimensions, surface reflectance, required lighting intensity and type of light sources. All classes were mapped in detail and the optimum number and placement of luminaires for each room was determined based on the spatial index, the lumen output of the proposed LED panel luminaires and the reflective characteristics of the surfaces.

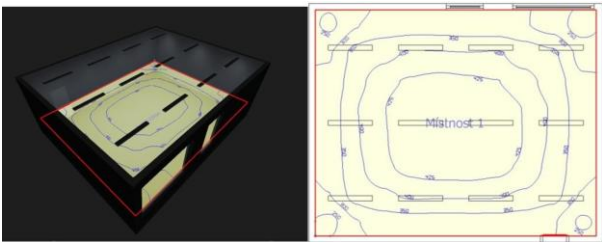


Figure 6. Original lighting

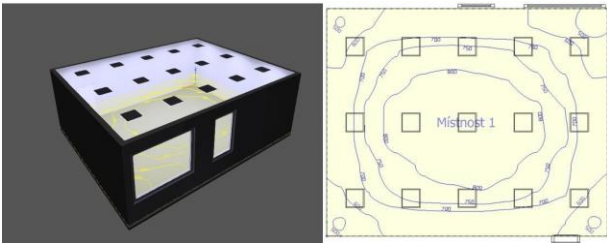


Figure 7. Proposed lighting

Energy savings for lighting

There are two solutions we can consider for saving electricity. The first type of cheaper energy saving is that the current types of fluorescent lamps are replaced with lamps with lower consumption. Obviously, the replacement will achieve savings in electricity consumption but it is then a problem to achieve the required lighting intensity of 500 lx based on STN EN 12 464-1. The second type is to design new lighting for each room in order to meet the lighting requirement presented in STN EN 12464-1. This type is initially more financially demanding due to the purchase of new luminaires and the installation itself.

Calculation of the number of luminaires according to power and efficiency for the room.

Room type: class - general activity (B101)

room height $h_m = 3.25\text{m}$

room width $b = 7.2\text{m}$

room length $l = 8.94\text{m}$

required illumination $E = 500\text{ lx}$

coefficient for installed power $p = 1.25$

Table height 0.85 m .

height of luminaires above the work surface h according to relation (5)

$$h = 3.25 - 0.85 = 2.4\text{ m}$$

The value for the spatial index k is then determined by calculations according to (4).

$$k = \frac{8.94 \cdot 7.2}{2.4 \cdot (8.94 + 7.2)} = 1.66\text{ m}$$

The ceiling and walls have a surface reflectance for daylight of 0.7 to 0.8 for white paint. The floor is a light brown colour, and this has a surface reflectance of 0.25 to 0.35. We find the space

efficiency based on the space index k and the surface reflectance. The room efficiency is $\rho_R = 89\%$. The reflectance of the square bath is $\rho_{LB} = 60\%$. The luminous flux of the luminaire $\Phi = 4950\text{ lm}$.

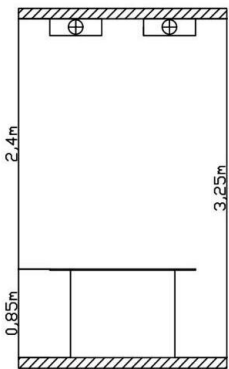


Figure 8. Height of luminaires above the work surface

Lighting efficiency according to relation (6)

$$\eta_B = 0.6 \cdot 0.89$$

$$\eta_B = 0.53$$

Number of light sources according to relation (7)

$$n = \frac{500 \cdot (8.94 \cdot 7.2) \cdot 1.25}{4950 \cdot 0.53}$$

$$n = 15.3 \pm 15$$

For room B101, 15 luminaires of 40 W are required. Calculation of the number of luminaires for the classes in the building.

Table 15. Calculation of the number of luminaires per class

Room	b - room width (m)	l - length of room (m)	h (m)	k - space index (-)	luminous flux Φ (lm)	lighting efficiency	required illuminance (lx)	number of luminaires (after)
B20 1	7.2	9.0	2.4	1.67	4950	0.53	500	15
B20 2	7.2	9.0	2.4	1.67	4950	0.53	500	15
B20 3	7.2	9.2	2.4	1.68	4950	0.53	500	16
B20 5	7.2	9.1	2.4	1.67	4950	0.53	500	16
B20 7	7.2	9.1	2.4	1.67	4950	0.53	500	16
B20 8	7.2	5.9	2.4	1.35	4950	0.53	500	10
B21 0	7.2	6.4	2.4	1.41	4950	0.53	500	11
B21 1	7.2	9.2	2.4	1.68	4950	0.53	500	16
B21 2	7.2	8.9	2.4	1.66	4950	0.53	500	15
B30 2	7.2	11.9	2.4	1.87	4950	0.58	500	19
B30 4	7.2	9.2	2.4	1.68	4950	0.53	500	16
B30 6	7.2	9.1	2.4	1.67	4950	0.53	500	16
B30 8	7.2	9.1	2.4	1.67	4950	0.53	500	16

B310	7.2	12.4	2.4	1.90	4950	0.58	500	19
B311	7.2	6.0	2.4	1.36	4950	0.53	500	10
B312	7.2	12.1	2.4	1.88	4950	0.58	500	19

Table 16. Comparison of total wattage of fluorescent lamps and LED luminaires

Comparison of total wattage of fluorescent lamps and LED luminaires				
Room	Total power consumption of fluorescent lamps (kW)	Total wattage of LED luminaires (kW)	Savings (kW)	Savings (%)
B201	0.864	0.6	0.264	30.56
B202	0.864	0.6	0.264	30.56

B203	0.864	0.64	0.224	25.93
B205	0.864	0.64	0.224	25.93
B207	0.864	0.64	0.224	25.93
B208	0.864	0.4	0.464	53.70
B210	0.864	0.44	0.424	49.07
B211	0.864	0.64	0.224	25.93
B212	0.864	0.6	0.264	30.56
B302	1.08	0.76	0.32	29.63
B304	0.864	0.64	0.224	25.93
B306	0.864	0.64	0.224	25.93
B308	0.864	0.64	0.224	25.93
B310	0.864	0.76	0.32	29.63
B311	0.648	0.4	0.248	38.27
B312	1.08	0.76	0.32	29.63
B101	0.864	0.6	0.264	30.56
	15.12	10.4	4.72	31.22

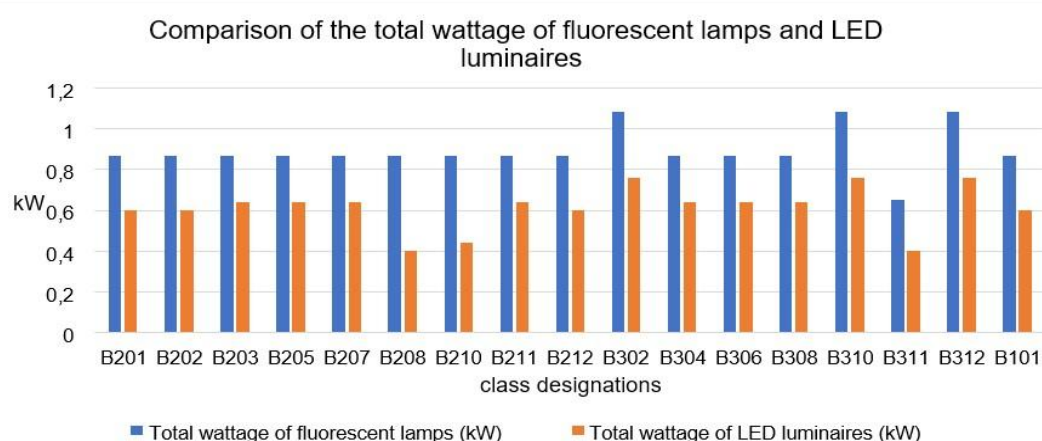


Figure 9. Graph comparing the wattage of linear fluorescent lamps and LED luminaires

3 DISCUSSION

The results of the analysis of the lighting in the building under study confirm the significant potential for energy efficiency improvements through retrofitting of lighting systems. The calculations showed that the total annual electricity consumption for lighting is 25 621.08 kWh, which represents a significant component of the energy balance of the building. The measurements showed that high levels of daylighting are achieved in the east-facing classrooms, while on the west side of the building, especially in the parts further away from the window, the lighting does not comply with the requirements of EN 12464-1 even when artificial lighting is switched on. A comparison of the current situation and the proposal to replace the luminaires with LED panel luminaires shows a possible saving of up to 31.22 % of the installed power consumption. At the same time, the proposed LED luminaires have been shown to meet the required illuminance (500 lx) according to the applicable standard, while their luminous flux and efficiency allow to reduce the number of luminaires needed in some rooms.

However, a number of important aspects need to be highlighted. Replacing luminaires alone is not sufficient if the dynamics of daylight are not taken into account. As measurements have shown, at times with sufficient daylight it may be possible to switch off artificial lighting or to control it

via sensors, thereby achieving further savings. From this perspective, the implementation of automated lighting control systems that take into account the intensity of daylight and the presence of occupants is another key step towards optimising operations. Furthermore, qualitative aspects of lighting such as lighting uniformity, colour rendering index (Ra) and chromaticity temperature should also be considered. The proposed LED luminaires with a Ra of 80 and a temperature of 4100 K provide a neutral white colour suitable for a school environment. At the same time, the load on the visual system is significantly reduced, which has a positive effect on the visual well-being and concentration of the pupils. On the other hand, the design has some limitations - the calculations are based on ideal conditions (clean luminaires, regular maintenance, precise fitting). In real operation, deviations may occur due to neglected maintenance, window shading or inappropriate interior layout.

4 CONCLUSIONS

The results of the analysis confirmed that lighting represents a significant share of the total electricity consumption in buildings, with its relative importance steadily increasing due to the increasing energy efficiency of other technical systems. A key prerequisite for energy-efficient lighting is a comprehensive approach that includes optimised use of daylight, quality design

of artificial lighting and implementation of modern technologies.

The analysis showed that efficient use of daylight - in particular through appropriate building orientation and lighting design of the opening structures - plays a crucial role in reducing the need for artificial lighting. Measurements in the school building analysed showed that the east-facing classrooms achieve above-standard levels of daylighting, while the west-facing rooms require additional supplementation with artificial lighting, which, however, does not always reach the required standard intensity.

Lighting modelling in Dialux software has shown that the proposed LED panel luminaires (40 W, 4950 lm) can reliably provide the required illuminance level of 500 lx according to STN EN 12464-1. Moreover, in some cases, they have made it possible to reduce the number of luminaires without compromising the quality of the illumination, thus reducing the total installed power consumption. The lighting retrofit proposal showed that by replacing the existing fluorescent luminaires with LED technology, electricity savings of up to 31.22 % could be achieved, while at the same time improving the quality of the lighting in terms of colour rendering ($R_a \geq 80$) and visual comfort.

In the long term, however, it is clear that technical upgrading alone is not enough. In order to achieve maximum energy savings and sustainable operation, an integrated approach is needed which includes:

- Appropriate lighting design with emphasis on daylight,
- selection of energy efficient LED luminaires,
- the introduction of intelligent control systems with automatic lighting control according to the presence of people and the intensity of daylight,
- regular maintenance of luminaires and lighting systems,
- and, last but not least, user education to prevent unnecessary energy waste.

Implementing these principles can not only significantly reduce the energy consumption of lighting, but also improve the quality of the indoor environment, increase visual comfort and contribute to the overall sustainability of buildings in line with modern environmental and operational standards.

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