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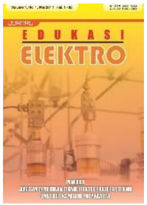

Simulation-Based Optimization of Indoor Lighting Systems for Simultaneous Illuminance Compliance and Energy Efficiency in a Higher Education Digital Library

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Abstract— Indoor lighting systems must satisfy illuminance standards while maintaining energy efficiency; however, achieving this balance remains challenging in practice. This study evaluates and optimizes lighting performance in a higher education digital library based on SNI 6197:2020. A quantitative framework integrating analytical modeling and DIALux evo simulation is developed. The problem is formulated as a constrained optimization to minimize illuminance deviation under lighting power density (LPD) limits, using field measurements for validation. Initial results show that only 48.3% of rooms meet illuminance standards, while 93.1% operate below allowable LPD limits. Severe under-illumination is observed in critical spaces, with deviations up to −60.3%, despite low LPD values (2.15 - 2.95 W/m^2), while some rooms exhibit over-illumination. Statistical analysis indicates a weak and non-significant relationship between LPD and illuminance (Pearson $r = 0.239$, $p = 0.212$, $R^2 = 0.057$), with a moderate monotonic trend (Spearman $\rho = 0.459$), confirming that installed power is not a reliable predictor of performance. These findings reveal that increasing installed power does not guarantee compliance. After optimization, all rooms achieve 100% compliance with an average illuminance improvement of 82.5%. These results demonstrate that lighting performance is primarily governed by spatial distribution rather than installed power.

Keywords: lighting system, illuminance, energy efficiency, optimization, simulation-based

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1. Introduction

Lighting systems constitute a fundamental component of building infrastructure, directly influencing visual comfort, occupant productivity, and energy consumption [1], [2]. In educational facilities, where activities such as reading, computer-based work, and collaborative learning are dominant, maintaining adequate illuminance levels is essential to ensure visual performance and user well-being [3], [4], [5]. Consequently, lighting design must simultaneously satisfy two critical requirements: compliance with illuminance standards and efficient utilization of electrical energy. The Indonesian standard SNI 6197:2020 [6] specifies both minimum illuminance levels and maximum allowable lighting power density (LPD), thereby providing a structured framework for achieving balanced lighting performance and energy efficiency. However, in practical implementations, achieving this balance remains a complex engineering challenge.

Existing studies on indoor lighting systems generally address either illuminance performance [7], [8] or energy efficiency as independent objectives [9], [10]. Approaches focused on energy efficiency tend to minimize installed lighting power [11], [12], often resulting in low LPD values but insufficient illuminance levels. Conversely, approaches aimed at improving lighting performance frequently rely on increasing the number or capacity of luminaires [13], [14], which may lead to excessive energy consumption without guaranteeing uniform light distribution. Although simulation tools such as DIALux are widely utilized for lighting design and evaluation [15], most existing methods rely on iterative trial-and-error processes and lack a rigorous mathematical formulation that integrates illuminance requirements with energy constraints. As a result, the interaction between lighting quality and energy performance is often inadequately addressed.

A significant research gap exists in the development of integrated methodologies that simultaneously consider illuminance compliance, spatial light distribution, and energy efficiency within a unified optimization framework. In practical systems, illuminance is not solely determined by the total installed lighting power but is strongly influenced by luminaire placement, photometric characteristics, and environmental factors [13], [16], [17]. Consequently, systems with low power consumption may still fail to meet required illuminance levels, while increasing installed power does not necessarily resolve lighting deficiencies if the spatial distribution remains inefficient. This indicates that the fundamental limitation of many existing lighting systems lies in suboptimal design and distribution rather than insufficient energy capacity.

This issue is evident in the Digital Library building of Universitas Negeri Yogyakarta (UNY), which functions as a primary academic facility for students [18]. The building consists of four floors and one basement with an approximate total area of 600 m^2 and is intensively utilized for studying, discussion, and accessing digital resources. Preliminary field observations indicate that several rooms exhibit inadequate illuminance distribution, and a number of luminaires are either non-functional or degraded [19], [20], [21], [22], [23]. These conditions lead to uneven lighting performance and potential non-compliance with SNI 6197:2020, particularly in task-oriented spaces such as computer rooms and collaborative areas. This real-world case highlights the practical challenges associated with maintaining both illuminance adequacy and energy efficiency in existing buildings.

To address these challenges, this study proposes a quantitative and simulation-based optimization framework for indoor lighting systems in accordance with SNI 6197:2020. The proposed approach integrates analytical lighting models with simulation using DIALux evo to capture both theoretical and spatial aspects of illuminance distribution. A multi-objective optimization formulation is developed to minimize illuminance deviation while satisfying LPD constraints, thereby achieving a balanced trade-off between lighting quality and energy efficiency. Unlike conventional approaches that primarily focus on increasing installed power, the proposed method emphasizes improving the spatial distribution of light through optimal selection, configuration, and arrangement of luminaires.

The contributions of this study are threefold. First, a unified mathematical framework is developed to quantitatively model illuminance performance, energy consumption, and deviation from standard requirements. Second, a simulation-based validation approach is implemented to ensure that the optimization reflects realistic lighting conditions. Third, the proposed method is applied to a real case study of a higher education digital library building, demonstrating its effectiveness in transforming a system with significant illuminance deficiencies into a fully compliant and energy-efficient lighting design. The results provide valuable insights into the critical role of spatial distribution in lighting systems and offer a practical methodology applicable to similar educational and commercial buildings.

2. Method and Formulation

This study develops a quantitative framework for evaluating and optimizing indoor lighting systems by integrating illuminance performance and energy efficiency criteria. The formulation is based on SNI 6197:2020 and is designed to identify performance gaps and establish a mathematical basis for optimization [24]. The primary parameter used to evaluate lighting performance is the average illuminance, calculated using the lumen method:

$$E_{avg} = \frac{\Phi_{tot} \cdot CU \cdot LLF}{A} \tag{1}$$

where E_{avg} is the average illuminance (lux), Φ_{tot} is the total luminous flux (lumen), CU is the coefficient of utilization, LLF is the light loss factor, and A is the illuminated area (m²).

The total luminous flux is defined as:

$$\Phi_{tot} = N \cdot \Phi_{lamp} \tag{2}$$

where N is the number of luminaires and Φ_{lamp} is the luminous flux per luminaire. The light loss factor accounts for system degradation and environmental conditions and is expressed as:

$$LLF = LLMF \cdot LSF \cdot LMF \cdot RSMF \tag{3}$$

where $LLMF$, LSF, LMF, and $RSMF$ represent lamp lumen maintenance factor, lamp survival factor, luminaire maintenance factor, and room surface maintenance factor.

To capture the spatial distribution of light, which cannot be fully represented by the lumen method, a point-based illuminance model is used:

$$E_i = \frac{I_\alpha \cdot \cos^3 \alpha}{h^2} \tag{4}$$

$$E_{total} = \sum_{i=1}^{N} E_i \tag{5}$$

where E_i is the illuminance contribution from luminaire i, I_α is the luminous intensity at angle α, and h is the mounting height. This formulation highlights that illuminance depends not only on total luminous flux but also on luminaire placement and angular distribution. Energy performance is evaluated using lighting power density (LPD):

$$LPD = \frac{P_{total}}{A} \tag{6}$$

where P_{total} is the total installed lighting power (W). This parameter is used to assess energy efficiency and compliance with maximum allowable limits.

To quantify the performance gap between actual and required illuminance, the deviation is defined as:

$$\Delta E(\%) = \frac{E_{measured} - E_{standard}}{E_{standard}} \times 100\% \tag{7}$$

where $E_{measured}$ is the measured illuminance and $E_{standard}$ is the required illuminance level. Negative values indicate under-illumination, while positive values indicate over-illumination.

To address the limitation of conventional single-objective approaches, the lighting design problem is formulated as a constrained multi-objective optimization problem that simultaneously considers illuminance accuracy and energy efficiency. The objective function is expressed using a normalized weighted-sum approach:

$$\min\ F = \sum_{i=1}^{m} \left[w_1 \cdot \frac{|E_i - E_{std,i}|}{E_{std,i}} + w_2 \cdot \frac{LPD_i}{LPD_{max,i}} \right] \tag{8}$$

where E_i is the illuminance in room i, $E_{std,i}$ is the required illuminance level based on SNI 6197:2020, LPD_i is the lighting power density, and $LPD_{max,i}$ is the maximum allowable value. The weighting coefficients w_1 and w_2 satisfy $w_1 + w_2 = 1$, representing the trade-off between illuminance accuracy and energy efficiency.

The normalization ensures that illuminance (lux) and power density (W/m²) are comparable within the objective function. The first term minimizes relative illuminance deviation, while the second term penalizes excessive energy consumption. The optimization is performed over the following set of decision variables:

$$\mathbf{x} = \{N_i, T_i, P_i\} \tag{9}$$

where N_i is number of luminaires in room i, T_i denotes luminaire type characterized by rated power and luminous flux, and P_i represent spatial arrangement including luminaire positions and spacing.

$$E_i(\mathbf{x}) \geq E_{std,i}, \forall i \tag{10}$$

$$LPD_i(\mathbf{x}) \leq LPD_{max,i}, \forall i \tag{11}$$

These constraints ensure compliance with illuminance standards and energy limitations. In addition to the primary constraints, several practical considerations are incorporated to ensure the feasibility of real-world implementation. The number of luminaires is treated as a discrete variable, such that $N_i \in \mathbb{Z}^+$, reflecting that luminaires can only take integer values. Furthermore, spatial feasibility constraints are imposed to ensure that luminaire placement conforms to room geometry and installation limitations, including allowable spacing and mounting positions. Finally, configuration constraints are applied by restricting the solution space to commercially available luminaire types, ensuring that the optimized design remains practical and implementable within existing building conditions.

To evaluate the effectiveness of the optimization, the improvement ratio is defined as:

$$Improvement(\%) = \frac{E_{new} - E_{initial}}{E_{initial}} \times 100\% \tag{12}$$

where E_{new} is the optimized illuminance and $E_{initial}$ is the initial measured illuminance.

This mathematical framework establishes a relationship between illuminance, spatial distribution, and energy consumption. It demonstrates that lighting performance is influenced installed power also by distribution efficiency and system losses [25], [26], forming the basis for the simulation-based optimization approach.

3. Proposed Method and Simulation Setup

The proposed method integrates analytical modeling with simulation-based validation to optimize indoor lighting performance under practical constraints. The overall workflow of the proposed lighting optimization method is illustrated in Figure 1. The simulation process was carried out using DIALux evo, which enables accurate modeling of light distribution based on luminaire photometric data and room geometry. The simulation model was developed using field measurement data, including room dimensions, luminaire types, number of luminaires, and installation configurations. Each room was modeled individually to represent its functional characteristics and lighting requirements. The working plane was defined at a height of 0.75 m [27], [28], corresponding to typical visual task conditions. Surface reflectance values were assumed using standard indoor parameters (ceiling: 0.7, walls: 0.5, floor: 0.2) [29], [30], and the light loss factor was incorporated to account for lumen depreciation and environmental conditions. These assumptions ensure that the simulation reflects realistic operating conditions.

The process begins with the development of a baseline model representing the existing lighting system. The model replicates the number, type, and spatial arrangement of luminaires in each room.

The simulated illuminance values are then compared with measured data to validate the model accuracy. The validation is quantified using the relative error:

$$\epsilon = \frac{|E_{sim} - E_{meas}|}{E_{meas}} \times 100\% \qquad (13)$$

where E_{sim} is the simulated illuminance and E_{meas} is the measured illuminance. This step ensures that the simulation model reliably represents real-world conditions.

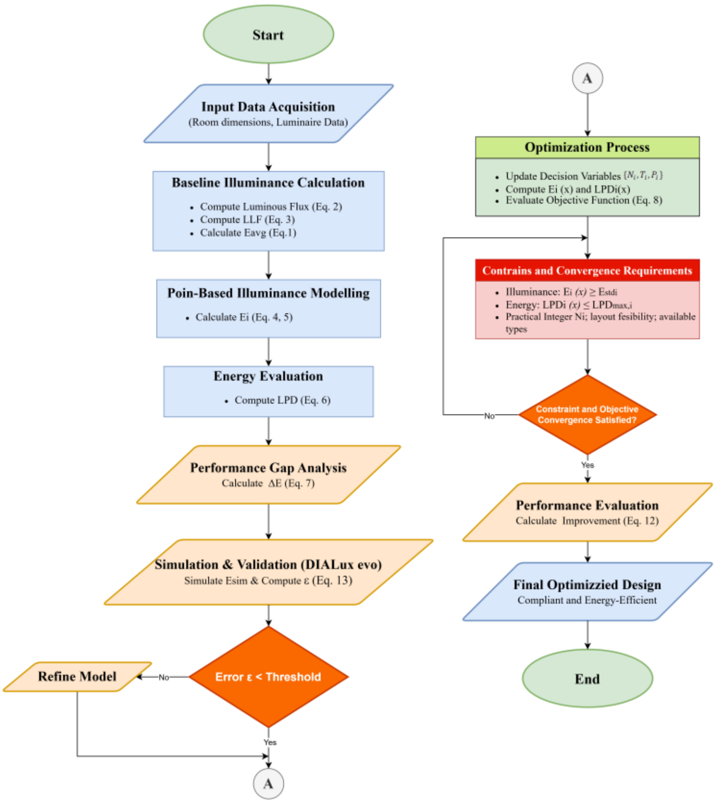

Figure 1. Flowchart of the proposed lighting optimization framework

After validation, an iterative optimization process is performed to improve lighting performance. The optimization focuses on adjusting three key variables: the number of luminaires, luminaire type, and spatial arrangement. For each iteration, the lighting configuration is modified and re-evaluated until the illuminance satisfies the required standards while maintaining acceptable energy performance.

The optimization follows the formulation defined in Section 2, where the objective is to minimize illuminance deviation under energy constraints. Unlike conventional approaches that increase installed power, the proposed method emphasizes improving light distribution efficiency through appropriate selection and arrangement of luminaires. Hybrid configurations, such as combinations of LED panels and downlights, are utilized to enhance spatial uniformity and achieve more effective illumination.

The optimization process is subject to practical constraints, including compliance with illuminance standards, adherence to LPD limits, and feasibility of installation. Excessive over-illumination is avoided to ensure that improvements are achieved without unnecessary energy consumption. The performance of the optimized lighting system is evaluated using quantitative metrics, including average illuminance, deviation from the standard, lighting power density, and improvement ratio. These metrics provide a comprehensive assessment of both lighting quality and energy efficiency.

The proposed method combines analytical modeling and simulation to address the limitations of conventional lighting design. The analytical formulation provides a theoretical basis for evaluating illuminance and energy consumption, while the simulation captures spatial distribution effects and practical constraints. This integrated approach enables systematic and effective optimization of indoor lighting systems, ensuring compliance with standards while maintaining energy efficiency.

4. Result and Discussion

4.1. Quantitative Analysis of Illuminance Performance and Compliance

The existing lighting performance of the digital library building, as presented in Table 1 and visualized in Figure 2, was evaluated based on SNI 6197:2020. The results reveal a significant mismatch between measured illuminance and standard requirements. Out of 29 evaluated rooms, only 14 rooms (48.3%) meet the required illuminance levels, while 15 rooms (51.7%) are non-compliant, indicating that more than half of the building operates under substandard lighting conditions. This reflects a systemic deficiency in the existing lighting system rather than isolated issues.

Table 1. Measured illuminance levels compared with standard requirements based on SNI 6197:2020

Floor	Room	Code	Dimensions (m) (L×W)	Lighting System	Standard (Lux)	Measured (Lux)	Deviation (%)
Basement	Computer Room	F0-R1	19 × 8	LED Downlight 16 W (50 units)	350	216	-38.3
	Panel Room	F0-R2	3.5 × 5.5	LED Downlight 18 W (2 units)	150	190	+26.7
	Storage	F0-R3	7 × 4	LED Downlight 18 W (2 units)	150	161	+7.3
	Toilet	F0-R4	4.5 × 5	LED Downlight 9 W (4 units)	150	130	-13.3
	Pump Room	F0-R5	7 × 4	TL LED 16 W (3 units)	200	155	-22.5
Floor 1	Open Discussion	F1-R1	16 × 8	LED Downlight 18 W (21 units)	300	155	-48.3
	Information Room	F1-R2	4 × 4	LED Downlight 18 W (9 units)	250	255	+2.0
	Toilet	F1-R3	4.5 × 5	LED Downlight 9 W (4 units)	150	153	+2.0
	Display Room	F1-R4	8 × 4	LED Downlight 18 W (6 units)	150	151	+0.7
	Storage	F1-R5	7 × 4	LED Downlight 18 W (2 units)	150	152	+1.3
	Panel Room	F1-R6	3.5 × 5.5	LED Downlight 18 W (2 units)	150	121	-19.3
Floor 2	Information Room	F2-R1	6 × 7	LED Downlight 18 W (6 units)	250	162	-35.2
	Panel Room	F2-R2	3.5 × 5.5	LED Downlight 18 W (2 units)	150	151	+0.7
	Computer Private 1	F2-R3	13 × 4.5	LED Downlight 16 W (40 units)	350	165	-52.9
	Computer Private 2	F2-R4	12 × 6	LED Downlight 16 W (40 units)	350	163	-53.4
	Toilet	F2-R5	4.5 × 5	LED Downlight 9 W (4 units)	150	200	+33.3
Floor 3	Computer Room (30 Units)	F3-R1	6.5 × 7.3	LED Downlight 16 W (12 units)	350	364	+4.0
	Computer Room (5 Units)	F3-R2	6 × 3	LED Downlight 16 W (3 units)	350	355	+1.4
	Computer Room (10 Units)	F3-R3	6.6 × 4.5	LED Downlight 16 W (4 units)	350	139	-60.3
	Collaborative Room	F3-R4	6 × 6	LED Downlight 18 W (26 units)	350	224	-36.0
	Storage	F3-R5	7 × 4	LED Downlight 18 W (2 units)	150	153	+2.0

Floor	Room	Code	Dimensions (m) (L×W)	Lighting System	Standard (Lux)	Measured (Lux)	Deviation (%)
	AV Meeting Room	F3-R6	6.4 × 8.5	LED Downlight + LED Strip	300	317	+5.7
	Information Room	F3-R7	6 × 8	LED Downlight 18 W (9 units)	250	130	-48.0
	Toilet	F3-R8	4.5 × 5	LED Downlight 9 W (4 units)	150	140	-6.7
	Panel Room	F3-R9	3.5 × 5.5	LED Downlight 18 W (2 units)	150	129	-14.0
Floor 4	Preparation Room	F4-R1	6 × 6.5	LED Downlight 18 W (6 units)	250	205	-18.0
	Panel Room	F4-R2	3.5 × 5.5	LED Downlight 18 W (2 units)	150	157	+4.7
	Toilet	F4-R3	4.5 × 5	LED Downlight 9 W (4 units)	150	150	0.0
	Meeting Room	F4-R4	19.6 × 12.6	LED Downlight + LED Strip	350	139	-60.3

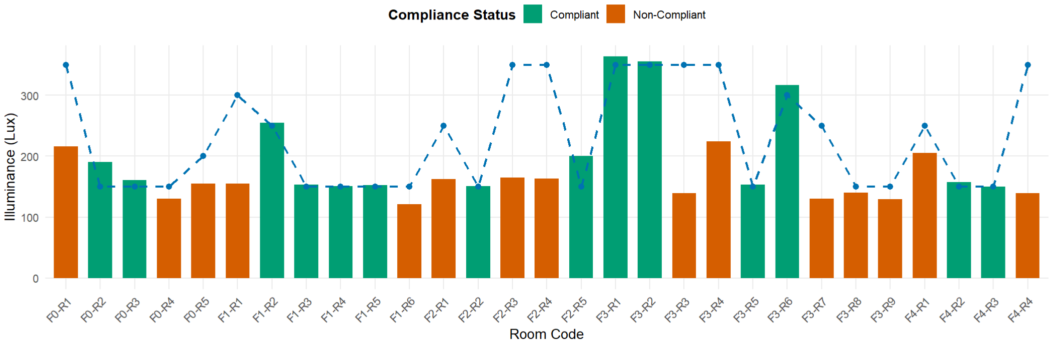

Figure 2. Measured Illuminance Performance Levels Relative to SNI 6197:2020 Requirements

A detailed quantitative assessment highlights that the most critical deficiencies occur in task-intensive environments. The Computer Private Room 1 and 2 (F2-R3 and F2-R4) record illuminance levels of 165 lux and 163 lux, corresponding to deviations of −52.9% and −53.4%, respectively, from the required 350 lux. Even more severe, the Computer Room (10 Units) (F3-R3) and Meeting Room (F4-R4) both exhibits only 139 lux, representing the largest deviation of −60.3%, which is the lowest performance observed across all rooms. Similarly, the Open Discussion Room (F1-R1) shows a substantial deficit of −48.3%, with only 155 lux compared to the required 300 lux. These findings clearly indicate that key functional spaces intended for reading, computing, and collaboration are inadequately illuminated, potentially degrading visual comfort and task performance.

From a spatial distribution perspective, non-compliance is unevenly distributed across floors. Floor 2 emerges as the most critical zone, where multiple essential rooms, including both private computer rooms and the information room (−35.2%) which fail to meet the standard. Floor 3 presents mixed performance, combining compliant areas such as Computer Room (30 Units) (364 lux, +4.0%) with severely deficient spaces like Computer Room (10 Units) (−60.3%), Collaborative Room (−36.0%), and Information Room (−48.0%). In contrast, the basement and Floor 1 exhibit moderate deficiencies, primarily in utility and support spaces such as the pump room (−22.5%) and panel room (−19.3%), suggesting localized design limitations rather than a complete lack of lighting infrastructure.

In addition to under-illumination, several rooms exhibit over-lighting, indicating inefficiencies in lighting allocation. For instance, the Toilet on Floor 2 (F2-R5) shows a significant positive deviation of +33.3%, while the AV Meeting Room (F3-R6) and Computer Room (30 Units) (F3-R1) exceed the standard by +5.7% and +4.0%, respectively. Although these rooms are classified as compliant, the excess illumination suggests unnecessary energy usage and suboptimal system design. This coexistence of over-lit and under-lit spaces reflects a lack of balance in luminaire distribution and control strategy.

As clearly illustrated in Figure 2, the disparity between measured and standard illuminance values is visually evident, with several rooms falling significantly below the required thresholds while others exceed them. This pattern confirms that the issue is not merely insufficient installed power, but rather an inefficient spatial distribution of lighting and non-optimized luminaire configuration. Consequently, the existing system fails to deliver uniform and adequate illumination across different functional zones. These findings strongly emphasize the need for a systematic optimization approach that simultaneously addresses compliance, uniformity, and energy efficiency.

4.2. Energy Efficiency Evaluation-based on Lighting Power Density (LPD)

The lighting power density (LPD) performance of all evaluated rooms, as presented in Table 2 and illustrated in Figure 3, provides critical insight into the energy efficiency of the existing lighting system. The results indicate that 27 out of 29 rooms (93.1%) operate below the maximum allowable LPD limits, demonstrating that the overall system is highly energy-efficient in terms of installed power consumption.

Table 2. LPD evaluation for all rooms

Floor	Room	Code	Dimensions (m) (L×W)	Standard Power Density (W/m²)	Calculated Power Density (W/m²)
Basement	Computer Room	F0-R1	19 × 8	10.12	5.26
	Panel Room	F0-R2	3.5 × 5.5	7.53	1.87
	Storage	F0-R3	7 × 4	3.88	1.29
	Toilet	F0-R4	4.5 × 5	6.78	1.60
	Pump Room	F0-R5	7 × 4	7.53	1.71
Floor 1	Open Discussion	F1-R1	16 × 8	11.84	2.95
	Information Room	F1-R2	4 × 4	8.50	6.75
	Toilet	F1-R3	4.5 × 5	6.78	1.60
	Display Room	F1-R4	8 × 4	9.04	3.38
	Storage	F1-R5	7 × 4	3.88	1.29
	Panel Room	F1-R6	3.5 × 5.5	7.53	1.87
Floor 2	Information Room	F2-R1	6 × 7	8.50	2.57
	Panel Room	F2-R2	3.5 × 5.5	7.53	1.87
	Computer Private 1	F2-R3	13 × 4.5	10.12	10.94
	Computer Private 2	F2-R4	12 × 6	10.12	8.89
	Toilet	F2-R5	4.5 × 5	6.78	1.60
Floor 3	Computer Room (30 Units)	F3-R1	6.5 × 7.3	10.12	4.04
	Computer Room (5 Units)	F3-R2	6 × 3	10.12	2.67
	Computer Room (10 Units)	F3-R3	6.6 × 4.5	10.12	2.15
	Collaborative Room	F3-R4	6 × 6	11.84	13.00
	Storage	F3-R5	7 × 4	3.88	1.29
	AV Meeting Room	F3-R6	6.4 × 8.5	7.53	3.31
	Information Room	F3-R7	6 × 8	8.50	3.38
	Toilet	F3-R8	4.5 × 5	6.78	1.60
	Panel Room	F3-R9	3.5 × 5.5	7.53	1.87
Floor 4	Preparation Room	F4-R1	6 × 6.5	8.50	2.77
	Panel Room	F4-R2	3.5 × 5.5	7.53	1.87
	Toilet	F4-R3	4.5 × 5	6.78	1.60
	Meeting Room	F4-R4	19.6 × 12.6	6.57	2.55

From a quantitative perspective, most rooms exhibit significantly lower LPD values compared to the standard thresholds. For instance, the Open Discussion Room (F1-R1) records an LPD of 2.95 W/m² compared to the allowable 11.84 W/m², while the Computer Room (30 Units) (F3-R1) shows 4.04 W/m² against a limit of 10.12 W/m². Similarly, utility and support spaces such as storage and panel rooms consistently operate below 2 W/m², indicating minimal energy usage. These findings suggest that the lighting system is generally designed with low installed power, potentially reflecting an intention to achieve energy savings.

However, despite this apparent energy efficiency, the illuminance performance presented in Table 1 reveals a contrasting outcome. A large proportion of rooms with low LPD values still fail to meet the required illuminance levels. For example, the Open Discussion Room (F1-R1), with an LPD of only 2.95 W/m², exhibits a severe illuminance deficit of −48.3%, while the Information

Room (F2-R1), with 2.57 W/m², shows a deviation of −35.2%. This indicates that low energy consumption is achieved at the expense of insufficient lighting performance.

More critically, two rooms exceed the allowable LPD limits: Computer Private Room 1 (F2-R3) with 10.94 W/m² (above 10.12 W/m²) and the Collaborative Room (F3-R4) with 13.00 W/m² (above 11.84 W/m²). Despite having higher power densities, both rooms still fail to meet the required illuminance levels, with deviations of −52.9% and −36.0%, respectively, as shown in Table 1. This finding is particularly significant, as it demonstrates that increasing installed power does not necessarily result in adequate illuminance.

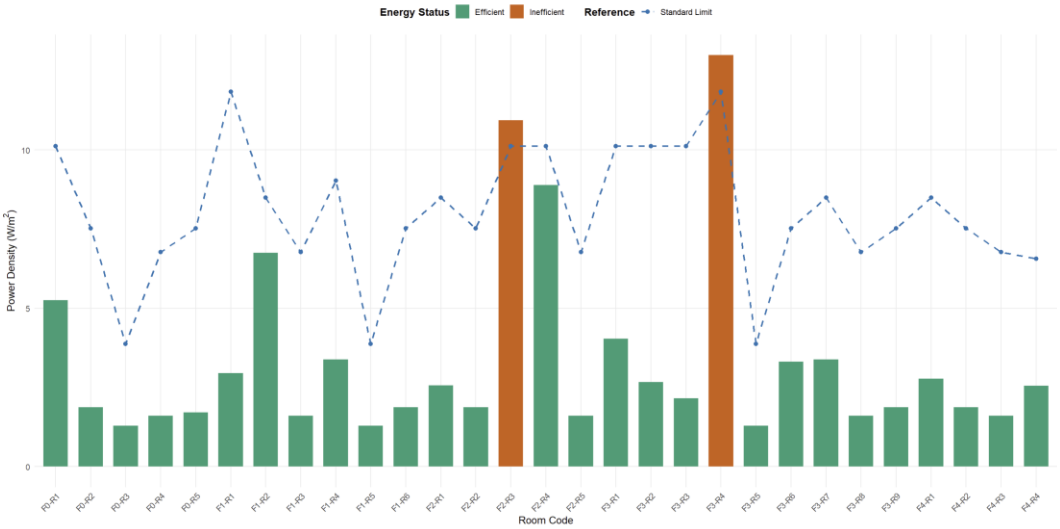

Figure 3. Distribution of LPD relative to standard limit

The relationship between lighting power density (LPD) and illuminance performance, as visualized in Figure 3, further confirms the observed inconsistency between energy consumption and lighting adequacy. While most rooms cluster within the low-LPD region, their illuminance values exhibit substantial variability, indicating that similar power densities can result in significantly different lighting outcomes. To rigorously quantify this relationship, a statistical correlation analysis was conducted using data from all 29 evaluated rooms. The Pearson correlation coefficient between calculated LPD and measured illuminance is $r = 0.239$, with a corresponding t-statistic of 1.278 and a p-value of 0.212 (df = 27, $\alpha = 0.05$), indicating that the linear association is not statistically significant. The coefficient of determination is $R^2 = 0.057$, meaning that LPD explains only 5.7% of the variance in measured illuminance across the evaluated rooms.

To further examine the monotonic relationship, the Spearman rank correlation coefficient was calculated, yielding $\rho = 0.459$with a p-value of 0.012. Although this result is statistically significant, it indicates only a moderate monotonic trend and does not imply strong predictive capability. The relatively higher Spearman value suggests the presence of a weak non-linear tendency; however, the large dispersion observed in Figure 3 confirms that LPD cannot serve as a reliable predictor of illuminance compliance. These results provide statistically grounded evidence that the relationship between lighting power density and illuminance is weak in both linear and practical terms. The findings demonstrate that illuminance performance cannot be effectively predicted by installed power alone and is instead primarily governed by spatial factors such as luminaire arrangement, photometric distribution, and configuration efficiency.

Table 3 summarizes the statistical correlation analysis between LPD and measured illuminance across all evaluated rooms. The consistently low coefficient determination and non-significant Pearson test reinforce that power density alone cannot be used as a surrogate indicator of lighting adequacy. Although the Spearman correlation suggests a moderate monotonic trend, its practical relevance remains limited in engineering applications. These results confirm that spatial configuration is the dominant factor influencing illuminance performance in the evaluated lighting system.

Table 3. Statistical correlation between LPD and measured illuminance

Metric	Value	p-value	Interpretation
Pearson correlation coefficient, *(r)*	0.239	0.212	Not statistically significant ($\alpha = 0.05$)
Coefficient of determination, (R^2)	0.057	-	LPD explains 5.7% of illuminance variance
Spearman rank correlation, (ρ)	0.459	0.012	Statistically significant but moderate monotonic relationship
t-statistic (Pearson, df = 27)	1.278	-	Below critical value (t_{crit}) ≈ 2.052, ($\alpha = 0.05$))

The LPD analysis highlights a critical paradox in the existing system: high energy efficiency does not guarantee lighting adequacy, and in some cases, even increased power consumption fails to achieve the required standards. Therefore, it can be concluded that the existing lighting system is not limited by energy capacity but by ineffective design and spatial distribution of luminaires. These findings strongly support the need for a multi-objective optimization approach that simultaneously considers illuminance compliance and energy efficiency, rather than treating them as independent criteria.

4.3. Optimization-based Improvement of Illuminance Compliance

The optimization results, summarized in Table 4 and visualized in Figure 4 and Figure 5, demonstrate a substantial improvement in lighting performance across all evaluated rooms. The proposed lighting reconfiguration successfully transforms all previously non-compliant spaces into fully compliant conditions with respect to SNI 6197:2020, achieving 100% compliance compared to 48.3% in the existing system.

Table 4. Optimized lighting configurations and illuminance improvement performance

Code	Room	Before (Lux)	Standard (Lux)	Simulated (Lux)	Improvement (%)	Lighting Configuration
F0-R1	Computer Room	216	350	365	+69.0	25 LED Panels + 5 LED Downlights
F0-R4	Toilet	130	150	193	+48.5	5 LED Downlights
F0-R5	Pump Room	155	200	205	+32.3	2 LED Panels
F1-R1	Open Discussion Room	155	300	319	+105.8	15 LED Panels
F1-R6	Panel Room	121	150	190	+57.0	2 LED Downlights
F2-R1	Information Room	162	250	253	+56.2	6 LED Panels
F2-R3	Computer Private 1	165	350	355	+115.2	22 LED Panels + 2 LED Downlights
F2-R4	Computer Private 2	163	350	365	+123.9	22 LED Panels + 2 LED Downlights
F3-R3	Computer Room (10 Units)	139	350	352	+153.2	4 LED Panels
F3-R4	Collaborative Room	224	350	412	+83.9	LED Downlights + LED Panels
F3-R7	Information Room	130	250	252	+93.8	6 LED Panels
F3-R8	Toilet	140	150	178	+27.1	10 LED Downlights
F3-R9	Panel Room	129	150	190	+47.3	2 LED Panels
F4-R1	Preparation Room	205	300	308	+50.2	6 LED Panels
F4-R4	Meeting Room	139	350	380	+173.4	LED Batten + Downlight + Spotlight + Panel

As illustrated in Figure 4, the simulated illuminance levels (green bars) consistently meet or exceed the standard requirements (blue dashed line), in contrast to the measured values (orange bars), which frequently fall below the required thresholds. The improvement magnitude is significant, with an average increase of 82.5% across all optimized rooms. Notably, the most critical improvements are observed in previously under-lit environments. The Meeting Room (F4-R4) exhibits the highest improvement of +173.4%, increasing from 139 lux to 380 lux, followed by the Computer Room (10 Units) (F3-R3) with +153.2%, and the Computer Private Rooms (F2-R3 and F2-R4) with improvements exceeding +115%. These results confirm that the optimization effectively addresses severe illumination deficiencies in task-intensive environments.

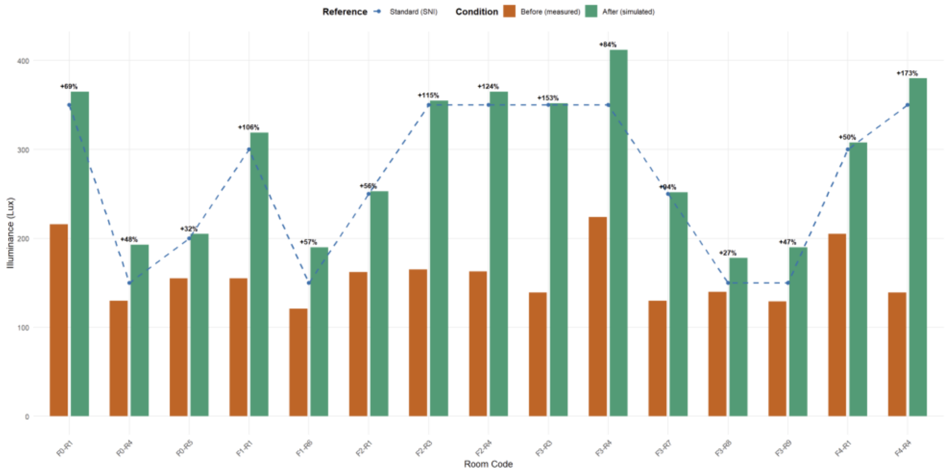

Figure 4. Comparison of measured and optimized illuminance levels relative to SNI 6197:2020

Moderate improvements are also observed in rooms with smaller initial deviations. For instance, the Information Room (F2-R1) improves by +56.2%, while the Preparation Room (F4-R1) increases by +50.2%, both achieving compliance with relatively minimal adjustments in lighting configuration. Even utility spaces such as toilets and panel rooms demonstrate consistent improvements ranging from +27.1% to +57.0%, indicating that the proposed approach is adaptable across diverse room types and lighting requirements.

The effectiveness of the optimization is further emphasized in Figure 5, which illustrates the reduction of illuminance deviation relative to the standard. Prior to optimization, several rooms exhibit significant negative gaps, reaching up to approximately −211 lux, indicating severe under-lighting conditions. After optimization, all gaps shift to non-negative values, with most rooms achieving small positive margins above the standard (typically between +2 lux to +62 lux). This complete shift from negative to positive deviation confirms that the optimization eliminates under-illumination entirely.

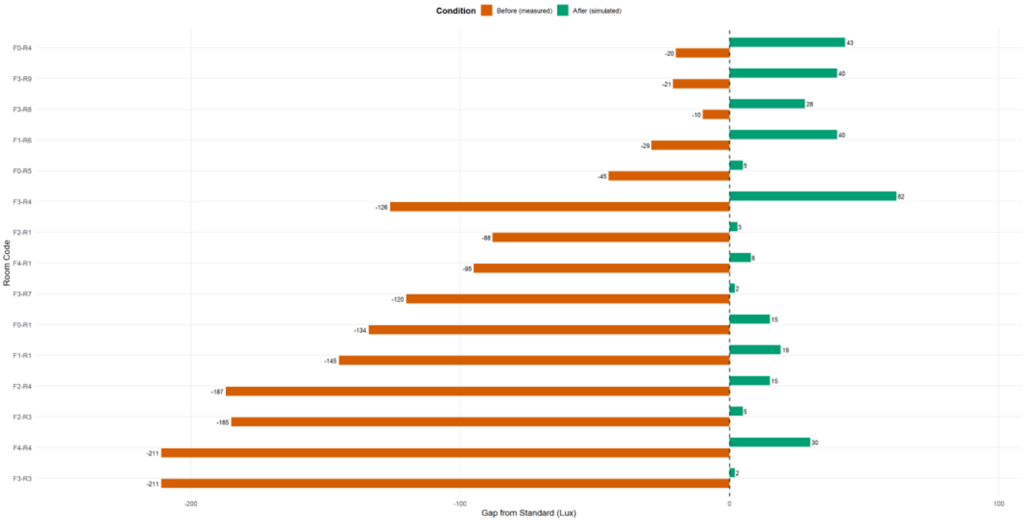

Figure 5. Reduction of illuminance deviation from SNI 6197:2020 before and after optimization

Importantly, the results reveal that the improvement is not solely driven by increasing lighting power, but rather by optimizing the spatial distribution and configuration of luminaires. As shown in Table 4, the use of LED panels and hybrid configurations, for example panel and downlight combinations, enables more uniform and effective light distribution, ensuring compliance without excessive overdesign. This finding is consistent with the LPD analysis in Section 4.2, which indicates that higher power density does not necessarily guarantee adequate illuminance.

The proposed optimization method demonstrates strong effectiveness in resolving both performance and design inefficiencies in the existing lighting system. By simultaneously addressing illumination levels and spatial distribution, the method achieves a balanced solution that ensures compliance, enhances visual comfort, and maintains energy efficiency. These results validate the applicability of the proposed approach for practical implementation in similar educational and office buildings.

4.4. Performance Relationship Between Illuminance and Energy Consumption

The performance of the lighting system is evaluated through an integrated analysis of illuminance compliance (Table 1), energy efficiency based on lighting power density (Table 2), statistical correlation results (Table 3), and optimization outcomes (Table 4). The results reveal a clear mismatch between energy consumption and lighting performance. This observation is statistically supported by the analysis in Section 4.2, which shows a weak and non-significant linear relationship between LPD and illuminance ($r = 0.239$, $p = 0.212$), with a low coefficient of determination ($R^2 = 0.057$). This indicates that only a small fraction of illuminance variation can be explained by power density.

From a quantitative perspective, the existing system exhibits a wide dispersion in illuminance performance despite relatively low power densities. The LPD values range approximately from 1.29 W/m^2 to 13.00 W/m^2, while the corresponding illuminance values vary significantly from 121 lux to 364 lux. This large variation under similar energy conditions highlights the inconsistency of lighting performance and reinforces that installed power alone does not determine illuminance adequacy. Furthermore, a comparison between compliant and non-compliant rooms reveals no consistent trend between LPD magnitude and performance outcome. Several rooms operating at low LPD levels ($<$ 3 W/m^2) exhibit severe under-illumination (up to −48.3%), while some rooms with higher LPD values ($>$ 10 W/m^2) still fail to meet the required illuminance levels. This confirms that increasing power density does not necessarily improve lighting performance in the absence of proper spatial distribution.

Following the optimization process, all rooms achieve full compliance with illuminance standards, with an average improvement of 82.5%. Importantly, these improvements are achieved without uniformly increasing LPD across all rooms, indicating that performance gains are primarily driven by improved luminaire configuration rather than increased energy input. To further interpret this relationship, the results suggest that lighting efficiency should be evaluated in terms of effective light utilization rather than installed power. The optimized configurations demonstrate that appropriate selection, positioning, and combination of luminaires can significantly enhance illuminance distribution while maintaining controlled energy consumption.

The findings confirm that spatial distribution characteristics (such as luminaire placement, photometric properties, and configuration strategy) are the dominant factors influencing illuminance performance, while installed power density plays a secondary role. This reinforces the importance of integrated, distribution-oriented design approaches for achieving both illuminance compliance and energy efficiency.

5. Conclusion

This study presents a quantitative and simulation-based optimization framework for indoor lighting systems in accordance with SNI 6197:2020, integrating illuminance performance and energy efficiency within a unified analytical approach. The results show that the existing lighting system in the Digital Library building of Universitas Negeri Yogyakarta exhibits significant performance deficiencies, with only 48.3% of rooms meeting the required illuminance levels, despite 93.1% of spaces operating below the allowable lighting power density (LPD). This indicates that inadequate lighting performance is primarily caused by inefficient spatial distribution and suboptimal luminaire configuration rather than insufficient power capacity. Statistical analysis confirms that the relationship between LPD and illuminance is weak and not statistically significant (Pearson r = 0.239, p = 0.212, R^2 = 0.057). Although a moderate monotonic trend is observed (Spearman ρ = 0.459), LPD cannot be considered a reliable predictor of illuminance compliance. These results indicate that lighting performance is governed primarily by spatial and photometric factors rather than installed power.

The proposed approach, combining analytical modeling and DIALux evo simulation, effectively improves lighting performance by optimizing luminaire type, quantity, and spatial arrangement. After optimization, all evaluated rooms achieve 100% compliance with SNI 6197:2020, with an average illuminance improvement of 82.5%, while maintaining controlled energy usage. These improvements are achieved without uniformly increasing power density, demonstrating that distribution efficiency plays a more critical role than installed power.

From an engineering perspective, the results reveal a fundamental decoupling between energy input and lighting output in non-optimized systems. Increasing installed power does not necessarily resolve illumination deficiencies, whereas appropriate spatial configuration significantly enhances lighting effectiveness. This highlights the importance of distribution-oriented design strategies over conventional power-based approaches.

It is important to note that this research is conducted within a simulation-based framework, where the optimization results are derived from analytical modelling and validated using DIALux evo simulations calibrated with field measurement data. While this approach enables accurate representation of spatial lighting behaviour, further experimental validation in real-world implementations is recommended to assess long-term performance and operational variability.

The study demonstrates that optimal lighting performance can be achieved through systematic spatial optimization rather than increased energy consumption. The proposed framework provides a practical and scalable solution for improving indoor lighting systems, particularly in retrofitting existing buildings. Future work may incorporate adaptive control strategies, real-time occupancy sensing, and experimental validation to further enhance system performance and applicability.

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7. References

[1] L. V. González, A. S. Melenchón, D. B. Moyano, and R. A. González-Lezcano, “Towards Sustainable Indoor Lighting Design: Ensuring Energy Efficiency, Health and Human Wellbeing—A Review,” *Sustain. Dev.*, vol. 34, no. S1, pp. 1067–1095, Jan. 2026, doi: 10.1002/sd.70201.

[2] S. Hammes *et al.*, “Concepts of user-centred lighting controls for office applications: A systematic literature review,” *Build. Environ.*, vol. 254, p. 111321, Apr. 2024, doi: 10.1016/j.buildenv.2024.111321.

[3] K. Kim and K. Lee, “Indoor Light Environment Factors That Affect the Psychological Satisfaction of Occupants in Office Facilities,” *Buildings*, vol. 14, no. 5, p. 1248, Apr. 2024, doi: 10.3390/buildings14051248.

[4] N. Makaremi, S. Yildirim, G. T. Morgan, M. F. Touchie, J. A. Jakubiec, and J. B. Robinson, “Impact of classroom environment on student wellbeing in higher education: Review and future directions,” *Build. Environ.*, vol. 265, p. 111958, Nov. 2024, doi: 10.1016/j.buildenv.2024.111958.

[5] M. Çelik, A. Didikoğlu, and T. Kazanasmaz, “Optimizing lighting design in educational settings for enhanced cognitive performance: A literature review,” *Energy Build.*, vol. 328, p. 115180, Feb. 2025, doi: 10.1016/j.enbuild.2024.115180.

[6] The Indonesian standard (SNI), *SNI 6197:2020*. Jakarta: The Indonesian standard (SNI), 2020.

[7] A. Zhou and Y. Pan, “Effects of indoor lighting environments on paper reading efficiency and brain fatigue: an experimental study,” *Front. Built Environ.*, vol. 9, Dec. 2023, doi: 10.3389/fbuil.2023.1303028.

[8] T. M. Brown *et al.*, “Recommendations for daytime, evening, and nighttime indoor light exposure to best support physiology, sleep, and wakefulness in healthy adults,” *PLOS Biol.*, vol. 20, no. 3, p. e3001571, Mar. 2022, doi: 10.1371/journal.pbio.3001571.

[9] A. S. J. Wardhana, Zamtinah, T. Sukisno, N. Yuniarti, and M. A. A. Bachrun, “Power Consumption Analysis and Evaluation of Energy Saving Potential of Lighting System in DEF Building,” *J. Edukasi Elektro*, vol. 9, no. 1, pp. 55–65, May 2025, doi: 10.21831/jee.v9i1.85443.

[10] Y. Zeng, H. Sun, and B. Lin, “Optimized lighting energy consumption for non-visual effects: A case study in office spaces based on field test and simulation,” *Build. Environ.*, vol. 205, p. 108238, Nov. 2021, doi: 10.1016/j.buildenv.2021.108238.

[11] J. L. Reyna and M. V. Chester, “Energy efficiency to reduce residential electricity and natural gas use under climate change,” *Nat. Commun.*, vol. 8, no. 1, p. 14916, May 2017, doi: 10.1038/ncomms14916.

[12] C. Skandali and Y. S. Lambiri, “Optimization Of Urban Street Lighting Conditions Focusing On Energy Saving, Safety And Users’ Needs,” *J. Contemp. Urban Aff.*, vol. 2, no. 3, pp. 112–121, Dec. 2018, doi: 10.25034/ijcua.2018.4726.

[13] R. A. Tobeishat and W. Sheta, “Impact of Innovative Lighting Strategies on the Performance of Workplace Environment,” 2024, pp. 282–300. doi: 10.1007/978-3-031-56121-4_28.

[14] C. Jettanasen *et al.*, “An approach to energy conservation in lighting systems using luminaire-based sensor for automatic dimming,” *Sci. Rep.*, vol. 15, no. 1, p. 3302, Jan. 2025, doi: 10.1038/s41598-025-87813-y.

[15] S. Shojaee Barjoee and S. Gendler, “Sustainable illumination: Experimental and simulation analysis of illumination for workers wellbeing in the workplace,” *Heliyon*, vol. 10, no. 24, p. e40745, Dec. 2024, doi: 10.1016/j.heliyon.2024.e40745.

[16] T. Kruisselbrink, R. Dangol, and A. Rosemann, “Photometric measurements of lighting quality: An overview,” *Build. Environ.*, vol. 138, pp. 42–52, Jun. 2018, doi: 10.1016/j.buildenv.2018.04.028.

[17] D. Czyżewski and I. Fryc, “The Influence of Luminaire Photometric Intensity Curve Measurements Quality on Road Lighting Design Parameters,” *Energies*, vol. 13, no. 13, p. 3301, Jun. 2020, doi: 10.3390/en13133301.

[18] Kemahasiswaan Universitas Negeri Yogyakarta, “GEDUNG DIGITAL LIBRARY UNY DIRESMIKAN,” kemahasiswaan.uny.ac.id.

[19] M. Jakubowsky and J. de Boer, “Façade elements for room illumination with integrated microstructures for daylight redirection and LED lighting,” *Energy Build.*, vol. 266, p. 112106, Jul. 2022, doi: 10.1016/j.enbuild.2022.112106.

[20] S. Masoud, Z. Zamani, S. M. Hosseini, and S. Attia, “A Review of Factors Affecting the Lighting Performance of Light Shelves and Controlling Solar Heat Gain,” *Buildings*, vol. 14, no. 6, p. 1832, Jun. 2024, doi: 10.3390/buildings14061832.

[21] L. Dębska and A. Białek, “Lighting conditions as the occupational health related issue – case study,” *MATEC Web Conf.*, vol. 354, p. 00059, Jan. 2022, doi: 10.1051/matecconf/202235400059.

[22] N. Nasrollahi and E. Shokry, “Parametric Analysis of Architectural Elements on Daylight, Visual Comfort, and Electrical Energy Performance in the Study Spaces,” *J. Daylighting*, vol. 7, no. 1, pp. 57–72, Mar. 2020, doi: 10.15627/jd.2020.5.

[23] S. S. Korsavi, Z. S. Zomorodian, and M. Tahsildoost, “Visual comfort assessment of daylit and sunlit areas: A longitudinal field survey in classrooms in Kashan, Iran,” *Energy Build.*, vol. 128, pp. 305–318, Sep. 2016, doi: 10.1016/j.enbuild.2016.06.091.

[24] S. Attia, M. Hamdy, W. O’Brien, and S. Carlucci, “Assessing gaps and needs for integrating

building performance optimization tools in net zero energy buildings design," *Energy Build.*, vol. 60, pp. 110–124, May 2013, doi: 10.1016/j.enbuild.2013.01.016.
[25] C. Velásquez, F. Espín, M. Á. Castro, and F. Rodríguez, "Energy Efficiency in Public Lighting Systems Friendly to the Environment and Protected Areas," *Sustainability*, vol. 16, no. 12, p. 5113, Jun. 2024, doi: 10.3390/su16125113.
[26] J. A. Lobão, T. Devezas, and J. P. S. Catalão, "Energy efficiency of lighting installations: Software application and experimental validation," *Energy Reports*, vol. 1, pp. 110–115, Nov. 2015, doi: 10.1016/j.egyr.2015.04.001.
[27] L. Bellia, F. Diglio, and F. Fragliasso, "Office workers' performance and satisfaction with the luminous environment under standard and daylight mimicking LEDs," *J. Build. Eng.*, vol. 97, p. 110942, Nov. 2024, doi: 10.1016/j.jobe.2024.110942.
[28] Zumtobel, *The Lighting Handbook*. Dornbirn: Zumtobel Lighting, 2018.
[29] P. Pracki, M. Dziedzicki, and P. Komorzycka, "Ceiling and Wall Illumination, Utilance, and Power in Interior Lighting," *Energies*, vol. 13, no. 18, p. 4744, Sep. 2020, doi: 10.3390/en13184744.
[30] L. Akimov, G. De Michele, U. Filippi Oberegger, V. Badenko, and A. G. Mainini, "Evaluation of EN15193-1 on energy requirements for artificial lighting against Radiance-based DAYSIM," *J. Build. Eng.*, vol. 40, p. 102698, Aug. 2021, doi: 10.1016/j.jobe.2021.102698.

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