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Article

Examination of the impact of lighting layout on energy efficiency in the case of open plan office

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ABSTRACT

Lighting plays a significant role in the electricity consumption of buildings. It is widely acknowledged that the key factors influencing minimal energy consumption to meet the requirements of lighting design criteria are lamp efficacy, luminaire efficiency, and lighting control systems. However, the impact of the relationship between luminaire arrangement, luminaire's luminous intensity distribution, and furniture arrangement on energy consumption has not been thoroughly examined. The objective of this study is to develop a method that can be utilized to determine luminaire positions while meeting values recommended in the EN 12464-1 for all occupants of an office based on luminaire's luminous intensity distribution and furniture layout. For this purpose, an open-plan office for 24 individuals, 2 different desk layouts, 3 lighting types, and 19 luminaires with different luminous intensity distributions were considered. In the initial stage of the research, luminaire position options that meet the targeted values for each luminaire and workstation layout (a total of 38 configurations) were determined through trial and error. Subsequently, these options were compared in terms of energy consumption, and the most economical option was identified for each configuration. The total luminous flux required for each configuration was considered in the energy comparison. The configuration where visual comfort requirements were met with the least luminous flux was considered the most economical. It was revealed that the quadruple-desk layout was more economical than the dual-desk layout for all luminaires. In the final stage of the study, the energy usage results for 38 configurations were compared and evaluated.

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INTRODUCTION

According to research by the International Energy Agency (IEA), electricity consumption in commercial and public buildings accounts for 21.2% of total consumption (IEA, 2021). Of the total electrical energy consumed in buildings, 20% is used for lighting. Office buildings occupy a large place among commercial and public buildings. Developments in LED technology and its widespread use are also reflected in office lighting. Efficiency in electric lighting is mainly considered in the context of the use of high-efficacy lamps,

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high luminaire efficiency, and lighting control systems. Nowadays, LEDs are widely acknowledged to be more economical than other alternative light sources (IEA, n.d.). Numerous studies have been conducted to highlight the energy consumption superiority of LEDs (Luewarasirikul, 2015; Kim & Yang, 2022; Pallis et al., 2021; Doulos et al., 2017; Principi & Fioretti, 2014). The significant role of high luminaire efficiency, as well as lamps with high luminous efficacy, in reducing consumed lighting energy is undeniable (Manolis et al., 2019). The luminaire efficiency is dependent on factors such as the materials used and optical design (Tsankov et al., 2022). Another crucial factor influencing energy efficiency is the utilization of lighting control systems (International Commission on Illumination, 2017; Simpson, 2003). Indeed, studies aimed at reducing energy consumption in office lighting are fundamentally focused on the implementation of various lighting control systems. In this context, numerous research works evaluate the impact of various lighting control systems such as personal control (de Korte et al., 2015; Kwon et al., 2019), daylight harvesting (Lu et al., 2010; Vathanam et al., 2021), and occupancy sensing (de Bakker et al., 2017; Pandharipande & Caicedo, 2011; Chraibi et al., 2019; Nagy et al., 2015) on energy conservation. Research has also been conducted on the combined implementation of different lighting control systems in office settings (Galasiu et al., 2007; Soori & Vishwas, 2013; Xu et al., 2017).

However, the parameters essential for the effective use of energy extend beyond lamp efficacy, luminaire efficiency, and lighting control systems. The luminous intensity distribution and placement of the luminaire in relation to the interior design also influence energy consumption. There are numerous luminaires suitable for use in offices. The technical and economic diversity of these luminaires complicates the comparison and evaluation of their features, potentially prolonging the lighting design process. In such cases, the selection among luminaires capable of providing the desired illuminances is often based on justifiable economic constraints such as purchase cost and luminaire efficacy. However, luminaires also vary as to luminous intensity distribution, and the arrangement of desks, including the luminous intensity distribution and position of the luminaire, should be considered in luminaire selection. In this context, establishing a relationship between luminaire's luminous intensity distribution and the task area presents a significant energy-saving opportunity that is often overlooked in contemporary practices.

Energy-efficient lighting cannot be considered independently of the requirements for lighting design criteria set by international standards. The goal should always be to meet these requirements with the most economical solutions. Few studies examined conditions where EN 12464-1 European standard criteria are met with minimal energy consumption (European Committee for Standardization, 2011a; Çelik et al., 2015). Çelik et al. (2015) maintained the positions of desks and luminaires constant in each lighting scenario while comparing different luminaires in terms of energy usage. De Bakker et al. (2018) took a different approach to lighting control related to occupancy detection, suggesting adjusting the illuminance in non-user work areas by dimming the light, thereby adapting to the recommended values for immediate surrounding and background area. In this study, the positions of office work desks and luminaires were also kept constant. Zhou et al., (2023) with the aim of improving lighting energy efficiency in offices, explored the results of placing luminaires at elevation angles ranging from 0° to 180° from the downward vertical, with ±10° steps on both sides, unlike the traditional approach of keeping luminaire openings parallel to the work area. In a research study aiming to provide the required illuminance on vertical display surfaces instead of the horizontal plane in offices, luminaire positions, where optimum results were obtained, were examined based on luminaire luminous intensity distribution, display surface position and size, and the results were compared in terms of energy consumption (Kalelioğlu & Dokuzer Öztürk, 2022).

In the literature, there is no study that comprehensively considers luminaire luminous intensity distribution, luminaire position, interior architectural arrangement, and EN 12464-1 standard requirements as a whole to assess the lighting energy efficiency of offices. This study aims to present a method that can be utilized to determine the luminaire type, luminous intensity distribution, and position that meet the requirements of the EN 12464-1 standard (European Committee for Standardization, 2021) for all users in open-plan offices. Two different interior architectural arrangements and nineteen lighting fixtures were considered, and the positions yielding the most economical results for each luminaire were identified.

LIGHTING CRITERIA FOR OFFICES

According to the actual European standard for lighting indoor work places, EN 12464-1, Table 1 provides the recommended lighting criteria based on the activities undertaken in this study (European Committee for Standardization, 2021).

In addition to the values in Table 1, illuminance on the immediate surrounding area and the background area and illuminance uniformities for these areas are recommended as follows (for task $\bar{E}_m$: 500 lx):

Immediate surrounding area: $\bar{E}_m$ (required): 300 lx, U_o: 0.40

Background area: $\bar{E}_m$ (required): 100 lx, U_o: 0.10

Table 1. Visual comfort criteria for offices

Type of task/activity area	$\bar{E}_m$ lx required	$\bar{E}_m$ lx modified	U_o	R_a	R_{UGL}	$\bar{E}_{m,z}$ lx $U_o \geq 0.10$	$\bar{E}_{m,wall}$ lx $U_o \geq 0.10$	$\bar{E}_{m,ceiling}$ lx $U_o \geq 0.10$
Writing, typing, reading, data processing	500	1000	0.60	80	19	150	150	100

$\bar{E}_m$ (required): minimum maintained average illuminance on the reference surface; $\bar{E}_m$ (modified): maintained average illuminance considering common context modifiers on the reference surface; U_o: minimum illuminance uniformity on the reference surface; R_a: minimum colour rendering index; R_{UGL}: Unified Glare Rating limit; $\bar{E}_{m,z}$: maintained cylindrical illuminance at eye height (1.20 m) including task and immediate surrounding area; $\bar{E}_{m,wall}$: maintained average illuminance on walls; $\bar{E}_{m,ceiling}$: maintained average illuminance on ceilings.

METHOD

In open-plan offices, numerous factors determine lighting energy efficiency. For each of these factors, multiple values can be established. However, in order to obtain meaningful and interpretable results, it is necessary to limit the number of variable factors. In this research, the factors have been categorized into constant and variable groups. The methodology of the study involves determining the values to be considered for constant and variable factors as well as analyzing the results of calculations for various combinations of these values. The steps of the research methodology are as follows:

- Assumptions related to constant factors
- Determination of variable factors
- Defining the calculation approach
- Execution of calculations

The following sections elaborate on the examinations conducted and the decisions made within each step.

Assumptions Related to Constant Factors

Within the scope of the study, an open-plan office for 24 occupants was designed. Existing office plans and architectural design guidelines were consulted for the office design (Buxton, 2018; Chiara et al., 1991; Crane & Dixon, 1991; Duffy et al., 1977). Constant factors related to the room and lighting criteria are listed below.

Constant Values Related to the Room

- Number of occupants: 24
- Office space length, width, and height: 27 m, 7.5 m, 3.25 m
- Window location: One long wall of the room
- Joinery width, reflectance, and spacing between mullion axes: 0.1 m, 70%, and 1.35 m
- Location of the joinery within the wall section: In the inner part of the wall section facing the office space
- Reflectance of the window glass: 10%
- Reflectance of walls, ceiling, and floor: 80%, 90%, 60%
- Desk dimensions and reflectance: 0.80 m x 1.60 m x 0.72 m (European Committee for Standardization, CEN 527-1:2011b), 70%
- Distance of the luminaires from the floor (Luminaire height): 2.75 m
- Cabinet dimensions and reflectance: 0.80 m x 0.40 m, 70%

Constant Values Related to the Lighting Criteria

In the context of office lighting alternatives, the objective was to achieve the illumination criteria provided in Table 1, and lighting schemes that meet these criteria were taken into consideration in the evaluation. Daylighting was excluded from the scope of the study. Calculation surfaces were established for each of the 24 occupants in the office in terms of task area, immediate surroundings area, background area, cylindrical illuminance, and direct glare (Figure 1).

- Task area (width, length, height, and position): 60 cm, 60 cm, 72 cm, and centered on the user's side of the desk surface (Figure 1, dark blue) (Figure 7 and 8, pale blue).
- Maintained average illuminance on task areas: 500 lx
- Height, width, and position of the immediate surroundings: Same height as the task area (72 cm), with a 50 cm wide band surrounding this area (Figure 1, light blue)
- Size and location of the background area: The area on the floor surface, 50 cm from the walls and surrounding the projection of the immediate surrounding

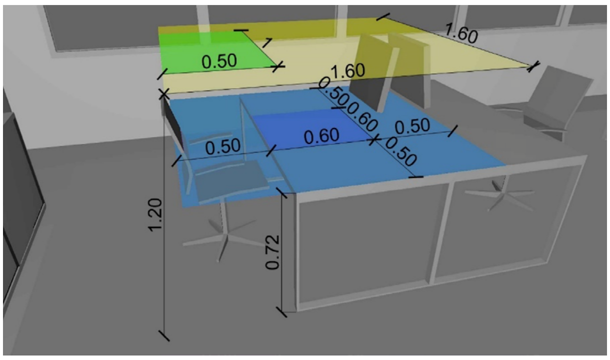

Figure 1. Position of the calculation surfaces.

- Width, length, height, and position of the cylindrical illuminance calculation surface: 160 cm, 160 cm, 120 cm, covering the projections of the task area and the immediate surrounding area (Figure 1, yellow)
- Width, length, height, and position of the calculation surface for Unified Glare Rating: 100 cm, 50 cm, 120 cm, adjacent to the projection of the task area, centered next to the table. The value (RUG) of Unified Glare Rating (UGR) is calculated for the ±90° viewing angle in the main viewing direction (Figure 1, green)

Determination of Variable Factors

Determinations regarding the variable factors of the study have been addressed under the following headings:

- Interior design
- Luminaire type
- Luminaire position

Interior Design

Fundamental architectural design books such as Neufert Yapı Tasarımı,Time-saver Standards, and Metric Handbook, as well as published books on the subject such as Planning Office Space, Architects' Data Sheets: Office Spaces, and architectural plans and furnishings of sample open-plan offices were examined in terms of dimensions, form, and user count (Neufert, 2000; Chiara et al., 1991; Buxton, 2018; Duffy et al., 1977; Crane & Dixon, 1991). In today's open-plan offices, user counts vary widely. Based on the average user count in the examined offices, a standard office for 24 people was designed. In the office room, two different furniture layouts were created, in which work desks were arranged in pairs and quads (Figure 2).

Luminaire Type

A total of 19 LED luminaires, including indirect-direct (3), semi-direct (6), and direct lighting (10) types, which are suitable for office lighting, were considered. Four of the direct lighting luminaires are square-shaped, while the remaining fifteen are rectangular. The characteristics of the luminaires are presented in Figures 3-6. The tables include the luminous intensity distribution, power (W), total luminous flux (lm), color temperature (CCT), and color rendering index (CRI) of the luminaires.

In the tables, luminaires are expressed as the following:

RID: Rectangular-shaped indirect-direct luminaire

RSD: Rectangular-shaped semi-direct luminaire

RD: Rectangular-shaped direct luminaire

SD: Square-shaped direct luminaire

Luminaire Position

The distance of luminaires from the floor has been kept constant at 2.75 m in all lighting configurations. A total of 627 luminaire layout alternatives were studied through three lighting types and nineteen luminaires. In all luminaire layout alternatives, luminaires were positioned parallel to the line of sight. To prevent reflected glare, luminaires were avoided from being placed perpendicular to the line of sight. In line with the objectives of the study, the positioning of luminaires to meet visual comfort requirements with minimum energy consumption has been examined through trial and error, separately for each luminaire and both interior design configurations.

In the initial phase of the study:

a. One luminaire was initially placed on the projection of the geometric center of the task areas (shown in pale blue in Figures 7 and 8, 0.60 m × 0.60 m) for both interior design configurations.
b. For both interior design configurations, two luminaires were initially placed on the projection of the right and left boundary of the task area (a total of 2 luminaires for a table).
c. For the layout of quadruple desks, one luminaire was initially placed on the projection of the junction of two adjacent desks and one luminaire for each on the projection of the right (or left) boundary of the task area of these desks.

Subsequently, for the b and c luminaire configurations, the luminaires were shifted towards the edges of the desk in 5 cm increments. Although it is possible to place square luminaires at different positions than rectangular luminaires, for the sake of ease of comparison, different positions were not considered. Some examples of the studied luminaire positions are shown in Figures 7 and 8. The luminaires are depicted in yellow in the figures, and

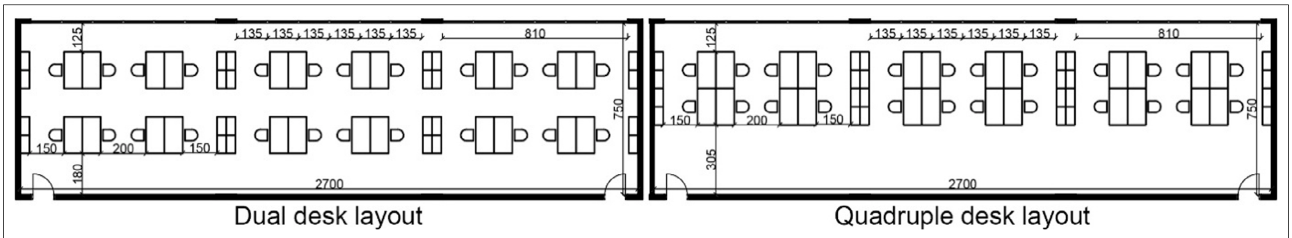

Figure 2. Workstation layouts.

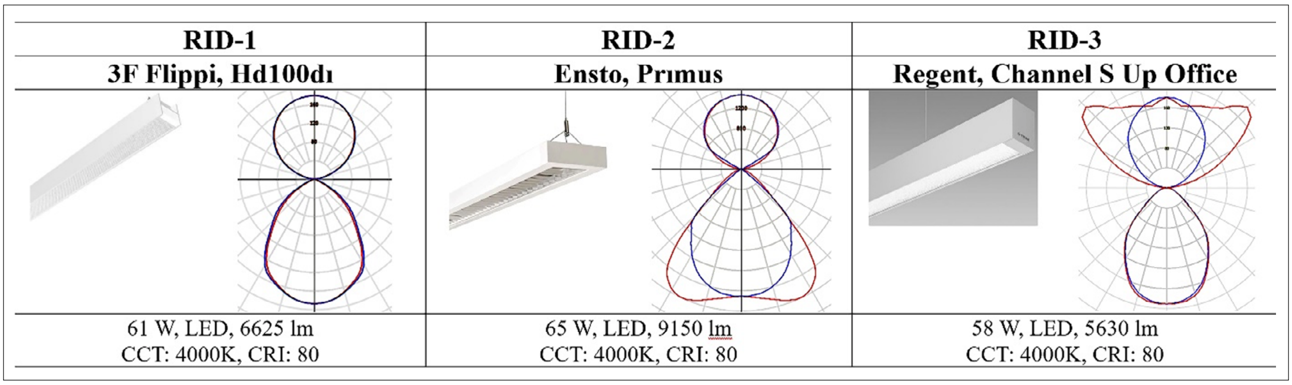

Figure 3. Indirect-direct luminaires.

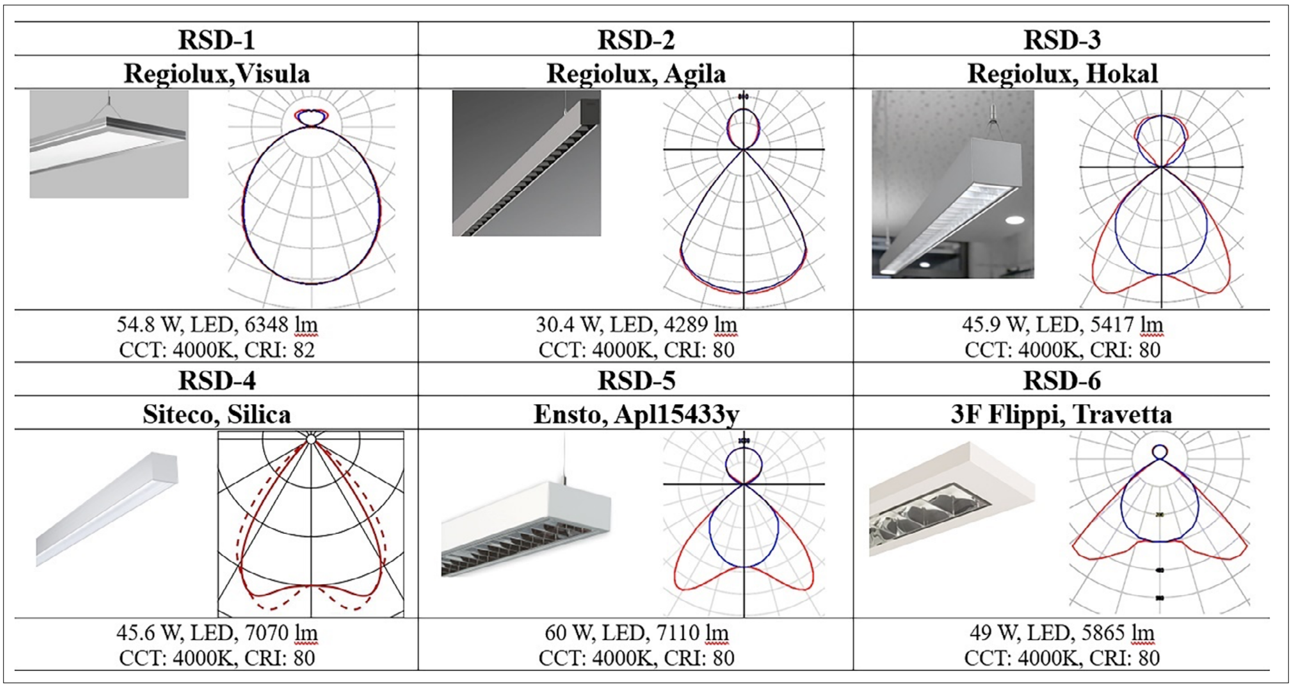

Figure 4. Semi-direct luminaires.

their positions are indicated by specifying the distances from the projection of the task area center shown in pale blue in Figures 7 and 8. This distance is zero for a luminaire located, for example, at the projection of the task area center, and 30 cm for a luminaire located at the projection of the right (or left) boundary of the task area.

In the second stage of the investigation regarding luminaire positioning, for each of the a, b, and c configurations, luminaires were shifted in increments of 2.5 cm in the direction of and opposite to the line of sight while maintaining their positions relative to the task area (Figures 7-8). An example of this shifting is illustrated in Figure 9. The direction of luminaire shifting varied for each desk, and the optimal shifting distance differed based on the desk's position to achieve the most favorable outcome. An example of shifting luminaires in the line of sight and vice versa for achieving the most favorable outcome with the RD-3 luminaire in the dual desk layout is provided in Figure 5. The arrows in the figure indicate the direction of luminaire shifting, and the average illuminance achieved on the task area of each desk is specified.

CALCULATION RESULTS

Within the scope of the study, numerous simulations were conducted using the validated DIALux evo program to examine the optimal luminaire positions for nineteen luminaires and two desk layout configurations, totaling thirty-eight office lighting alternatives (Figures 7-8) (Rizki A. Mangkuto, 2015). Among these, the configurations in which the recommended values in the EN 12464-1 standard (Table 1) were met with minimum energy consumption are presented in this section.

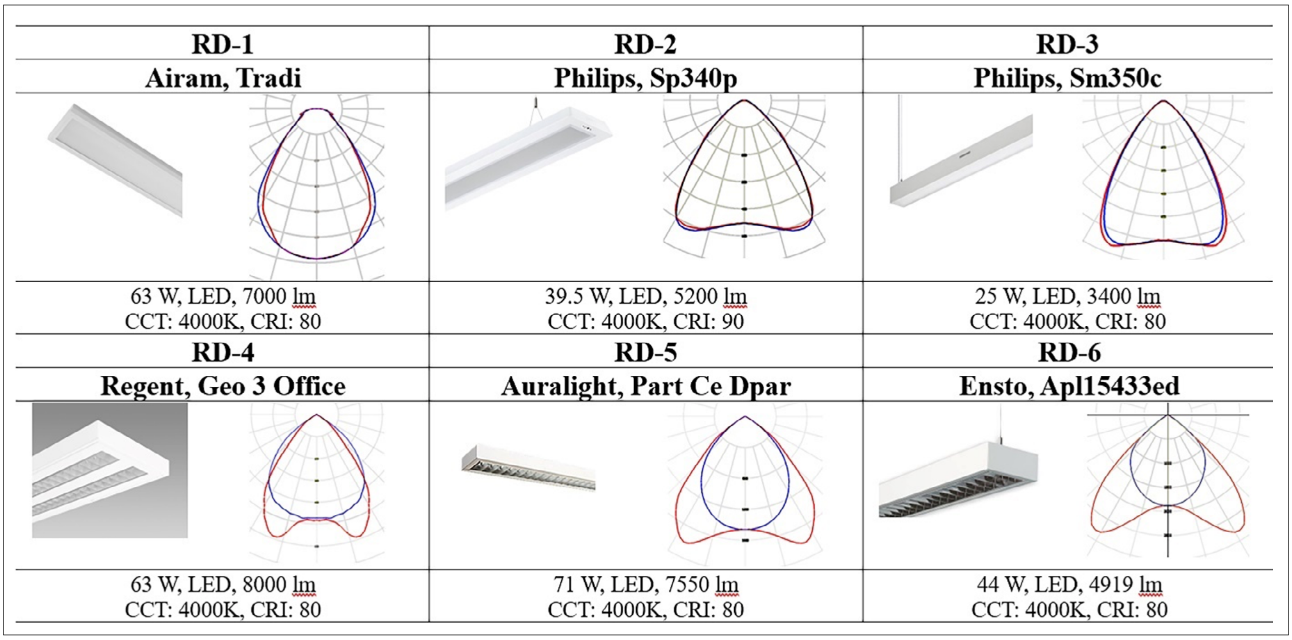

Figure 5. Rectangular shaped direct luminaires.

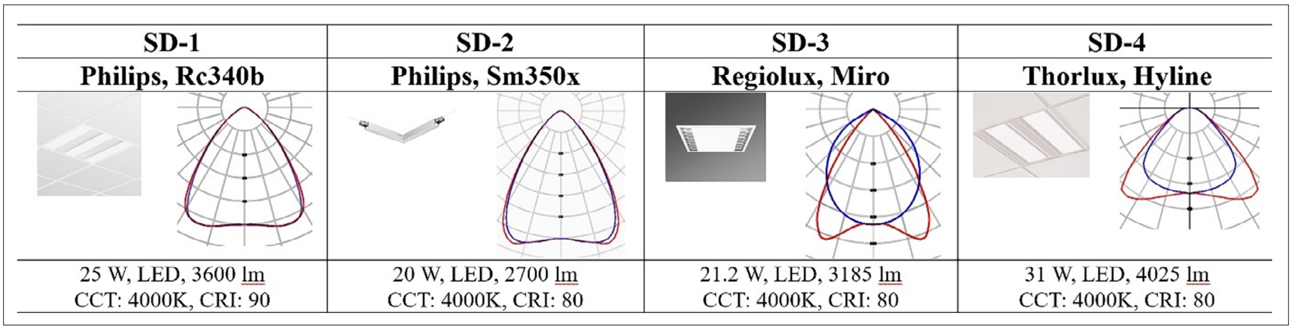

Figure 6. Square shaped direct luminaires.

In the comparison for minimum energy consumption, the quantity of luminous flux emitted from luminaires was taken into consideration. This approach prevented the influence of lamp efficacy and luminaire efficiency in the comparison. Thus, the impact of design decisions regarding luminaire shape (rectangular, square), lighting type (direct, semi-direct, indirect-direct), and luminaire position on lighting energy consumption was evaluated. To make the energy consumption comparison meaningful, the desks with the lowest illuminance in the office were identified, and the luminous flux from the luminaires was adjusted to achieve an average illuminance of 500 lx on the task areas of these desks as much as possible. Following this adjustment, the total luminous flux from all luminaires in the space was used as the basis for the comparison. The range of task area illuminances, range of UGR values for all desks, and the required total luminous flux for dual and quadruple desk layouts, based on lighting type and luminaire position, are presented in Tables 2-4. The luminaire configurations of values given are marked with an asterisk (*) in Tables 2-4.

Regarding the indirect-direct lighting type, the most favorable outcome for both dual and quadruple desk layouts was achieved when a single luminaire was located at the projection of the task area center (configuration a). According to the comparison for meeting visual comfort requirements with minimum energy consumption, the most favorable luminaire for the dual desk layout was RID-1, followed by RID-2 and RID-3, respectively. In this respect, the ranking was RID-2, RID-1, and RID-3 for the quadruple desk layout

Concerning the semi-direct lighting type, the most favorable outcome regarding luminaire positioning varied based on luminaire type and desk layout, as seen in Table 3. The luminaire RSD-1 provided the most favorable result in ‘configuration a’ for both dual and quadruple desk layouts. However, for other semi-direct lighting luminaires, the most favorable results were mainly yielded in configuration b for the dual desk layout and mainly in configuration c for the quadruple desk layout. Moreover, the distance by which luminaires, placed at the projection of the right

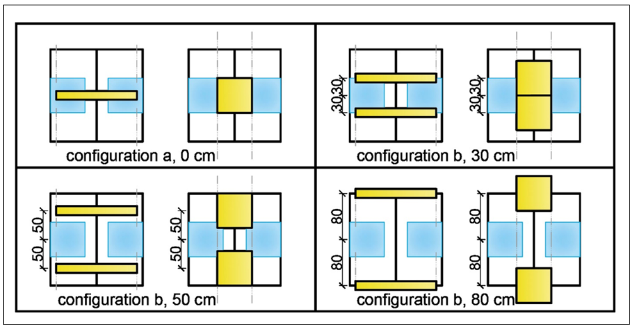

Figure 7. Luminaire configuration examples for dual desk layout.

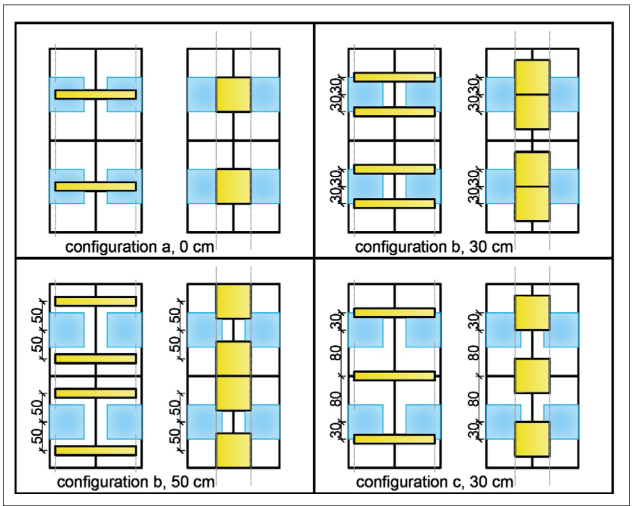

Figure 8. Luminaire configuration examples for quadruple desk layout.

and left boundary of the task area (configuration b), were shifted toward the edges of the desk varied depending on the luminaire type. In the quadruple desk layout, for instance, the distance for shifting the luminaire, placed at the projection of the right (or left) boundary of the task area (configuration c), toward the edge of the desk was 30 cm. For some cases, the distance by which the luminaire was shifted toward the edge of the desk was not a single measure but a range. For example, for the luminaire RSD-3 in the dual desk layout, when shifted toward the edge of the desk in configuration b by, 65 cm, and 70 cm (65 cm-70 cm), the required total luminous flux remained the same. Similar situations were observed in which different luminaire configurations resulted in the same required total luminous flux. In the quadruple desk layout, shifting the luminaire RSD-5 in configuration c by 30 cm and in configuration b by 30 cm-50 cm yielded the same result. In the comparison performed for effective energy use, the luminaire RSD-2 ranked first in the dual desk layout, followed by RSD-4, RSD-6, RSD-3, RSD-1, and RSD-5, respectively. In this context, the ranking for the quadruple desk layout was RSD-2, RSD-4, RSD-6, RSD-3, RSD-5, and RSD-1. For the most economical result, luminaire RSD-2, under the condition of being located in "configuration a, 0 cm", different from the locations stated in Table 3, further reduced the required total luminous flux for both desk layouts. However, in these cases, the RUGL value exceeded 19 for some desks, indicating that visual comfort could not be fully achieved for all desks.

In the direct lighting type, the most advantageous outcome regarding luminaire positioning varied based on luminaire type and desk layout, as seen in Table 4. For both dual and quadruple desk layouts, configuration a for RD-1, and configuration b for RD-5 and RD-6 generated the best results. Generally, for other luminaires, configuration a in the dual desk layout and primarily configurations b and c for the quadruple desk layout resulted in the most convenient outcomes. The distance by which luminaires were shifted toward the edges of the desk at the most beneficial luminaire positions varied depending on the luminaire type. In the dual desk layout, the findings obtained for SD-1, SD-2, and SD-3 were the same in two different configurations. Similarly, in the dual desk layout, the result remains the same for the RD-5 luminaire when shifted toward the edge of the desk within the range of 30 cm to 80 cm. Likewise, in the quadruple desk layout, the result remains unchanged

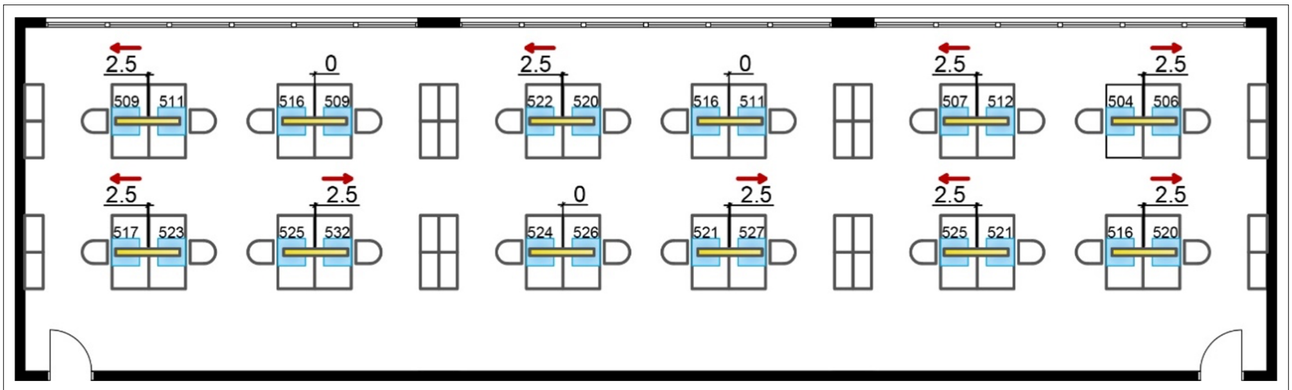

Figure 9. Example of shifting luminaires in the direction of the line of sight and vice-versa in a dual desk layout: RD-3, configuration a, 0 cm.

when shifting the RD-6 luminaire toward the edge of the desk within the range of 30 cm to 50 cm. In the comparison conducted for minimum lighting energy consumption, the ranking from most favorable to least favorable is SD-2, RD-3, SD-1, RD-2, RD-1, SD-3, RD-4, RD-6, RD-5 for the dual desk layout, and SD-2, RD-3, SD-1, SD-3, RD-2, RD-1, RD-4, RD-5, RD-6 for the quadruple desk layout. The RD-6 luminaire, which is at the end of the ranking for the quadruple desk layout, requires less luminous flux when placed in "configuration a, 0 cm", as opposed to the positions stated in Table 4. However, in this arrangement, the RUGL value exceeds 21 for some desks, indicating that visual comfort is not fully enabled for all desks.

EVALUATION AND CONCLUSION

Within the scope of the study, nineteen luminaires suitable for office use and covering three different lighting configurations were considered, along with two distinct desk layouts. For each combination of luminaire and desk layout (a total of 38 configurations), the optimal luminaire placement was examined. Luminaire placement meeting the targeted visual comfort criteria with minimum energy consumption was deemed favorable. The comparison in terms of energy consumption was based on the required luminous flux quantity for each lighting configuration. The configuration where visual comfort requirements were met with the least luminous flux was considered the most economical configuration.

This approach considers only the energy consumption during the use of the lighting system. Factors influencing the total cost of a lighting system are certainly not limited to this. For a comprehensive cost comparison, factors such as the number of luminaires, purchase cost, installation of luminaires, and expenses related to electrical installations must also be considered. Additionally, the amount of luminous flux emitted in relation to the power consumed by luminaires is crucial for effective energy use. On the other hand, numerous luminaires are available for office lighting; hence, factors such as lamp efficacy, luminaire efficiency and appearance, and compatibility with interior design have been excluded when selecting the appropriate luminaires in this study. Thus, the configurations under which the most favorable results are obtained have been explored by investigating the relationship between the luminous intensity distribution of luminaires and desk layout.

The evaluation of the results can be conducted as follows:

- Generally, less energy is consumed in direct lighting compared to the other two types of lighting. This result is parallel to the findings of Çelik et al. (2015). That is, the required luminous flux according to the lighting type was, as expected, the lowest in direct lighting, followed by semi-direct lighting and indirect-direct lighting respectively. In this comparison, the average of the required luminous fluxes was considered on the lighting type scale. For instance, in the indirect-direct lighting type, the average of the required luminous flux for RID-1, RID-2, and RID-3 luminaires was considered (Table 2). In other words, this ranking is not applicable for each luminaire within a lighting type. When comparing on a single luminaire scale, the required luminous flux, for example, was 61608 lm for RD-5 in the direct lighting of the dual desk layout, 49631 lm for RSD-4 in the semi-direct lighting of the quadruple desk layout, and 57096 lm for RID-2 in the indirect-direct lighting of the quadruple desk layout (Tables 3-4).
- In all considered luminaires, the required luminous flux in the quadruple desk layout is lower than in the dual desk layout. On average, 20% less luminous flux is needed in direct lighting, 21% less in semi-direct lighting, and 18% less in indirect-direct lighting in the quadruple desk layout. In other words, the quadruple desk layout is more advantageous in terms of energy consumption.
- Comparison within luminaires providing indirect-direct lighting: Considering all the results obtained for configurations a, b, and c, the most successful outcomes were achieved with the RID-2 luminaire, which emits direct light into the widest angle, in both desk layouts. The RID-3 luminaire, which emits direct light into the narrowest angle, ranked third in the success ranking. The beam angle of downward-emitted light in the indirect-direct lighting type proved to be decisive for the results. Another conclusion drawn from the results is that the most favorable luminaire position in this lighting type is the 'configuration a'.
- Comparison within luminaires providing semi-direct lighting: When considering all the results obtained for configurations a, b, and c, the most favorable outcomes were achieved with the RSD-2 luminaire in both desk layouts. This was followed by RSD-4 and RSD-6. The positive outcome were obtained by positioning the RSD-2 and RSD-4 luminaires 30 cm away from the projection of the center of the task area, as their downward luminous intensity distributions were similar. For the RSD-6 luminaire, whose downward beam angle is the widest, achieving economical results required the luminaires to move away from the center of the task area in the case of the dual desk layout. In the case of the quadruple desk layout, the RSD-6 luminaire needed to be located at the projection of the task area center. The RSD-1 and RSD-5 luminaires shared the last two ranks in the success ranking. Consequently, luminaires with a downward spatial distribution of luminous intensity resembling a sphere (RSD-1) were considered

Table 2. Indirect-Direct Luminaires

Luminaire type	Dual desk layout				Quadruple desk layout			
	Luminaire configuration type	$\bar{E}_m$ (lx)	R_{UGL}	Required total flux (lm)	Luminaire configuration type	$\bar{E}_m$ (lx)	R_{UGL}	Required total flux (lm)
RID-1	config. a, 0 cm	502-533	14.1-14.9	70755	config. a, 0 cm	507-531	14.3-14.7	60420
RID-2	config. a, 0 cm	506-541	15.7-16.7	74664	config. a, 0 cm	501-521	16.6-17.0	57096
RID-3	config. a, 0 cm	502-543	13.6-14.3	76344	config. a, 0 cm	508-534	13.4-13.7	64182

Table 3. Semi-Direct Luminaires

Luminaire type	Dual desk layout				Quadruple desk layout			
	Luminaire configuration type	$\bar{E}_m$ (lx)	R_{UGL}	Required total flux (lm)	Luminaire configuration type	$\bar{E}_m$ (lx)	R_{UGL}	Required total flux (lm)
RSD-1	config. a, 0 cm	500-533	16.0-17.1	70844	config. a, 0 cm	503-525	16.3-17.1	58656
RSD-2	config. b, 30 cm	500-529	17.9-18.4	52510	config. c, 30 cm	505-520	17.8-18.1	43243
RSD-3	config. b, 65 cm-70 cm*	503-527	14.8-15.7	70204	config. c, 30 cm	508-525	15.5-16.1	54603
RSD-4	config. b, 30 cm	506-543	16.1-16.6	62782	config. c, 30 cm	510-527	16.2-16.6	49631
RSD-5	config. b, 80 cm	507-540	15.7-16.5	73375	config. c, 30 cm; config. b, 30 cm-50 cm*	501-518	15.6-16.0	56311
RSD-6	config. b, 90 cm*-100 cm	500-529	15.6-16.8	67565	config. a, 0 cm	500-518	18.2-19.0	50674

Table 4. Direct Luminaires

Luminaire type	Dual desk layout				Quadruple desk layout			
	Luminaire configuration type	$\bar{E}_m$ (lx)	R_{UGL}	Required total flux (lm)	Luminaire configuration type	$\bar{E}_m$ (lx)	R_{UGL}	Required total flux (lm)
RD-1	config. a, 0 cm	507-532	16.0-17.9	50400	config. a, 0 cm	503-517	15.3-17.4	42840
RD-2	config. b, 30 cm	506-530	16.3-16.5	48672	config. c, 30 cm	501-519	15.7-16.0	41184
RD-3	config. a, 0 cm	504-532	18.4-18.8	45696	config. c, 30 cm	500-516	15.6-15.8	37944
RD-4	config. b, 50 cm	501-526	15.5-16.1	57600	config. c, 30 cm	502-526	15.9-16.3	44640
RD-5	config. b, 30 cm*-80 cm	504-532	16.4-16.8	61608	config. b, 50 cm	500-519	16.3-16.6	45300
RD-6	config. b, 90 cm	501-525	18.0-18.9	60221	config. b, 30 cm*-50 cm	501-525	17.7-18.1	47232
SD-1	config. a, 0 cm	501-529	17.9-18.3	49248	config. a, 0 cm*; config. b, 30 cm	501-520	17.2-17.7	40176
SD-2	config. a, 0 cm	503-524	18.6-19.0	41148	config. c, 30 cm; config. b, 50 cm*	500-517	14.6-15.0	34992
SD-3	config. a, 0 cm	502-530	16.2-17.0	52356	config. b, 45 cm	500-514	12.9-13.3	40513
SD-4	config. a, 0 cm	500-529	16.4-17.2	65208	config. a, 0 cm	500-518	15.9-16.7	48300

unsuitable for both desk layouts. The big difference between luminous intensity at the luminaire axis and maximum luminous intensity, along with a little angle between the direction of maximum luminous intensity and the luminaire axis (RSD-5), is also unfavorable for the considered desk layouts. Although the distribution of luminous intensity of the RSD-3 luminaire is similar to that of the RDS-5 luminaire, the difference between luminous intensity along the luminaire axis and maximum luminous intensity is less.

- Comparison within luminaires providing direct lighting: When evaluating all the results obtained for positions a, b, and c, it was observed that, in both desk layouts, the SD-2 square luminaire provided the most favorable results. Following this, the rectangular RD-3 luminaire and the square SD-1 luminaire were in order. The spatial distribution of luminous intensity of these three luminaires was very similar, and they needed to be positioned in the 'configuration a, 0 cm' for the dual desk layout. However, in the case of the quadruple desk layout, the luminaire positions yielding the most favorable results differed (Table 4). The luminaires SD-4, RD-5, and RD-6 ranked at the bottom three in success. It can be noted that these three luminaires share the common characteristic of having a big angle between the direction of maximum luminous intensity and the luminaire axis. Comparing the required luminous flux averages for square luminaires with those for rectangular luminaires, it can be stated that square luminaires are more economical in both desk layouts. On the other hand, among the total of ten luminaires providing direct lighting, the least favorable result was obtained with the SD-4 square luminaire. The conclusion to be drawn from this is that the luminous intensity distribution and the luminaire position are more decisive factors for the results achieved than the luminaire shape. This conclusion is consistent with Kalelioğlu & Dokuzer Öztürk (2022).

The decision regarding the luminous intensity distribution of the luminaire to be used in illuminating an office should be made considering the interior design. This study examined optimal luminaire positions based on the luminous intensity distribution of luminaires and desk layout to achieve the most economical results. The presented data in this research provides valuable insights into lighting design for the considered 19 luminaires and 2 desk layouts. It is evident that the results of this study can be applied to spaces with different functionalities having desk layouts similar to the ones examined in this research. Furthermore, for conditions where the desk layout and/or luminous intensity distribution of luminaires differ from the examples in this article, the most economical decisions can be made following the approach outlined in the study.

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