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Effect of Luminaries' Arrangement and Type on Visual Comfort and Energy Consumption

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Abstract: The current study seeks to evaluate the effect of luminaries' arrangement and type on visual comfort and energy consumption. Two identical classrooms with different luminaries' arrangements were selected to evaluate the efficacy of the existing lighting system in terms of illuminance uniformity, unified glare rating, and installed load efficacy ratio. DIALux Evo software validated against measured illuminance then employed to assess other suggested luminaries' arrangement and replacing the existing fluorescent lamp with LED type to recommend the best scenario. The findings of the study indicate that the Luminaries' arrangement and type are decisive factors that affect visual comfort and save energy wastage. Accordingly, we recommend distributing the luminaries in a way that the number of rows equals the number of columns and consider the longitudinal length of the luminaire to be parallel to the longitudinal length of the illuminated space. Field measurements revealed that the existing lighting system does not offer visual comfort for occupants and simulation findings recommend using LED luminaries in classrooms to ensure visual comfort and save energy wastage up to 50%.

Keywords: Visual Comfort, Energy Consumption, Illuminance Uniformity, Unified Glare Rating, DIALux evo.

1 Introduction

The United Nations Environment Program (UNEP) revealed that up to 40% of the global energy is consumed in the building sector [1]. Artificial Lighting systems consume between 20 - 45% of the electrical consumption in a building to provide the occupant with comfortable vision [2]. In Bahrain, which is one of the Gulf Cooperation Council (GCC) countries, this percentage is extremely close to the global value with 46% according to the action plan of Bahrain's sustainable energy unit [3].

Visual comfort is defined as "a subjective condition of visual well-being induced by the visual environment" [4]. Visual comfort has a decisive impact on occupants' performance, mood, and functionality, in this regard some researchers focused on student's health, wellbeing, learning, and visual performance [5], others found insufficient illuminance level leads to disrupt human rhythms, safety, and health [6]. Visual comfort indices such as illuminance uniformity (U_o) and unified glare rating (UGR) can be used to optimize processes of integrated design of buildings, and consequently energy saving [7]. Many studies were carried to optimize lighting performance and minimize the energy consumption that is consumed in illuminating interior environments artificially, and to be aligned with the global concern to minimize global warming issues and mitigate environmental pollutants [8, 9]. One of the cost-effective strategies is to use daylight as a tool to minimize the artificial lighting demand and provides occupants with good health [10].

Architects can save their buildings energy consumption by using passive techniques related to building design optimization such as the effect of building orientation, glazing material, window to wall ratio on daylight factor percentage [11-13].

A computational study employed the DIALux evo software to be validated against field measurements carried by Makaremi et al. [14] to assess the relationship between visual comfort indices and interior surfaces' reflectance, the study showed that walls reflectance steeply can improve the illuminance uniformity (U_o) and controls the unified glare

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rating (UGR). Furthermore, some studies [2, 15] focused on replacing traditional luminaires with light-emitting diodes (LEDs) to improve visual comfort and minimize the energy consumption of indoor artificial lighting. Ciampi et al. [16] studied five retrofitting strategies were replacing existing luminaires with efficient luminaries, using different arrangement, using different type and arrangement, manipulating mounting height, and using a different ratio between glass to window area to improve the lighting system of an office with the lighting energy numeric indicator (LENI) index. The findings indicated to reduce the energy consumption it's suggested to reduce the mounting height, and use colors with high reflectance help to reduce LENI value. Makaremi et al. [17] studied the effect of mounting height, luminaires type, number, and surface finishing on visual comfort, the study provided different lighting strategies to save energy by using DIALux evo software. The findings revealed that the decisive parameter that affects quantity and quality of lighting system is the type of luminaire. In addition, increasing the surface reflectance can save system energy up to 45%.

In classrooms, the absence of visual comfort drives to inability of achieving the learning outcomes because it lacks learners' health, productivity, and wellbeing. Many studies evaluate the illuminance quality inside educational environments. Ibañez et al. [18] analyzed the luminous comfort by using HDR (high dynamic range) picture and digital lux meter inside technical drawing classroom, results showed around noon time the illuminance was adequate associated with glare near windows. Doulos et al. [19] examined different lighting technologies with AC and DC supply with daylight harvesting systems. The study aimed to reduce energy consumption and carbon dioxide emissions inside the classroom by controlling the daylight. Another study [20] carried in ninety classrooms illuminated by fluorescent luminaires with 100 Hz flicker, showed 80% of these classrooms affected students with headaches and insufficient visual quality, in addition, the authors revealed the ceiling-mounted data-projector caused specular reflection which led to disability glare and visual discomfort. Gou et al [21] compared between naturally-lit and artificially-lit environments, the study recommended daylight illuminated classroom rather than artificially illuminated due to the significant change in the students' mood, the study discussed the impact of incident asymmetry light and heat associated with daylight on performance and suggested suitable daylighting design.

In real life, some applications/buildings depend dramatically on artificial lighting rather than daylight such as museums, conference rooms, and galleries. In addition, some building lacks the availability of daylight in the high portion of its interior space due to many reasons such location, orientation, poor design, and functionality. In this study, we selected the Gulf University (GU) campus which is located in the Kingdom of Bahrain, as GU offers nighttime lectures and exams in educational environments that are artificially illuminated. Many lectures and exams were conducted after the sunset on GU campus. These considerable number of sessions draw our attention to study the performance of existing lighting system efficacy by evaluating the visual comfort and energy consumption. We studied the effect of luminaires' arrangement and the type of luminaries of the artificial lighting system in order to achieve learners' performance, functionality and eventually to decrease energy wastage.

2 Methodology

To evaluate the extent to which learners are exposed to inadequate sources of visual comfort in a learning environment with highly wasted energy. We selected two typical classrooms namely (103) and (104) located on the first floor at Gulf University in the Kingdom of Bahrain, illuminated by ceiling-mounted fluorescent lamps as shown in Fig. 1a, Fig. 1b, and Fig. 1c with a different arrangement of luminaries as shown in Fig. 1d. To study the effect of luminaires arrangement of artificial lighting system on visual comfort and energy consumption.

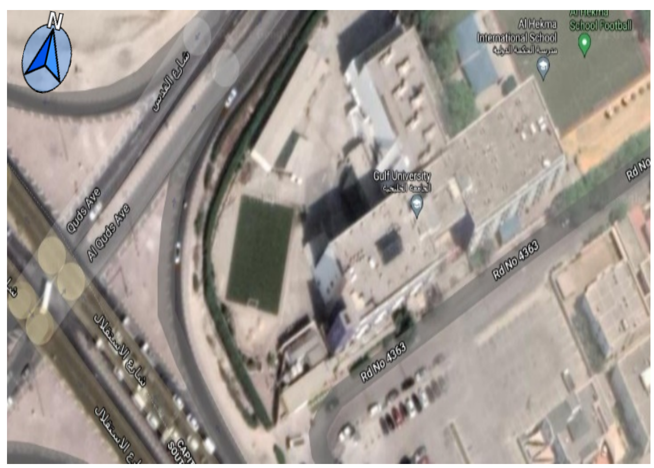


Fig. 1a: A google map view for Gulf University, Kingdom of Bahrain where Latitude: 26° 15' N, and Longitude: 50° 57' E.

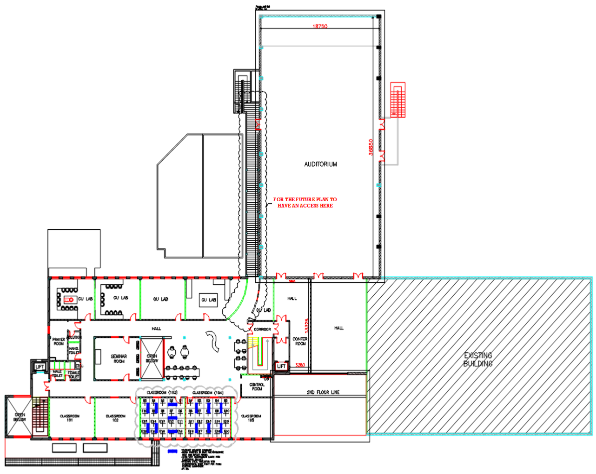


Fig. 1b: Plan view of the first floor at Gulf University (not to scale).

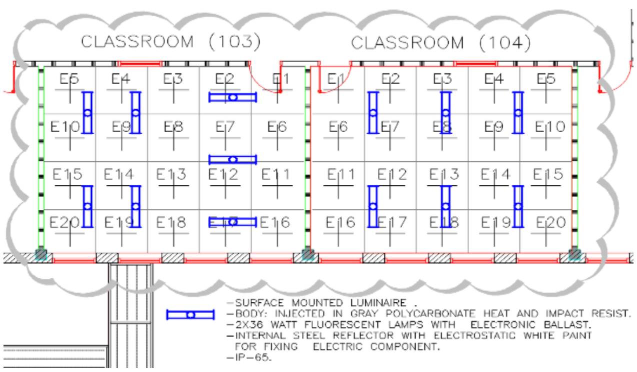


Fig. 1c: Plan view of classrooms (103), and (104) on the first floor at Gulf University (not to scale).

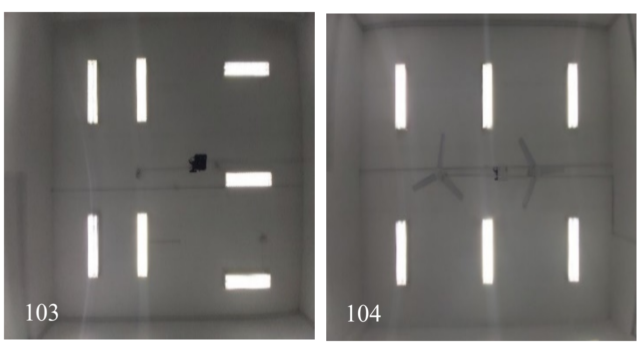


Fig. 1d: Luminaries' arrangement of classrooms (103), and (104).

Moreover, we assessed the visual comfort indices including illuminance uniformity (U_o), and unified glare rating (UGR). We evaluated many arrangements and replaced the existing luminaires with LED type to select the best scenario that can reduce energy consumption by calculating the Installed Load Efficacy Ratio (ILER) and ensure visual comfort according to the aforementioned indices.

2.1 Test Room Setup

We prepared the test room for illuminance measurement and divided the measurement plane into equal areas. First, we calculated the room index "K" which is a function of the space geometry to find the required number of measurement points for adequate characterization of artificial illuminance. Room index is required to achieve green lighting design [22]. The classroom floor length equals 7.0 m, width equals 5.9 m, and height equals 3.3 m, therefore the room index equals (K=1.26) from equation (1).

$$K = (L\times W) / (H_m\times (L+W)) \quad (1)$$

Where: K is room index, L is length, W is width, and H_m is the height of the luminaries above the illuminance measurement plane.

2.2 Experimental Measurement of Illuminance

We followed the CIBSE method in our research, as it widely used in UK practice and aligned with the recommendation of the CIE guide to interior lighting [23]. The concept is to divide the working plane into nearly equal squares as possible (in this study equals 1.4 × 1.46 m), then to measure the illuminance at the center of each square. Table 1 gives a relationship between the room index and the number of measurement points for given degrees of accuracy under the limitation of maximum spacing to mounting height ratio (S/H) less than 1.5:1, (in this research S/H <1.5). After we calculated the room index (K=1.26), we used Testo 400 [24] device which was connected to lux meter probe as shown in Fig. 2a, and Fig. 2b to measure illuminance at the working plane of desk level (75 cm from floor level) in both classrooms at (20) locations "E1-E20" as shown appendix (1). Table 2 shows the specifications of the used lux probe in this study.

In order to accurately model the test room, four factors were considered. First, we carried all experiments after sunset and covered all windows with aluminum siding shutter from the inner direction to avoid any effect of daylight or external source of light on readings. Second, we mounted a small wireless camera on the tripod for remote monitoring of the illuminance level (lux value), which connected to a smartphone as shown in Fig. 2c to avoid any interfering with results. Third, we adjusted the configuration of the measurement device to record 60 measurements for one minute (time step one second) at each location of measurements. Finally, we repeated each experiment twice to check the accuracy of used measurement devices.

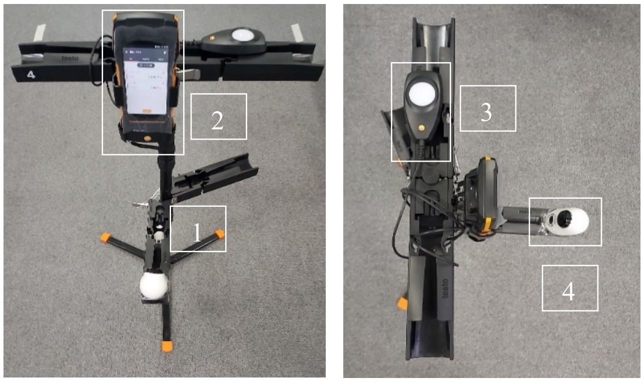


Fig. 2a:, and Fig. 2b: 3D and plan view of measurement apparatus, that used in the study (1. Tripod, 2. Testo 400, 3. Lux probe, 4. Wireless camera).

Fig. 2c: Sample of remote measurement taken by the wireless camera connected to the smartphone.

Table 1: Relationship between room index and the minimum number of measurement points in CIBSE method.

Room Index (K)	Minimum Number of Measurement Points	
	±5% Accuracy	±10% Accuracy
K < 1.0	8	4
1.0 ≤ K < 2.0	18	9
2.0 ≤ K < 3.0	32	16
3 < K	50	25

Table 2: Specifications of used lux probe.

Item	Description
Measuring Range	0 – 100,000 lux
Accuracy	Class C According to DIN 5032-7 f1 = 6% = V-Lambda f2 = 6% cos
Resolution	0.1 lux (<10,000 lux) 1.0 lux (>10,000 lux)

2.3 Simulation Measurement of Illuminance

DIALux evo software version 9.2 [25] was employed in this study to investigate the effect of luminaires arrangement of artificial lighting system on visual comfort and energy consumption. DIALux evo software was validated by many researchers [14, 17, 26, 27] for both artificial light and daylight, it offers acceptable simulation results against field measurement results in interior modeling. European Lighting Standard [28] (EN12464-1:2011) specifies the threshold of visual comfort indices as shown in Table 3. In this study, we used the selection of (evening classrooms occupied with adult learners). DIALux evo is employed to calculate illuminance uniformity (U_o), and unified glare rating (UGR) at the working plane for different arrangements and types of luminaries.

Table 3: Visual comfort indices for educational buildings according to EN12464-1:2011[28].

Type of area, task or activity	$\bar{E}_m$	UGR_L	U_o	R_a
Classrooms, tutorial rooms	300	19	0.6	80
Classrooms for evening classes and adults education	500	19	0.6	80

$\bar{E}_m$: is the average illuminance.
UGR_L: is the upper limit for direct glare.
U_o: is the ratio between lowest and average illuminance.
R_a: is the lower limit of color rendering index.

To get an appropriate simulation of artificial lighting by using DIALux evo software, at an earlier stage of research we measured the reflection factor of interior surfaces of the test room (classroom 104) as shown in Table 4.

Then, we gathered the technical specifications from the manufacturer catalog of ceiling-mounted fluorescent luminaires that were already used to illuminate the classroom (104) and the suggested luminaires to be used are LED luminaries as shown in Table 5. Fig. 3a, and Fig. 3b show the simplified model of the classroom (104) and the existing one on the first floor at Gulf University Campus.

Table 4: Reflection factor of interior surfaces of the classroom (104).

Surface	Material	Reflection factor
Walls	Gypsum plastering white painted	85%
Ceiling	Gypsum plastering white painted	85%
Floor	Carpet, single-colored, grey	20%

Table 5: Specifications of ceiling-mounted luminaries.

Item	Fluorescent (existing)	LED (suggested)
Luminous Flux	2500 lm	4500 lm
Correlated Color Temperature (CCT)	6200 K	6500 K
Color Rendering Index (CRI)	72	80
Power	36 W	50 W

Fig. 3a: Simplified classroom (104) modeled by DIALux evo software.

Fig. 3b: Existing classroom (104) on the first floor at Gulf University Campus.

2.4 Luminaries Arrangements and Type

As shown in Fig. 1d the existing two classrooms (103) and (104) were experimentally assessed by comparing average illuminance ($\bar{E}_{avg}$) and illuminance uniformity (U_o) at the same working plane. Then after validating the DIALux evo software we suggested many different arrangements to be evaluated in terms of the aforementioned indices ($\bar{E}_{avg}$, U_o, UGR) of visual comfort to recommend the best arrangement of artificial lighting luminaires that reduce electrical consumption inside classrooms. We calculated the installed load efficacy ratio (ILER) for different arrangements of luminaries which are shown in Fig. 4 on the classroom (104) namely (104-01:06) to estimate the annual energy wastage in terms of kWh/annum. Eventually, we compared the effect of using LED light instead of the existing fluorescent type from visual comfort and energy consumption perspective.

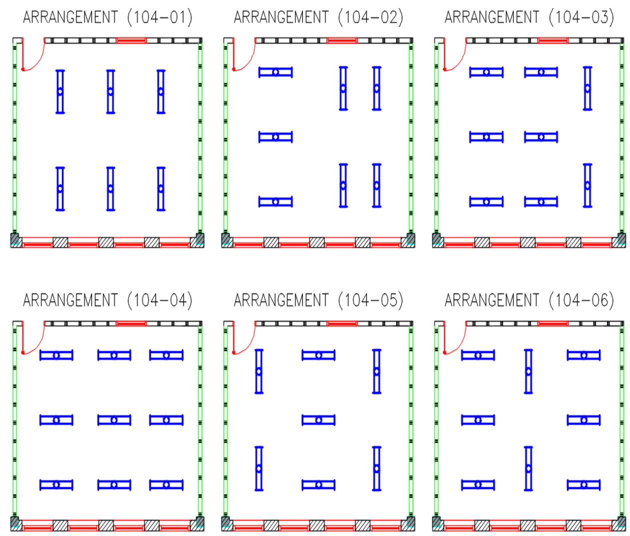
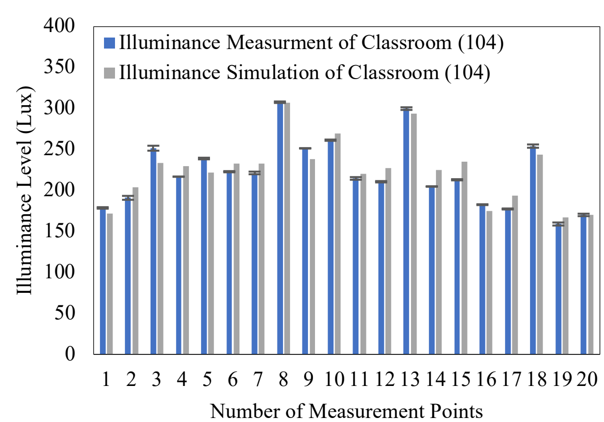


Fig. 4: Different arrangements of luminaries of the classroom (104).

3 Results and Discussions

3.1 Validation of DIALux evo Software

We examined the accuracy of using DIALux evo's results against the measurement of illuminance, this validation process was carried in the classroom (104) to find the percentage of error between the experimental and simulation readings. Findings showed that the percentage of error was acceptable less than 10% at all locations as shown in Fig. 5a, and Fig. 5b. Hence, this model reveals that DIALux evo is reliable software to simulate artificial illumination in classrooms.



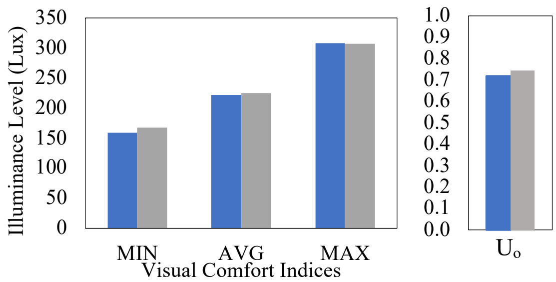


Fig. 5a:, and Fig. 5b: Validation of DIALux evo against illuminance measurement for classroom (104).

3.2 Accuracy of Lux Meter

We examined also the accuracy of the lux probe that used to measure illuminance in this study. On the 22th and 23th of March 2021 we carried two experiments in classrooms (103) and (104) on the first floor at Gulf University campus after sunset. Therefore each experiment repeated twice to check the accuracy of lux probe that connected to the measurement device. Fig. 6a, and Fig. 6b show that the used lux meter is trustworthy to depend on, and the readings were extremely identical at each location.

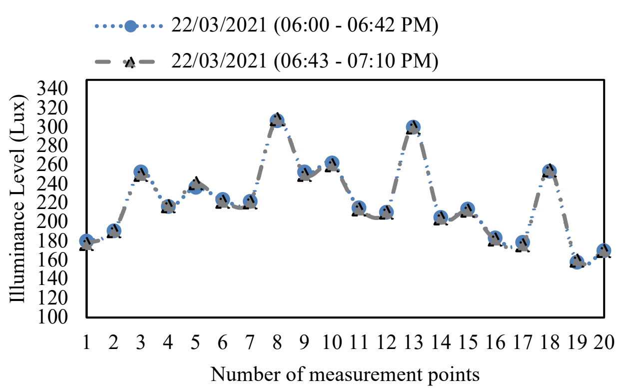


Fig. 6a: Repeated experiments of illuminance measurement in the classroom (104).

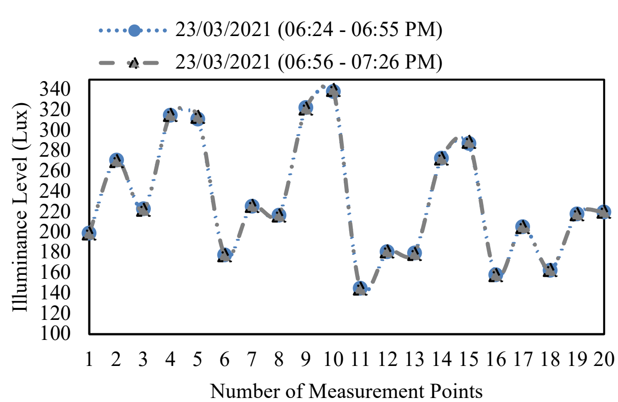


Fig. 6b: Repeated experiments of illuminance measurement in the classroom (103).

3.3 Effect of Luminaries Arrangement and Type on Visual Comfort

Fig. 7a illustrates the effect of different arrangements of luminaries on visual comfort obtained from DIALux evo for the classroom (104) based on the configurations assigned to meet the target illuminance according to EN12464-1:2011. All proposed arrangements including the existing arrangement in the classroom (104) which is (104-01), and classroom (103) which is (104-02) show an insufficient illuminance level, less than 500 lux. This result drives to replace the existing fluorescent lamp with LED type, despite the number of luminaries was increased from six to nine, the proposed arrangement (104-04) was not able to achieve the desired level of illuminance.

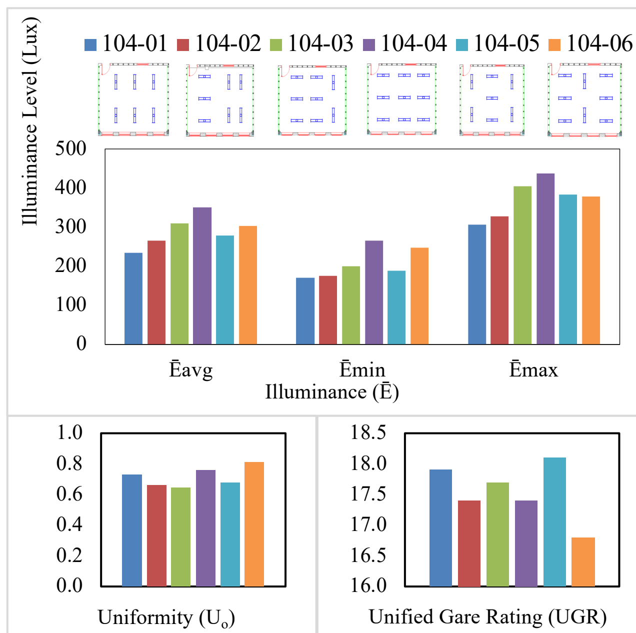


Fig. 7a: Effect of luminaries’ arrangement on visual comfort.

The existing arrangement in the classroom (104-01) is the worth from the sixth arrangement, while the arrangement (104-04) shows the best arrangement. All arrangements show acceptable limits of illuminance uniformity (U_o) and unified glare rating (UGR). The highest uniformity value equals 0.81 and the lowest glare value is 16.8, both values achieved by the arrangement (104-06).

Fig. 7b reveals that using LED lamp instead of fluorescent achieves occupant visual comfort as shown the average illuminance equals 485 Lux which is very close to 500 Lux (3% below), illuminance uniformity equals 0.81 above than 0.6, and glare value equals 15.6 less than 19.

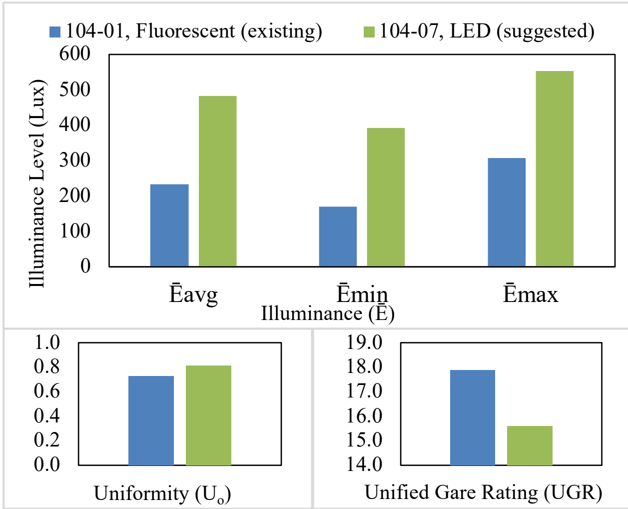


Fig. 7b: Effect of luminaries' type on visual comfort.

3.4 Effect of Luminaries' Arrangement and Type on Energy Consumption

In this section, we present the results of the calculated installed efficacy of existing luminaries for the six arrangements (104-01:06) in terms of (Lux/Watt/m2), Fig. 8a shows that all values of ILER for different arrangements ranged between (0.54-0.57). Referring to Table 6, these values of ILER suggest reviewing the existing system of artificial lighting in classrooms (103) and (104), consequently, we suggested replacing the existing fluorescent lamp with LED.

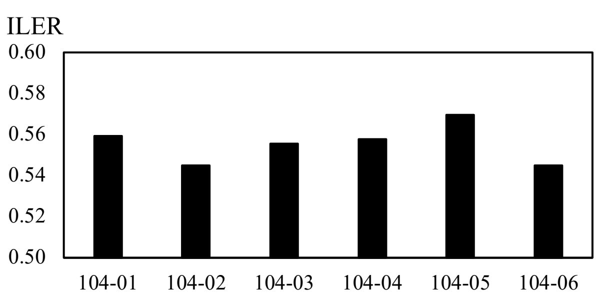


Fig. 8a: Installed Load Efficacy Ratio (ILER) for different arrangements of luminaries.

Table 6: Indicators of performance according to ILER[29].

ILER	Assessment
0.75 or above	Satisfactory to good
0.51 – 0.75	Review suggested
0.5 or less	Urgent action required

Furthermore, Fig. 8b illustrates the annual energy wastage for the six arrangements (104-01:06) based on four working hours per day after sunset and 260 days of the academic year. In the classroom (104) or [104-01] the existing lighting system wastes about 200 kWh/annum, while in the classroom (103) or [104-02] about 240 kWh/annum. This wastage due to that the efficacy of the existing lamp represented in ILER less than 0.75. In addition, to decrease this percentage we have two options, either to decrease the number of lamps because it is directly proportional with the annual energy wastage or to replace it with a new type with higher ILER. Other suggested arrangements (104-03:06) waste energy more than the existing arrangements, because it depends on increasing the number of luminaries.

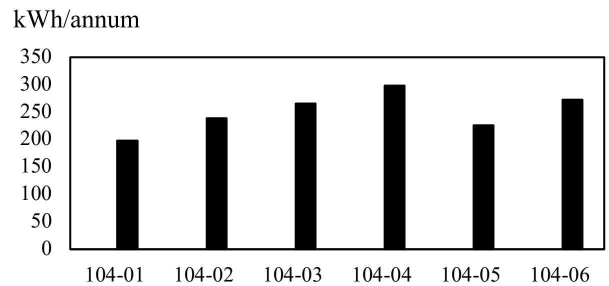


Fig. 8b: Annual energy wastage for different arrangements of luminaries.

We suggested replacing the existing fluorescent lamp with LED type to save the electrical demand for artificial lighting systems in the studied classrooms. As shown in Fig. 8c the average illuminance ($\bar{E}_{avg}$) is duplicated from 234 to 485 Lux, in addition, the installed load efficacy ratio (ILER) raised from 0.56 to 0.83, and the annual energy wastage decreased two folds from 200 to 100 kWh/annum due to using LED light instead of fluorescent one.

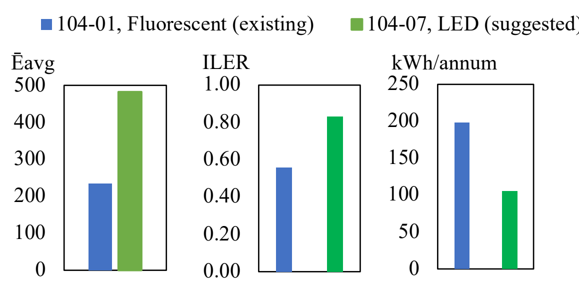


Fig. 8c: Effect of luminaries' type on Energy Consumption.

4 Conclusion

This paper deliberates two factors that play a decisive role in artificial lighting system efficacy in classrooms which are the arrangement and type of luminaries. We evaluated the existing lighting system from visual comfort and energy consumption perspective. In two typical classrooms with different arrangements of luminaries, we measured and compared the average illuminance by using a lux meter. Then we validated the simulated model of the test room by using DIALux Evo software against field measurements. Furthermore, we suggest four arrangements to be compared with the existing two arrangements. Finally, we suggested replacing the existing fluorescent lamp with LED one. The Findings of the research provide visual comfort and minimize energy wastage of artificial lighting systems to ensure quality that meets the European Lighting Standard. In addition, to help electrical designers who desired to illuminate interior spaces of different applications.

The results of the study indicate that the Luminaries' arrangement is a dominant factor that affects visual comfort and energy consumption. Accordingly, it is recommended to distribute the luminaries in a way that the number of rows equals the number of columns and to consider the longitudinal length of the luminaire to be parallel to the longitudinal length of the illuminated space. The arrangement [104-02] of the classroom (103) is better than the arrangement [104-01] of the classroom (104) if we compared the visual comfort indices. The recommended arrangement for the studied classroom is [104-04]. The existing fluorescent lamp is not a proper selection for classroom application. We recommend using LED lamp as an optimal selection in terms of energy-saving and visual comfort. It offers up to 50% energy saving and achieves the recommended average illuminance ($\bar{E}_{avg}$), in addition to increasing the illuminance uniformity, and decreases the glare.

All obtained results based on experiments and simulations performed on the test room that studied considered as a small scale. Whilst visual comfort and energy consumption results depend on the geometry, hence we expected if we repeated this study on a larger scale application, all results might go higher values. The study was carried in a classroom, but the methodology can be applied in other applications, so we believed the findings of this study are valid for all indoor environments.

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Appendix 1: Twenty measurement locations (E1-E20) in the classroom (103).