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Energy efficient lighting of public buildings with architectural restrictions: the challenges and limits of the glare assessment approach applied to the case study of San Salvatore Hall

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Abstract. In some applications, glare might result critical in indoor lighting design of historical buildings, due to the high performance required and the strict architectural restraints. Such issue is discussed referring to a real case study of a relamping project for a deconsecrated church turned into auditorium. In these cases, the standard glare evaluation typically adopted (UGR index) can only provide a preliminary estimation as some of the assumptions are not usually met. So, the level of glare of the current state is estimated by means of a numerical model developed in DIALux Evo (©DIAL GmbH), validated basing on both onsite measurements and the results of a human subject study conducted over the most frequent occupants of the room. The differences between estimated glare (quantitative) and subjective feelings (qualitative) are accounted to assess the glare level in the design stage of the auditorium. The results show that the preliminary estimation of UGR leads to underestimated values, especially when a relevant part of the light is provided indirectly or a change in the lighting system occurs (e.g., from direct and indirect to only direct lamps). Then, a comparison between lighting performance and energy saving for the specific case is proposed.

1 Fundamental photometric quantities adopted in lighting design

As better illustrated in the next section, the lighting design faces the need to respect quantitative, measurable and objective parameters, relating them to subjective human feelings about the illuminated environment. The main parameters illustrated below are the ones adopted in standard lighting design (e.g., according to UNI EN 12464-1 [1] for indoor workplaces and UNI EN 12464-2 [2] for outdoors workplaces). To the Authors' knowledge many other indexes are available (about 30-40) [3], some of them still on an academic level, others used for specific applications (e.g., Daylight Glare Probability), that anyway will be omitted, since they are beyond the aim of the present work.

- *Illuminance (E):* it defines the amount of available light over a surface that allows the performance of users' specific visual tasks. According to the standard, such parameter must be interpreted as minimum or average over the surface interested by the task (e.g., desk for drawing). One of the most diffused standards for workplaces [1, 2] expresses the required illuminance as an average over the area of the task. This parameter is present both as a specific index and as a coefficient in the formulation of other parameters, such as illuminance uniformity.

- *Illuminance uniformity (U_1 or U_0):* while illuminance expresses the amount of light over a surface, uniformity grants the absence of relevant variations in illuminance between minimum and maximum (U_1) or between minimum and average (U_0):

$$U_1 = \frac{E_{min}}{E_{max}} \qquad U_0 = \frac{E_{min}}{E_{mean}} \tag{1}$$

Uniformity and illuminance are usually coupled to grant both average level of light and its uniform distribution. A good uniformity means visual comfort, since it prevents the difficult and demanding eye adaptation among areas with excessively high and low illuminance.
The choice of the uniformity index depends on the adopted standard. For instance, the emergency lighting according to UNI EN 1838 [4] uses U_1, while the lighting of indoor workplaces [1] adopts U_0.

- *Glare:* it is a temporary effect on the human sight that can cause dazzling or even temporary blindness [5]. It can be usually divided into two groups:
  - *Discomfort glare*: the main issue is associated to the tiredness of the eye, with eventual side effects such as headache [6]. This kind of glare is caused by a dramatic contrast in the luminance of different parts over the field: some appear very bright, while others very dark. Discomfort glare causes no direct physiological consequence, but it affects the general and individual feeling of comfort in an environment. Therefore, some occupants might not be able to clearly distinguish the effect of this kind of glare among the possible causes of the perceived general discomfort [7].
  - *Disability glare*: it is caused by an excess of illuminance over the observer's eye. This occurrence can be clearly identified as the glared subject tends to blink, moves the eyes away and in some cases a temporary and brief blindness is experienced.

Usually, the existing indexes are concerned with discomfort glare since the disability glare must be a priori avoided, while a proper evaluation of discomfort glare is useful to identify the perceived level of annoyance. The formulations appear very complex, usually involving recurrent parameters (e.g., luminance, illuminance) and often with a logarithmic dependence. Such correlations have been mainly determined by means of laboratory simulations with artificial light, only lately extended to natural daylight using real case studies [8]. In any case, the perception of glare depends on the observers' line of view for each possible position over the room, thus requiring an integrated calculation method; furthermore, the correlation between index and subjective feeling may present dramatic variation depending on the individuals, their health conditions and adaptation capacities to the environment.

While the previous parameters (e.g., illuminance, uniformity, etc.) can be easily associated to an operational definition (and therefore measurement), the topic of glare evaluation still deserves attention. Nowadays, the most widespread index for indoor applications is the Unified Glare Rating (UGR) [9-12] as defined below [1]:

$$UGR = 8\log_{10}\left(\frac{0.25}{L_B}\sum\frac{L^2\omega}{p^2}\right) \tag{2}$$

Where:

L_B is the background luminance, that can be estimated as a function of the indirect illuminance E_{ind} over the observer's eye: $L_B = E_{ind} \cdot \pi^{-1}$ [cd/m^2];

L is the luminance of each lamp along the observer's direction of view [cd/m^2];

ω is the solid angle of each lamp along the observer's direction of view [sr];

p is Guth's position index, expressing the angle of deviation from the line of sight [-]

The formulation in (1) belongs to the tabular approach and it expresses the level of glare for a given position, along a chosen line of sight.

For different positions and lines of sight, the approach must be repeated, resulting more suitable for software simulation than for hand calculations. The values assumed by UGR can be then related to a likely users' level of perception, as shown in Table 1 [1, 13, 14].

Table 1. UGR limits and likely glare perception for indoor environments

Glare perception	Imperceptible	Perceptible	Disturbing	Intolerable
UGR value	<13	13-22	22-28	>28

Actually, the available studies as well as the standard [1] do not completely agree on the limits for each level of perception although the proposed values show very little variation one from the other.

The results of the proposed UGR approach are considered reliable when all the following assumptions are met:

- Only one kind of lamp present in the room,
- Rectangular space,
- Lamps arranged on a regular grid, with the same mounting height and orientation.

Furthermore, the method does not apply to indirect lighting (e.g., by means of reflections on the walls and ceilings), wall washers, lamps with asymmetric photometric solid, adjustable spotlights and luminous surfaces excessively small or large.

For every other case, the standards still allow the use of the UGR tabular method, but the results will be only preliminary and not fully representative of the glare level. Usually LED installations in historical buildings fall in the latter case.

Another implicit limit of the method is represented by the fact that all the lines of sight fall over an almost horizontal plane (-2° with respect to the horizontal), representing the natural plane of sight of people looking in front of them. All the other possible views in the tridimensional space are neglected by the approach. Moreover, the viewer is assumed still, with a constant angle of sight, excluding all the tasks where frequent eye movements occur.

Different studies have been carried out to highlight the limits of the UGR approach and some specifically referring to LEDs, due to their widespread diffusion [14-17]. For instance, [18] estimates a difference within the range of 12%-30% for glare calculation between manual and simulated calculation for a medium size room illuminated with LEDs. Other studies [19] show that the light distribution over an angle of 90° leads to very good uniformity, still preserving acceptable levels of glare (i.e., UGR < 19). In [20] symmetric and asymmetric lamps were enquired and in [21, 22] the issues of irregular and extended light sources were specifically studied. The research reported in [23] proved that for large installations (e.g., museums) with multiple potential sources of glare as in the case of auditoriums, the degree of uncertainty of the UGR method is about ±35%. Another interesting work was presented in [24] where a volleyball field was analysed enquiring the issues of static glare angle and the performing of tasks which require a rapid eye movement, even sometimes towards the lights.

In the end, uncertainty in glare evaluation plays a relevant role as it is not directly measured, but it depends on other parameters (e.g. illuminance, luminance, etc.) according to specific experimental formulations. In addition, even the UGR limits are associated to statistical concepts as they represent the percentage of population potentially glared (e.g., UGR = 19 is associated to a 35% of people who is likely to get glared). Moreover, glare index represents the trial to combine quantitative, measurable parameters with subjective feelings. So, the UGR (and its uncertainty) not only depends on the light features, but also on the subjects and on the room as well (i.e., room sizes, shape, reflection coefficients).

Some previous studies, [25] estimated the uncertainty for glare index between 2% and 20%.

There is no common approach to account for uncertainty when comparing the UGR index with the established limits. Generally, two different approaches have been formulated:

- Comparison of the upper limit with the measurement, expanded with uncertainty
- Definition of a guard band referred to the uncertainty range of the measurements.

As a consequence, each standard can adopt a different approach, lacking uniformity for the designer. As concerns the UNI EN 12464-1 standard, there is no information on how uncertainty should be estimated and then accounted in the final result. According to the Authors' this topic should be deeply integrated in the oncoming versions of the standard, to provide the designers with a reliable and common approach.

2 Lighting design and main objectives of the present work

Lighting design is often roughly considered in new constructions or refurbishments since it is seen as a practical aspect of indoor and outdoor light applications. Nevertheless, a correctly designed lighting system plays a central role under different points of view.

- *Functional aspects:* the current European standard [1, 2] and even specific national laws prescribe minimum requirements (e.g., level of light, uniformity, colour rendering and glare) to allow the safe execution of different tasks for various applications, spacing from universities, hospitals up to workplaces. More specific requirements and higher levels of illuminance can be introduced for applications where camera recording is required (e.g., TV sets, sports arenas, etc.) [26]. In addition, although the contribution of natural daylight must be enhanced and maximised [27-31], the artificial lighting still has to be designed for the worst scenario consisting in cloudy and nighttime periods.
- *Energy saving:* the energy need associated to lighting represents a relevant amount over the total annual consumption in most applications, especially non-residential ones [32-34]. Indeed, lighting covers about 30% of the total consumed electricity for tertiary applications while it decreases to about 15-20% for residential ones [35, 36]. In addition, still a relevant number of existing installations (even up to 70-90% according to specific studies), is outdated with consequences on both energy efficiency and annual maintenance costs [37, 38].

  So, a general increase in the number of newly installed lamps (+62%) is expected [39]. Nevertheless, the consumptions should not increase, as energy efficiency measures (e.g., eco design, energy labelling) are adopted in parallel to the lamp installation.

  In addition, both regulations [40] and international environmental performance rating schemes [41-43] involve lighting efficiency to reach the goals of the EPDB directives and grant a better, certified performance of the activity.

- *Emergency:* the lighting system has a strategic role not only during the standard usage of the building, but under emergency as well. Such topic involves the successful and fast people exodus, avoiding mass panic and properly identifying the safety exits and the security devices (e.g., fire extinguishers or emergency buttons) in case of emergency (e.g., fire or blackout) [4].
- *Comfort and psychological communication:* a proper lighting nonverbally communicates information to the users, to better understand the purpose of spaces, conveying comfort, allowing the correct recognition of colours (e.g., in commercial centres) or even transmitting feelings for specific architectural installations [44-46]. Few researches try to relate the indoor quality of light to physical and psychological wellness [47], some with specific insights on the different sub-processes that occur (e.g., visibility and the stress arousal, photobiology and the environmental appraisal) [48-50].

  Some studies highlight the correlation between users' satisfaction and artificial lighting both in residential and office applications [51-54]. Moreover, artificial lighting can be optimized to speed the breeding of plants, or to simulate the effects of the Sun in places with poor solar irradiation over the year [55-57].

Within the illustrated context, the design of a lighting system applied to buildings of architectural and historical value must cope with the added issue of restraints that deeply limit the possible mounting points, negatively affecting comfort, easy maintenance and respect of the requirements. The Constraint Satisfaction Problems is a very interesting branch of research applied to lighting, trying to automate the lamp choice and positioning according to the requirements and restrictions applied by the user [58-60]. Nevertheless, the added difficulty in the field of historical buildings lies in the subjective aspect of the architectural restraints where the lighting system must be respectful of the shapes and wisely harmonised with the style adopted in the construction.

The present paper shall deal with the relamping of a deconsecrated church used as an auditorium (San Salvatore Hall) of the Polytechnic School of the University of Genoa. As better illustrated below, the architectural restraints united with the required, high level of illumination leads to potentially critical parameters, mainly concerned with glare. Indeed, the lamps can be mounted only at a fixed height (about 10 m), at given points along the perimetral wall of the room. Therefore, the required, high level of illuminance (i.e., up to 750 lux) and uniformity can only be granted by means of powerful luminaires, making the occupants' glare more likely, since the contrast between veiling and background luminance is more apparent. Moreover, since the room is quite large (25 m long and 15 m wide) and the height of the lamps is noticeable (10 m above the floor) it is very likely the risk of glare due to the oblique aiming direction of the lamps. In addition, the standard tabular method for glare estimation [1] can only be considered as a preliminary estimation, since not all the assumptions, illustrated in the section before, are met as better illustrated in the next section.

After a global description of the auditorium and the mandatory limits, a more detailed evaluation for the level of glare in the design stage shall be performed, according to the steps below:

- Preliminary estimation of the current level of glare (i.e., before the relamping), by means of a numerical model built using the commercial software DIALux Evo and validated using the onsite measurements of illuminance and uniformity.
- Adjustment of the simulated glare index, basing on the specific enquiry performed over a class of students attending to the auditorium all year long.

- Estimation of the glare level in the design stage (i.e., after the relamping) according to the UGR tabular method, compared to the previous results obtained basing on the questionnaire and the onsite measurements.
- In the end, a brief estimation of the energy consumption shall be proposed between the two scenarios (current and design states) providing the Reader with a preliminary estimation of the energy saving under standard usage of the room.

3 Case study of San Salvatore auditorium

3.1 General description of the indoor environment and of the existing lighting plant

The building (Figure 1) was previously a church, now deconsecrated, that is used as a conference hall and it is also the location for different classes held by the Polytechnic School of the University of Genoa.

With respect to the original destination as church, the apse is no longer used and the speakers' stage has been installed just behind the main entrance, now closed (Figure 2).

Figure 1. External view of San Salvatore.

Figure 2. Internal views of San Salvatore Hall: the old apse (on the left), the new stage (on the right).

The surfaces inside the building are mainly covered in plaster, with light colouring (yellow-beige for the walls, pearly white for the ceiling) and some surfaces either frescoed or covered with paintings. The floor is made of squared, black and white tiles. Some decorations in white stucco can be found on the pilaster strips and on the side altars.

With reference to the lighting system, all the existing lamps are installed at the same mounting height (about 10 m) along the perimetral wall, near the maintenance walkway. Each light is located in correspondence of either the pillars or the keystone of the arches. The lights installed can be divided into two main groups:

- Indirect lamps: they are 14 ceramic discharge metal halide lamps, associated to the most powerful luminous flux (17500 lm – 360 W – type A), with an almost horizontal inclination, aiming at the ceiling.
- Direct lamps: they are 15, 4 of which belong to the previously illustrated type A, while the others are based on updated, former LED technology (4500 lm – 500 W – type B). In particular, the type A projectors are the ones near the speakers' stage, to provide an added luminous flux to the area.

Figure 3 shows the alternance between direct and indirect lights along one side of the auditorium. For both types of lamps, the photometric solid presents a smooth, water-drop looking shape, as shown in Figure 4.

In addition, the hall is subjected to architectural restrictions that allow almost no change in the lamp layout. For instance, addition of specific lamps (with consequent extension of the electrical wires) would change the historical value of the building. Even the installed materials (e.g. floor tiles, stuccoes etc) belong to the classical building techniques and therefore they are subjected to restrictions. For this reason, the following results are referred to the worst case scenario, in which the architectural restrictions are assumed as immovable.

Figure 3. Direct and indirect lamps

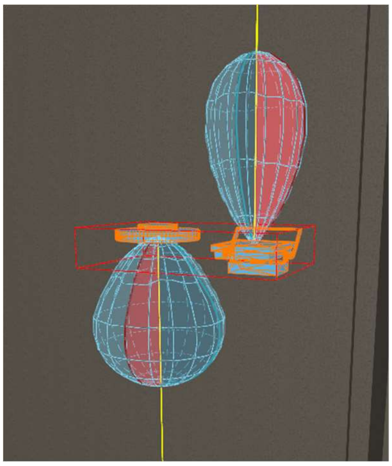

Figure 4. Qualitative shape of the photometric solids extracts from DIALux evo model: upwards (type A); downwards (type B).

3.2 Main target design values

The UNI EN 12464-1 applies to the considered case, providing minimum requirements, depending on the usage of the room, as briefly resumed in Table 2.

Table 2. Main minimum requirements for lighting design based on UNI EN 12464-1.

Parameter	Average illuminance E_m [lux]	Uniformity U_0 [-]	Glare UGR [-]
Auditorium, teaching room	> 500 to 750	> 0.6	< 19
Attendance to classroom	> 200 to 300	> 0.6	< 19

More limits are present for such applications (e.g., illuminance over walls, ceilings, etc.), but the present study shall neglect them, to focus on the intrinsic issue of granting high illuminance with lamps installed only at given points still respecting the limits about glare.

3.3 Numerical model assembly, onsite measurements and validation of the numerical model referred to the current state

The numerical model reproducing the auditorium (Figure 5) has been implemented by means of DIALux Evo software (©DIAL GmbH), adopting the following simplifications:

- The presence of the side altars has been overlooked.
- Equivalent, averaged surface reflective coefficient: floor 40%, walls 55%; ceiling 70%. Such values are aligned with the information reported in handbooks about building materials such as plaster or tiles.
- Simplification of the existing decorations leaving only the geometrical aspects that might affect light propagation and reflection.
- Maintenance factor equal to 0.8, representative of a typical, on the safe side condition.

Figure 5. Overview of the numerical model developed by means of DIALux evo.

The model has been then validated by means of the on-site illuminance measurements that were collected following the instructions reported in UNI EN 12464-1. Namely, the measurements were performed using a lux-meter about 1 m high (corresponding to the average height of a sitting person) following the maximum spacing for the measurement grid allowed by the approach. The data collection occurred without daylight, previously assessing the correct working of each lamp and the achievement of steady state conditions for the lamps (especially type A lamps, i.e., ceramic discharge metal halide lamps). The seating areas were subjected to more measurements as most critical, demanding and frequent tasks (e.g., reading, writing, etc.) occur in those regions.

Table 3 resumes the main results in terms of average illuminance (E_m) and uniformity (U_0) divided into the main areas of interest, as outlined in Figure 6.

Table 3. Main measured results in the current state: average illuminance (E_m) and uniformity (U_0) divided by sectors.

	Stepped seats (bottom of the room)	I sector	II sector	III sector	IV sector	Stage
Average illuminance (E_m) [lux]	140	169	164	189	186	317
Uniformity (U_0) [-]	0.89	0.86	0.85	0.82	0.84	0.88

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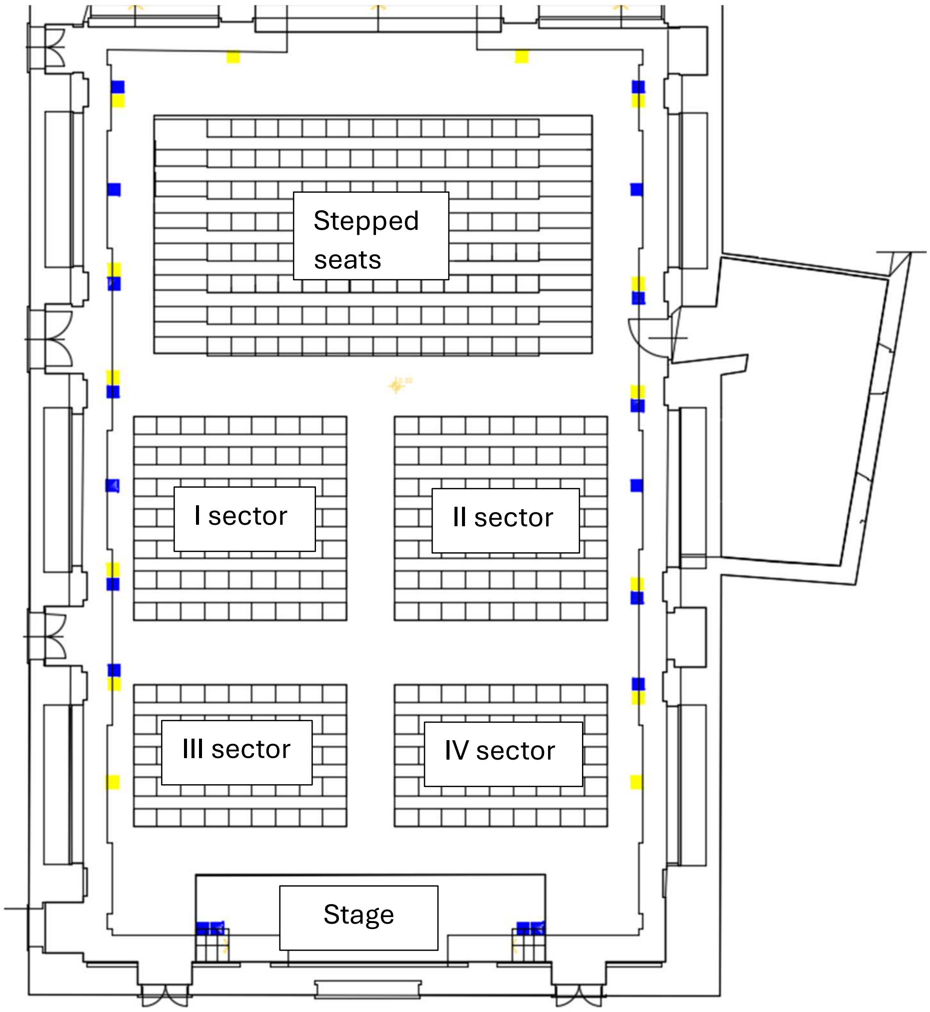

Figure 6. Outline of the main areas of interest for the performed measurements.

The different parameters of the assembled model (e.g., light orientation) have been adjusted to fit the measured information within a maximum approximation of 15% (Table 4). Such uncertainty is perfectly comparable to the one due to measurements that is between 10 and 15%. In addition, the same maximum tolerance has been applied when comparing point by point the simulated and measured values.

Table 4. Main simulated results in the current state: average illuminance (E_m) and uniformity (U_0) divided by sectors (in brackets the variation with respect to measurements in Table 3).

	Stepped seats (bottom of the room)	I sector	II sector	III sector	IV sector	Stage
Average illuminance (E_m) [lux]	156 (+11%)	160 (-5%)	162 (-2%)	215 (+14%)	201 (+8%)	299 (-5%)
Uniformity (U_0) [-]	0.92 (+3%)	0.92 (+7%)	0.95 (+12%)	0.77 (-5%)	0.79 (-6%)	0.79 (-6%)

3.4 Questionnaire for discomfort glare: formulations and results, compared to the glare estimation of the numerical model

Basing on the validated model, the UGR tabular method was performed, estimating levels between 15 (at the bottom of the room) up to 19 in all the four sectors and the stage. According to the limitations illustrated in Section 1, the results can be considered only as indicative and preliminary estimations. Indeed, a relevant part of the lighting system is based on indirect light, there is more than one kind of lamp, their spacing is not constant along a grid and the orientation changes as well.

For these reasons, more information to compare the simulated, preliminary level of glare was gathered by means of specific questionnaire conducted over 15 students, regularly attending all year long to a class that is held in the auditorium. The subjects were aged between 20 and 30, without known diseases concerned with sight.

The questions were conceived basing on the review studies available in literature [46, 61, 62]. Some questions directly ask information about the subjective feeling of glare, or the presence of any annoying lamp; others require the comparison of possible glaring causes to other potential, critical issues (e.g., low temperature, comfortable seats, etc.). The specific questions and the results are described below:

- Usual seat/seats: the users' most frequent positions within the auditorium are uniform over the main areas, as identified in Figure 6. About 17% usually chooses the stepped seats at the bottom of the room, while another 17% seats in the IV sector. The remaining 66% is equally distributed over the sectors from I to III.
- Most frequent visual tasks performed: 70% of the users looks at the presentation shown on the stage and copies or writes down occasional notes. Almost nobody reads or extensively writes in the room.
- Uncomfortable aspects of the auditorium in order of importance: the students were asked to sort in ascending order the aspects of the auditorium that affected most their level of comfort (Table 5). Among the eight given alternatives, four were concerned with different aspects of glare (e.g., shaded areas, light brightness or inclination, lack of illuminance or presence of annoying lights), while the remaining four were referred to other topics such as temperature, humidity and comfort of the seats. The aim was to obtain a comparison between feelings caused by different, potentially annoying causes.

Table 5. Aggregated results of the survey about the most uncomfortable issues of the auditorium in order of importance.

Number of comfort issues concerned with lighting at the very first three places	3	2	1	No comfort issues concerned with lighting
%	20%	20%	33%	27%

Therefore, the issue of glare can be considered relevant as 73% of the answers identified at least one problem concerned with lighting within the first three causes of discomfort.
Among the answers, some subjects substantially compared the feeling of glare to the one due to the room temperature and to the comfort of the seats, which lack of proper support for writing.

- Level of perceived glare for different tasks: following the same distinction of Table 1, the question required to assign a judgement of the glare annoyance (from 1 – negligible up to 4 – intolerable) when performing different tasks (i.e., writing, reading, etc.). The aggregated results can be found in Table 6: the level of perceived glare is almost aligned with the UGR method for the tasks with an almost fixed line of sight. On the other hand, the results of the UGR method tend to underestimate the level of glare when performing the copy of information from stage (i.e., a case of dynamic angle of view). Moreover, the feeling of glare can be considered independent from the habitual position within the auditorium since 80% of the students consider the glare at least disturbing.

Table 6. Aggregated results about the level of perceived glare for different tasks.

	Reading	Writing	Looking at the stage	Copying information from the stage
Imperceptible	46.5%	40%	53%	20%
Perceptible	46.5%	26.7%	13%	0%
Disturbing	7%	26.7%	27%	67%
Intolerable	0%	6.6%	7%	13%

- Visual discomfort due to lighting: the students were asked if they experienced any inconvenience either directly or indirectly related to sight. Table 7 shows that more than half of the students feels moderately tired at the end of the classes, while only a small part (13%) feels stronger discomfort (up to queasiness).

Table 7. Aggregated results about the level of perceived visual fatigue due to lighting.

	None	Moderate	Strong	Debilitating
Visual fatigue	33%	53%	13%	0%

- Identifications of specifically annoying lights: the students were asked to circle any light turned on that was perceived as glaring or annoying. The entire investigated group (100%) defined as annoying or glaring the lights around the speakers' stage, as highlighted in Figure 7. It can be noted that this region loses the indirect component as all the lamps point downwards and none of them is towards the ceiling. Also in this case, the result does not depend on the habitual seating position, and it is in accordance with the high sensation of glare experienced by 80% of students when copying information from the stage.

Figure 7. Lamps perceived as glaring or annoying by the students (red circles). The picture is a zoom of the lights over the speakers' stage visible in Figure 2.

Finally, the following observations can be drawn comparing the preliminary predictive UGR values with the results of the questionnaire:

- The prevision of UGR is not on the safe side for areas where a dramatic change in the lighting system occurs. Indeed, the bottom and the central seats of the room are subjected to the contribution of both direct and indirect light while area around the stage is illuminated only by direct lights.
- The glare prevision is underestimated in case of tasks requiring a continuous eye movement as well as in the case of copying information from the presentation on the stage.
- Even in places where the values of UGR were lower and very near to the threshold of perceptibility (i.e., UGR = 15), the users are annoyed by specific lamps, as shown in Figure 7.
- The statistical representativeness of the questionnaire can be considered preliminary satisfactory. Indeed, all the regular users of the hall have been involved. Clearly in absolute terms, the sample space should be more extended, for instance considering occasional occupants, Professors and Students of other academic years. Anyway the current results completely represent the opinion of the group of students who attended to the hall all year long, therefore having the chance to form a reasoned opinion about the lighting comfort of the room.

3.5 Prevision of the lighting plant performance after relamping

The existing architectural restraints do not allow any change in the lamp positioning. Consequently, the relamping has been performed by acting only on the kind of lamp and its orientation. Specific attention was paid to the lights near the stage, keeping the same lighting (direct and indirect) adopted all over the auditorium, to make the light diffusion more uniform. Figure 8 shows the lamp orientation over the stage: the two closest lateral luminaires are pointing upwards, while the four lamps above the stage have been orienteered downwards to provide more light on the stage, without glaring the occupants of the very first rows. Both direct and indirect lamps are of the same kind (LED) and they should provide a luminous flux of 30000 lm and an electric consumption of 200 W with a wide photometric solid (Figure 9). Then, on the sides of the auditorium, the same alternance between direct and indirect light has been preserved (Figure 10). In this way, the indirect lighting contributes to uniformity while the direct component helps reaching the demanding target of up to 750 lux required in the most restrictive condition (Table 2).

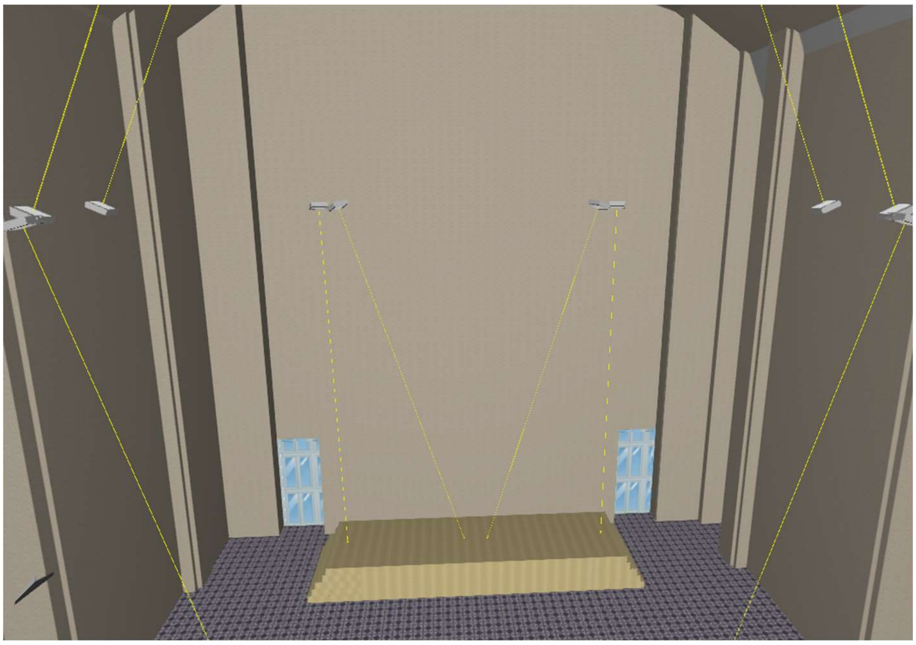

Figure 8. New lamps orientation. Focus of the area above the stage.

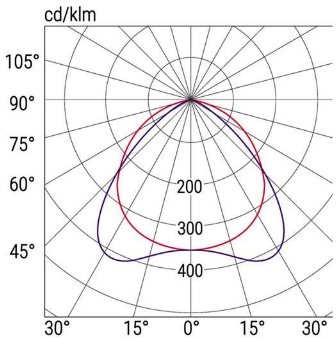

Figure 9. Photometric solid of the lamps chosen for the relamping.

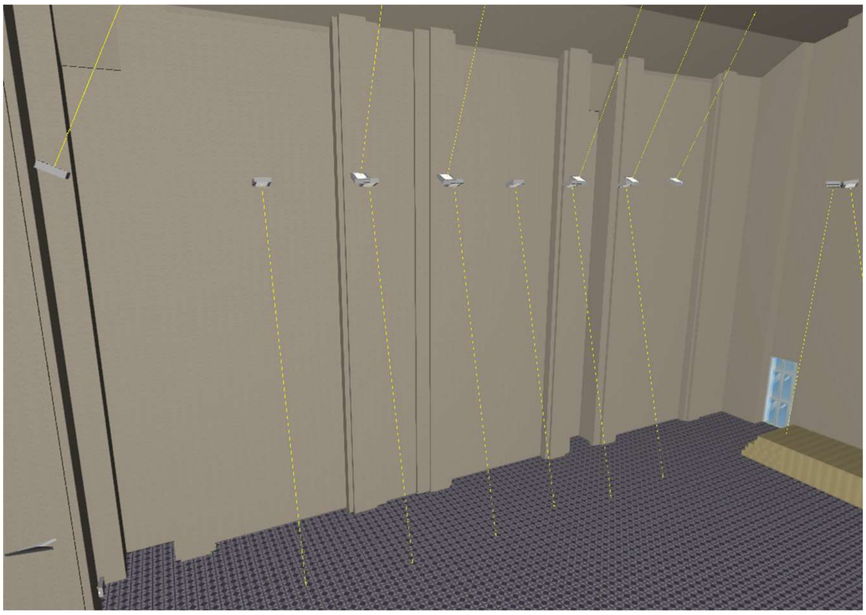

Figure 10. New lamps orientation. Focus on the area on the side of the auditorium.

The results of the simulation are shown in Table 8. The average illuminance (880-900 lux) is about 20% higher than the required minimum to safely account for eventual mistakes and inaccuracies during the installation. Table 8 shows in brackets the percentage enhancement with respect to the stricter limits reported in Table 2 when considering the room as an auditorium (i.e., 750 lux, uniformity > 0.6 and UGR <19).

Table 8. Main simulated results after relamping: average illuminance (E_m), uniformity (U_0) and glare (UGR); 100% lamps luminous flux; in brackets the variation with respect to the limits in Table 2.

Parameter	Average illuminance E_m [lux]	Uniformity U_0 [-]	Glare UGR [-]
Stage (Figure 6)	880 (+17%)	0.90 (+50%)	27.6 (+45%)
Sectors from I to IV (Figure 6)	900 (+20%)	0.88 (+47%)	26.9 (+42%)
Stepped seats at the bottom of the room (Figure 6)	750 (0%)	0.77 (+28%)	27.9 (+47%)

Table 9 shows the same results when considering the room instead as a classroom (second line in Table 2, i.e. 300 lux, uniformity > 0.6 and UGR <19) using a 50% dimming of the same LEDs.

Table 9. Main simulated results after relamping: average illuminance (E_m), uniformity (U_0) and glare (UGR); 50% lamps luminous flux; in brackets the variation with respect to the limits in Table 2.

Parameter	Average illuminance E_m [lux]	Uniformity U_0 [-]	Glare UGR [-]
Stage (Figure 6)	433 (+44%)	0.90 (+50%)	24.9 (+31%)
Sectors from I to IV (Figure 6)	439 (+46%)	0.88 (+47%)	24.6 (+29%)
Stepped seats at the bottom of the room (Figure 6)	340 (13%)	0.78 (+30%)	25.5 (+34%)

The comparison of Table 8 and 9 with Table 2 allows the following conclusions:

- The values of average illuminance and uniformity are within the limits. The larger values reached are on the safe side to account for any problem occurring during the installation phase (e.g., inaccuracies, mistakes, etc.).
- The estimation of glare, by means of tabular method, is largely out of the maximum limit of 19 required in both cases. As illustrated before, the assumptions of the UGR method are not fully met, and so the results can only be considered as a preliminary estimation. Anyway, a more detailed analysis over the calculation report shows that the critical issue is not concerned with specific glaring lights, but with the generally high level of illuminance that is required by the standard. Figure 11 shows the polar representation of the UGR value for each calculation node of the seats for the worst scenario (i.e., 100%). Each node has a circle whose radius represents the maximum admitted UGR. Then each circle presents radial lines whose length is the value of UGR along that direction. The red lines (overpassing the limit circle) are associated to UGR values higher than the maximum limit of 19 along that specific direction. It can be noticed that the overpassing of the glaring is uniform almost in every direction (especially for the calculation nodes falling in the centre of the room) and also the values of UGR show very low variation among the considered calculation nodes (minimum 26 and maximum 27). Therefore, the UGR overpassing is not caused by specific, wrongly orientated lamps, but it is more associated with a generally high level of illuminance caused by the luminous flux required to grant the average illuminance with lamps 10 m high. Indeed, the simple dimming of the lights of 50% (as in the case of Table 9), with no other change in position or inclination, leads to a reduction in the average illuminance and consequently in the glare index of about 13%. A further dimming up to the levels of illuminance comparable to the ones of the current state (i.e., average illuminance of 160-190 lux) leads the UGR again within the required limits.

In the end, it appears that the respect of all the existing limits (i.e., architectural and photometric) cannot be fully achieved. Actually, glare rating represents the most critical aspect, although the results from the UGR tabular method cannot be considered completely reliable.

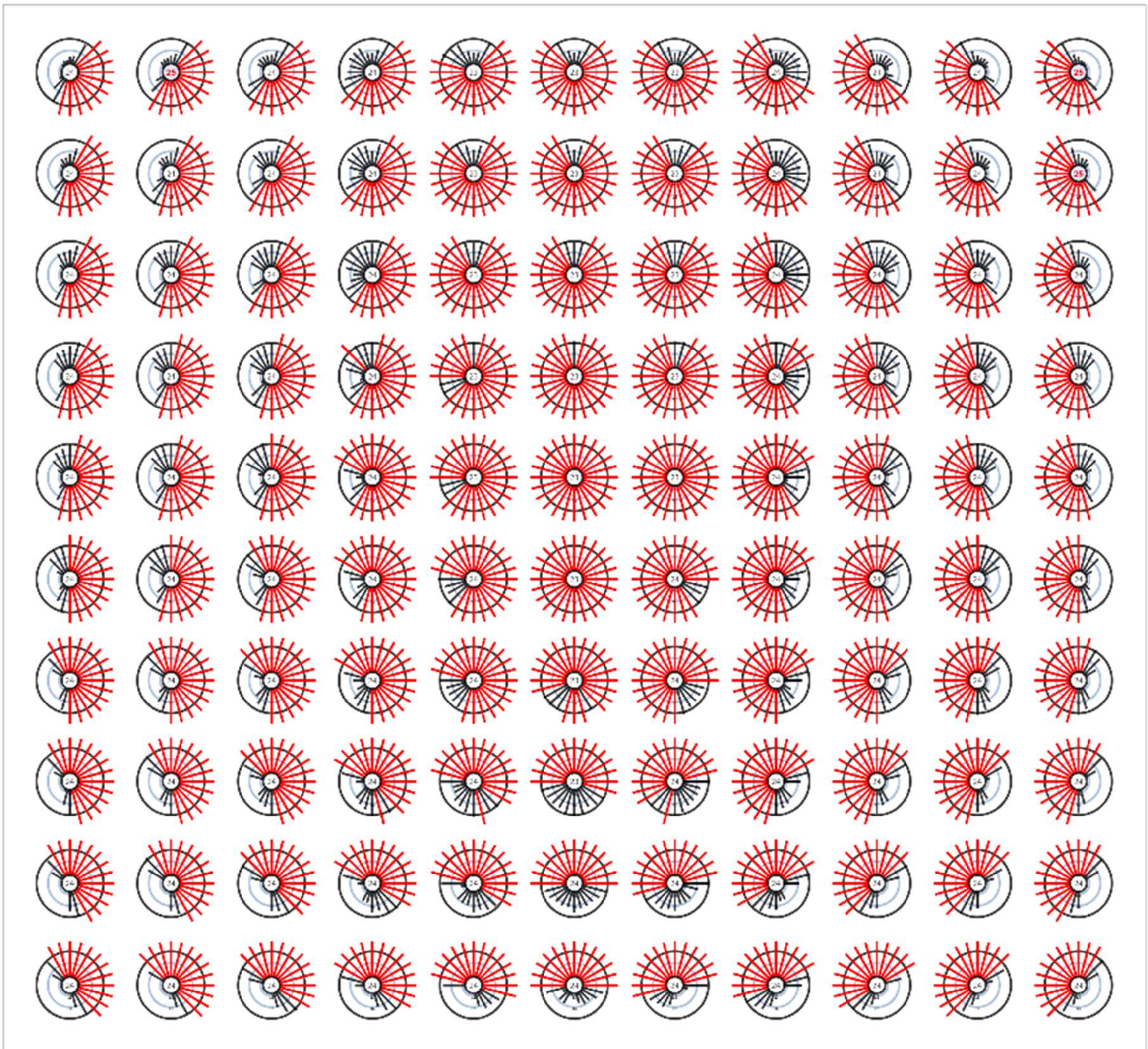

Figure 11. Nodal results for UGR coefficient on the seats (sectors from I to IV of Figure 6) -100% lamps luminous flux.

In conclusion, two possible alternatives are available:

- More detailed glare rating, even considering new measurements after the relamping to assess the real level of perceived annoyance. Indeed, many works in the previously recalled state of the art estimate a degree of uncertainty within the UGR method up to 30-40% that is comparable to the exceeding of the limits illustrated in Tables 8 and 9. In addition, the experience acquired by means of the questionnaires shows that the most relevant issue with glare was concerned with specific lamps near the stage whose orientation has been changed in the design. For the other positions, the provisional glare rating is out of the limits, but uniform both along different directions and different positions. In addition, not all the lines of sight should be enquired as most of the eye-challenging tasks involve the direction between the seats and the stage (e.g., looking at the stage or at their own notebook).
- Removal of some of the existing restraints, to carry out a design capable of respecting all the mandatory limits. A major freedom of installation locations could help to reach a better luminance distribution, leading to lower values of UGR.

3.6 Preliminary estimation of the energy saving under standard usage of the auditorium

A preliminary energy saving is here briefly proposed to provide the Reader with a complete overview about the problem of relamping. Even if an increase of luminous flux is required to respect the current minimum requirement, the energy saving can be met as well. The evaluation is intended as preliminary and therefore simplified, with no calculation of specific indices (e.g., LENI) and assuming a standard usage, according to UNI/TS 11300-2 [63]. The latter assumption might not be representative of the actual usage of the auditorium, but it is meant to allow the comparison between actual and design scenarios. Table 10 reports the main results of the cost-benefit analysis.

Table 10. Provisional cost-benefit analysis between the current and design scenarios, assuming standard utilization according to UNI/TS 11300-2.

Scenario	Number of lamps	Single lamp electrical power [W]	Total installed power [kW]	Annual working hours (UNI TS 11300-2) [h/year]	Annual electricity consumption [kWh]
Current	28	360	10.1	1800	18180
Design	28	200	5.6	1800	10080

A global annual saving of 8100 kWh can be preliminary assessed, which is equivalent to about 2400 €/year assuming a unitary price of 0.3 €/kWh for electricity.

4 Conclusions and future developments

In the present work, the relamping project for an auditorium has been presented. The main photometric parameters have been calculated, also recalling the multiple roles that a good light design plays in terms of both comfort and functionality of the inhabited environments. More in detail, the topic of indoor glare evaluation was deepened, highlighting the different available studies that describe the limits of the UGR method. Indeed, glare is likely to result critical in installations where further restrictions are present (e.g., in historical buildings) and a lamp configuration that satisfies all the boundary conditions might not result feasible. In addition, the most widespread calculation method for glare index (i.e., UGR tabular method) can provide only a preliminary estimation as not all the assumptions can be easily met (e.g., only one type of lamp, only direct light, regular lamp installation grid, etc.).

The issue of glare concerned with historical buildings and its measurement was deepened with reference to the real case study of San Salvatore Hall, an auditorium of the Polytechnic School of the University of Genova which once was a church.

A numerical model of the auditorium was developed in DIALux evo environment (© GmbH) and validated by means of on-site illuminance measurements. Then, the tabular UGR method for glare assessment was compared to the results of a questionnaire compiled by the students who regularly attended a class in the auditorium all year long. The comparison highlighted the unsuitability of the current UGR formulation for lighting systems with both direct and indirect lighting, especially when performing tasks that require the recurrent movement of the eye (e.g., looking at the stage and copying some information). The most annoying region was the one associated to only direct light, immediately above the stage, for all the users, independently from their seats. On the other hand, the UGR estimation showed good reliability for tasks with fixed glaring angle (e.g., reading, writing, etc.).

Then, the same model was used to run the design scenario, by installing more powerful LED lamps and by changing only their orientation, to respect the architectural restraints which do not allow any displacement of the lamps. In parallel a preliminary cost-benefit analysis was performed.

The obtained results allowed the following conclusions: the level of glare estimated in the design stage with the tabular UGR method is negatively affected by the added luminous power of the lamps, mandatory to reach the minimum for illuminance and uniformity. In fact, the results show values of UGR having very little dependence on the line of sight and position in the room. The problem becomes more apparent as the minimum, required, average illuminance increases. In addition, the fixed installing position prevents other possible lamp layouts.

Besides of the improved performance in terms of illuminance and uniformity, the preliminary economic analysis clearly shows the cost-effectiveness of the relamping intervention.

As it concerns the future developments, a full approach or adjustment coefficient should be defined to extend the UGR method to the irregular lamp configurations, characterised by both direct and indirect light. More in detail, the specific issue of the presented auditorium could be solved adopting one of the following possible strategies:

- Removal/revision of some of the existing constraints (e.g., fixed lamp installation points) to respect all the photometric limits, identifying solutions that must still be respectful of the building historical heritage and be well placed and harmonised as well.
- Measurements of the illuminance after the relamping and repetition of the same questionnaire, to effectively assess the UGR reliability in case of applications with high illuminance required over large areas.
- Extend the questionnaire to a wider range of users, including also those occasionally attending to the hall.

Nomenclature

E	Illuminance	lux
L	Luminance	cd/m^2
p	Guth's position index	-
U_0	Uniformity	-
UGR	Unified Glare Rating	-
ρ	reflection coefficient	-
ω	solid angle	[sr]

References

[1] UNI EN 12464-1, Light and lighting. Lighting of work places. Part 1: Indoor work places, 2021. https://store.uni.com/uni-en-12464-1-2021. Access date: 05/06/2025.
[2] UNI EN 12464-2, Light and lighting. Lighting of work places. Part 2: Outdoor work places, 2025. https://store.uni.com/uni-en-12464-2-2025. Access date: 05/06/2025.
[3] Carlucci, S., Causone, F., De Rosa, F., Pagliano, L., 2015, A review of indices for assessing visual comfort with a view to their use in optimisation processes to support building integrated design. Renewable and Sustainable Energy Reviews, 47 1016–1033. https://doi.org/10.1016/j.rser.2015.03.062
[4] UNI EN 1838, Lighting Applications. Emergency lighting, 2013. https://store.uni.com/uni-en-1838-2013. Accesss date: 05/06/2025.
[5] Illuminating Engineering Society of North America (IESNA), The lighting handbook, 2000, 9th edition, New York (USA).

[6] Osterhaus, W. K. E., 2005, Discomfort glare assessment and prevention for daylight applications in office environments. Solar Energy, 79 (2) 140–158. http://dx.doi.org/10.1016/j.solener.2004.11.011
[7] Reinhart, C., Wienold, J., 2011, The daylighting dashboard – A simulation-based design analysis for daylit spaces. Building and Environment, 46 (2) 386–96. DOI:10.1016/j.buildenv.2010.08.001
[8] Wienold, J., Christoffersen, J.,2006, Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy and Buildings, 38 (7) 743–757. DOI:10.1016/j.enbuild.2006.03.017
[9] Erdem, L., Trampert, K., Neumann, C., 2012, Evaluation of discomfort glare from LED lighting systems. Ingineria Iluminatului, 14 (2) 17-26.
[10] Geerdinck, L. M., Van Gheluwe, J. R., Vissenberg, M., 2014, Discomfort glare perception of nonuniform light sources in an office setting. Journal of Environmental Psychology, 39 5–13. DOI:10.1016/j.jenvp.2014.04.002
[11] CIE 117, Discomfort glare in interior lighting, 1995. https://cie.co.at/publications/discomfort-glare-interior-lighting.
[12] CIE 190, Calculation and presentation of unified glare rating tables for indoor lighting luminaires, 2010. https://cie.co.at/publications/calculation-and-presentation-united-glare-rating-tables-indoor-lighting-luminaires
[13] Geerdinck, L., 2012, Glare perception in terms of acceptance and comfort. Industrial Engineering & Innovation Science, Graduation report, Eindhoven University of Technology.
[14] Scheir, G.H., Hanselaer, P., Bracke, P., Deconinck, G., Ryckaert, W.R., 2015, Calculation of the Unified Glare Rating based on luminance maps for uniform and non-uniform light sources. Building and Environment, 84 (1) 60–67. DOI:10.1016/j.buildenv.2014.10.027
[15] Reda, I., Elzefzafy, H., Al Rawi, P. Y. M., 2021, Effect of Luminaries' arrangement and type on visual comfort and energy consumption. Information Sciences Letters, 10 (3) 417-426. http://dx.doi.org/10.18576/isl/100304.
[16] Faraji, A., Rezaei, F., Rahnamayiezekavat, P., Rashidi, M., Soleimani, H., 2023, Subjective and Simulation-Based Analysis of Discomfort Glare Metrics in Office Buildings with Light Shelf Systems. Sustainability, 15 1-21. https://doi.org/10.3390/su151511885.
[17] Giang, D. T., Duong, P. H., Quan, N. V., Trang T, N. T., Khanh, T. Q., 2024, A Study on Pendant and Blackboard Asymmetric Lens LED Luminaires for Optimal Illumination in Classrooms. Sustainability, 16 1-16. doi.org/10.3390/su162210015
[18] Abbasinejad, R., Kacprzak, D., Abeywardana, D. K., 2024, UGR calculation methods reliability investigation for LED luminaires", IEEE Sustainable Smart Lighting World Conference & Expo (LS24), 1-4. DOI:10.1109/LS2463127.2024.10881640.
[19] Ye, Z.T., Ruan, M., Kuo, H.-C., 2020, CSP–LEDs Combined with Light Guide Without Reflective Matrix for Antiglare Design. IEEE Accesss, 8, 156718–156726. Digital Object Identifier 10.1109/ACCESS.2020.3019314
[20] Babadi, S., Ramirez–Iniguez, R., Boutaleb, T., Mallick, T., 2020, Symmetric and asymmetric freeform lens to produce uniform illumination. Optical Engineering, 59 1-9. DOI:10.1117/1.OE.59.1.015102
[21] Sorgato, S., Chaves, J., Thienpont, H., Duerr, F., 2019, Design of illumination optics with extended sources based on wavefront tailoring. Optica, 6 966–971. DOI:10.1364/OPTICA.6.000966
[22] Li, Y., Feng, Z., Cheng, D., Wang, Y., 2021, Designing double freeform surfaces for large ray bending irradiance tailoring of extended LED sources. Opt. Express, 29 (9) 13469-13485. DOI: 10.1364/OE.423629
[23] Rui Dang, Zi'ang Gao, Zhenyu Hu, Yang Cong, Xingcan Sun, 2023, Glare quantification in Chinese museum exhibition halls based on visual field luminance distribution. Developments in the Built Environment, 16 1-10. https://doi.org/10.1016/j.dibe.2023.100237.
[24] Pakkert, M., Rosemann, A. L. P., Duijnhoven, J., Donners, M., 2018, Glare quantification for indoor volleyball. Building and Environment, 143 1-16. DOI:10.1016/j.buildenv.2018.06.053
[25] Ribeiro, A.S., Martins, L., Santos, A., Conformity assessment of glare in buildings considering the uncertainty of the parameter UGR_L, Journal of Physics: Conferences Series 1379 1-6, doi:10.1088/1742-6596/1379/1/012018
[26] UNI EN 12193, Light and lighting. Sports lighting, 2019. https://store.uni.com/uni-en-12193-2019. Access date: 05/06/2025.
[27] Mavromatidis, L. E., Marsault, X., Lequay, H., 2014, Daylight factor estimation at an early design stage to reduce buildings' energy consumption due to artificial lighting: A numerical approach based on Doehlert and Box-Behnken designs. Energy, 65 488-502. http://dx.doi.org/10.1016/j.energy.2013.12.028
[28] Cheong, K. H., Teo, Y. H., Koh, J. M., Rajendra Acharya, U., Man Yu, S. C., 2020, A simulation-aided approach in improving thermal-visual comfort and power efficiency in buildings. Journal of Building Engineering, 27 1-10. https://doi.org/10.1016/j.jobe.2019.100936
[29] Young Yun, G., Hyoin Kim, Tai Kim, J., 2012, Effects of occupancy and lighting use patterns on lighting energy consumption. Energy and Buildings, 46 152-158. doi:10.1016/j.enbuild.2011.10.034

[30] Al-Ashwal, N. T., Budaiwi, I. M., 2011, Energy savings due to daylight and artificial lighting integration in office buildings in hot climate. International Journal of Energy and Environment, 2 (6) 999-1012.
[31] Ghisi, E., Tinker, J. A., 2005, An Ideal Window Area concept for energy efficient integration of daylight and artificial light in buildings. Building and Environment, 40 51-61.
[32] Hinnells, M., 2008, Technologies to achieve demand reduction and microgeneration in buildings. Energy Policy 36 (12) 4427–4433. https://doi.org/10.1016/j.enpol.2008.09.029
[33] Li, D.H.W., Lam, J.C., 2003, An analysis of lighting energy savings and switching frequency for a daylit corridor under various indoor design illuminance levels. Applied Energy, 76 (4) 363–378. DOI:10.1016/S0306-2619(02)00121-6
[34] Li, D.H.W., Lam, T.N.T., Wong. S.L., 2006, Lighting and energy performance for an office using high frequency dimming controls. Energy Conversion Management, 47 (9-10) 1133–1145. DOI:10.1016/j.enconman.2005.06.016
[35] Pohl, W., Werner, M., 2010, Lighting, comfort and energy and the evaluation of the recommendations of EN15251. Intelligent Energy Europe.
[36] Jenkins, D., Newborough, M., 2007, An approach for estimating the carbon emissions associated with office lighting with a daylight contribution. Applied Energy, 84 (6) 608–622. https://doi.org/10.1016/j.apenergy.2007.02.002
[37] Krarti, M., Erickson, P. M., Hillman, T. C., 2005, A simplified method to estimate energy savings of artificial lighting use from daylighting. Building and Environnment, 40 (6) 747–754. doi:10.1016/j.buildenv.2004.08.007
[38] Linhart, F., Scartezzini, J.L., 2011, Evening office lighting – visual comfort vs. energy efficiency vs. performance?. Building Environment, 46 (5) 981–989. DOI:10.1016/j.buildenv.2010.10.002
[39] https://energy-efficient-products.ec.europa.eu/product-list/light-sources_en. Access date: 05/06/2025.
[40] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401275&pk_keyword=Energy&pk_content=Directive. Access date: 05/06/2025.
[41] https://www.usgbc.org/leed. Access date: 05/06/2025.
[42] https://breeam.com. Access date: 05/06/2025.
[43] https://www.wellcertified.com. Access date: 05/06/2025.
[44] Sanmargaraja, S., Wei, T. L., Ponniah, V., Olanrewaju, A. L.A., Cheen, K. S., 2021, Perception of Lecturers and Students Regarding the Illuminance in the Lecture Theatres and Tutorial Rooms: Case Study in Universiti Tunku Abdul Rahman (UTAR). Engineering Journal, 25 83-95. DOI:10.4186/ej.2021.25.7.83
[45] Sholanke, A., Fadesere, O., Elendu, D., 2021, The Role of Artificial Lighting in Architectural Design: A Literature Review. IOP Conference Series: Earth and Environmental Science, 665 1-13. doi:10.1088/1755-1315/665/1/012008
[46] Tedjawinata, G. K., Jurizat, A., Karlardi, A. F., 2021, Lighting Optimization for Reused Building: Case Study of PLN Convention Hall, Soekarno Hatta, Bandung. IOP Conference Series: Earth and Environmental Science, 738, 1-12. doi:10.1088/1755-1315/738/1/012030
[47] Kong, Z., Liu, Q., Li, X., Hou, K., Xing, Q., 2022, Indoor lighting effects on subjective impressions and mood states: A critical review. Building and Environment, 224 1-16. https://doi.org/10.1016/j.buildenv.2022.109591
[48] J.Veitch, A., 2001, Lighting quality contributions from biopsychological processes. Journal of Illuminating Engineering Society, 30 (1) 3–16.
[49] Jakubiec, J.A., Quek, G., Srisamranrungruang, T., 2020, Long-term Visual Quality Evaluations Correlate with Climate-Based Daylighting Metrics in Tropical Offices – A Field Study. Lighting Research andTechnology, 53 1-27. DOI:10.1177/1477153520926528
[50] Kong, Z., Jakubiec, J. A, 2021, Evaluations of Long-Term Lighting Qualities for Computer Labs in Singapore, Building and Environment, 194. DOI:10.1016/j.buildenv.2021.107689
[51] Yun, G. Y., Kong, H. J., Kim, H., Kim, J. T., 2012. A Field Survey of Visual Comfort and Lighting Energy Consumption in Open Plan Offices. Energy and Buildings, 46 146-151. DOI:10.1016/j.enbuild.2011.10.035
[52] Oluwunmi, A. O., Izobo-Martins, O. O., 2012, User's Satisfaction with Residential Facilities in Nigerian Private Universities: A Study of Covenant University. Transnational Journal of Science and Technology, 2 (11) 89-112.
[53] Konis, K., 2013, Evaluating daylighting effectiveness and occupant visual comfort in a side-lit open-plan office buildings in San Francisco, California, Building and Environment, 59 662-677. DOI:10.1016/j.buildenv.2012.09.017
[54] Baeza Moyano, D., San Juan Fernandez, M., Gonzalez Lezcano, R. A., 2020, Towards a sustainable indoor lighting design: Effects of artificial light on the emotional state of adolescents in the classroom. Sustainability, 12 1-27. doi:10.3390/su12104263
[55] Jähne, F., Hahn, V., Würschum, T., Leiser, W., 2020, Speed breeding short-day crops by LED-controlled light schemes. Theoretical and Applied Genetic, 133, 2335–2342. https://doi.org/10.1007/s00122-020-03601-4.

[56] Craig, D. S., Runkle, E. S., 2013, A moderate to high red to far-red light ratio from light-emitting diodes controls flowering of short-day plants. Journal of the American Society for Horticultural Science, 138 (3)167–172. https://doi.org/10.21273/JASHS.138.3.167.
[57] Hickey, L. T., Hafeez, A. N., Robinson, H., Jackson, S. A., Leal-Bertioli, S. C. M., Tester, M., Gao, C., Godwin, I. D., Hayes, B. J., Wulff, B. B. H, 2019, Breeding crops to feed 10 billion. Nature Biotechnology, 37 744–754. https://doi.org/10.1038/s41587-019-0152-9.
[58] Moeck, M., 2005, Constraint Satisfaction Software for Architectural Lighting Design: A Case Study. LEUKOS The Journal of the Illuminating Engineering Society of North America, 1 (1) 101-127. DOI:10.1080/15502724.2004.10732009
[59] Tolidis, A., 2019. Parametric Lighting Design. DOI:10.1109/BLJ.2019.8883626
[60] Tourre, V., Martin, J. Y., 2006, Expression of luminous ambience intention in CAAD. 24th eCAADe Conference Proceedings, Volos (Greece), 6-9 September 2006, pp. 650-655.
[61] Quek, G., Jain, S., Karmann, C., Pierson, C., Wienold, J., Andersen, M.,2023, Comparison of questionnaire items for discomfort glare studies in daylit spaces. Lighting Research and Technology. DOI:10.1177/14771535231203564
[62] Suk, Y. J., Schiler, M., Kensek, K., 2017, Investigation of existing discomfort glare indices using human subject study data, Building and Environment, 113 121-130. https://doi.org/10.1016/j.buildenv.2016.09.018].
[63] UNI/TS 11300-2, Energy performance of buildings. Part 2: Evaluation of primary energy need and of system efficiencies for space heating, domestic hot water production, ventilation and lighting for non-residential buildings, 2019. https://store.uni.com/uni-ts-11300-2-2019. Access date: 05/06/2025.