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A method to assess lighting quality in educational rooms using analytic hierarchy process

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ABSTRACT

Nowadays, the belief that lighting can influence comfort, productivity and people's health is well established. In educational rooms the absence of adequate levels of indoor comfort can greatly influence the learning ability of students. The evaluation of lighting indoor quality is often limited to test and check the illuminance levels of the main tasks. However, the lighting quality and the achievement of adequate levels of visual comfort strongly depend on other factors that cannot be overlooked in a detailed analysis. The authors propose an original lighting quality assessment method for the evaluation of lighting in educational rooms, aimed at analysing all the main aspects and at defining a ranking of the critical issues, in order to consider improvements. The method based on the selection of lighting criteria, sub-criteria, and related indicators. Since an analytic hierarchy process was applied to assign a weight to each criterion that has a different impact on the lighting quality. The proposed method was applied at the scale of the single classroom and of a group consisting of six classrooms, considering the buildings of the School of Engineering at University of Pisa as case study. Finally, with the aim of verifying the correspondence between results of the proposed method and actual users' perception, a subjective survey was carried out in the same investigated classrooms. A total of 420 questionnaires were filled, and the results revealed the correspondence between the proposed method and the subjective surveys, proving the validity of the method.

1. Introduction

The absence of an adequate level of indoor comfort can greatly influence the learning ability of students. In the last decade, it has been widely demonstrated that a comfortable environment enhances productivity of workers and recently this concept was also extended to educational rooms [1,2]. It is well known that poor indoor environmental quality (IEQ) in schools may result in illness, leading to students absenteeism, as well as adverse health symptoms, and decreases learning performance [3]. In the past it was thought that the only influence of the lighting systems on IEQ arose from the heating of electric lamp bulb surfaces when they are used [4]. Nowadays, the conviction that lighting can influence (especially through non-visual effects) comfort, productivity, and people's health is well established [5,6]. Since the late 1990's, the Commission Internationale de l'Éclairage (CIE) shifted its emphasis from lighting for visibility to a more broad definition of lighting quality, encompassing human needs, architectural integration, and economic constraints, including energy consumptions [7]. According to Winterbottom and Wilkins [8], lighting quality plays an important role for a good IEQ in classrooms and it is very important for pupils' learning and several studies identified a number of problematic aspects of existing classrooms' lighting [8–11].

The assessment methods of the lighting quality are still subject of discussion in the scientific community, because they are often limited to the evaluation of the quantity of light (illuminance and luminance) [12]. The lighting quality assessment methods based on illuminance levels are those of less recent development and provide relevant information, but they are limited to the average conditions on the task areas [13,14]. Recently the High Dynamic Range (HDR) technology has been commonly used to develop lighting quality assessment methods based on direct determination of luminance values and indirect determination of illuminance values, also in order to calculate various glare indicators [15–17]. Alternative (or integrative to the previous) methods to assess the lighting quality are based on questionnaires administration, in order to evaluate subjective perception of the visual environment [18,19]. However it is now common opinion in the scientific community that lighting quality should be assessed through a holistic approach [12,20], in which multiple aspects are taken into account [11,21–24]: quantity of light, distribution of light, glare, spectral power distribution, daylight,

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List of symbols

Average Illuminance E_m (lx)
Circadian stimulus CS
Correlated Colour Temperature CCT(K)
Daylight Factor DF
Deviation D
Deviation Indicator DI
Final Score FS
Flicker index f_{FI}
General Colour Rendering Index Ra
Illuminance uniformity U_0
Lighting Criteria LC
Lighting Sub-Criteria LSC
Luminance ratio LR
Optimal value of lighting indicator P_R
Overhead luminance OL(cd/m^2)
Significant Indicator SI
Wall luminance WL(cd/m^2)

directionality of light, and dynamics.

Usually, multiple factor assessments require the use of analytical tools that allow the comparison and ranking of the relevance of the evaluated factors; one of these tools is, as for example, the analytic hierarchy process (AHP). The AHP was extensively studied and used in a wide number of applications in which a multiple criteria decision making (MCDM) is required [25,26]. AHP was used in several technical fields to pursue different purposes. In particular in the building sector, Nadoushani et al. [27] used AHP for supporting the selection of building façade systems, based on sustainability criteria. Some researchers used AHP for the selection of the most appropriate renewable energy package [28–30]. Kurka [31] and Ng [32] proposed AHP for the evaluation of environmentally-friendly bioenergy and products development, respectively, while Hopfe et al. [33] and Kangaraj and Mahalingam [34] applied it in the evaluation of the overall building performance and of the energy performance design. Other authors used AHP for supporting the identification of the best energy retrofit in historic buildings [35], in non-domestic buildings [36], and in government buildings [37]. The AHP was also applied for the selection and development of intelligent building systems [38,39], whereas Lai and Yik [40] proposed a method for the evaluation of the facility management services of residential buildings. In the field of safety in construction processes, Aminbakhsh et al. [41] proposed a method for creating risk rankings, Tavares et al. [42] for the identification of the most probable fire origin room, and Naziris et al. [43] for optimizing the fire protection of the cultural heritage structures. Regarding health and comfort in indoor environment, AHP was used by Santos et al. [44] for the evaluation of the social Life Cycle Assessment of school buildings and Lee et al. [45] for the evaluation of the well-being index in super tall residential buildings. Liu et al. [46] proposed AHP to quantify the weight of the physiological, behavioural, and psychological portions inside the adaptation process in the evaluation of thermal comfort. The application of AHP in the evaluation of the acoustic quality of the learning environment and for the identification of the best improvement interventions was proposed by Madbouly et al. [47] and by Yang and Mak [48]. As regards lighting, the application of AHP was proposed only for the evaluation of the potential energy saving of different control strategies [49], whereas it was not yet used to assess the lighting quality.

In this paper an original lighting quality assessment method (LQAM) based on AHP for the evaluation of lighting quality in educational buildings is proposed. According to the recent trend which involves the aggregation of multiple aspects in the lighting quality assessment, the LQAM method allows to consider the main contributions to achieve high levels of visual comfort and to determine a ranking of the criticisms, in order to plan improvement interventions. This method was designed to be adaptable and relevant for other kind of work environments too, in such a way as to represent a tool of practical use for experts and technicians. In particular, the LQAM was applied both at the scale of the single classroom and of a group of six classrooms, considering the buildings of the School of Engineering of the University of Pisa as case study. Finally, in the same classrooms used as case studies, subjective surveys were collected, in order to verify the correspondence between the results of LQAM and the actual perceptions of users. It was observed a substantial correspondence between LQAM and subjective surveys, proving the validity of the proposed assessment method.

2. Methodology

The LQAM developed in the present paper aims to be an effective and practical tool for the assessment of the lighting quality and the identification of its most critical aspects in educational buildings. The proposed method can facilitate the task of the personnel devoted to the assessment of the lighting conditions in such environments and can be used for guiding the choices of improvement interventions necessary to guarantee adequate levels of visual comfort.

2.1. Structure of the method and use of the AHP

The AHP is a multiple criteria decision-making method that allows the breakdown of a complex problem into a system of hierarchies, by reducing complex decisions to a series of pairwise comparisons, and then synthesizing the results [50,51]. The AHP generates a weight for each evaluation criterion, according to the decision maker's pairwise comparisons of criteria. The higher the weight is, the more important the corresponding criterion and it is possible to create a rank among the analysed criteria. In addition, the AHP incorporates a useful method for checking the consistency of the results, thus reducing the bias in the decision making process. The description of the AHP is included in the *Supplementary materials*.

The proposed LQAM is composed of three main different steps, summarized as follows:

- first step: a set of lighting criteria and sub-criteria is identified for evaluating the quality of lighting in educational rooms. For each sub-criterion, an indicator (reference values of which are fixed by technical standards or scientific literature) is identified, in order to quantitatively or qualitatively assess the sub-criterion itself. The deviation between the value of each indicator and the respective reference value is used to evaluate the quality of each sub-criterion;
- second step: the AHP is applied to define the relative weights of each criterion and sub-criterion on the lighting quality of the investigated room. For this purpose the results of a survey through questionnaires, submitted to a sample of experts in building physics, are collected and analysed. The experts are called to evaluate the importance of the various criteria and sub-criteria by a series of pairwise comparisons. This step ends with an analysis aiming at evaluating the consistency of the assigned weights;
- third step: the values of the indicators used to evaluate the sub-criteria in the current situation are acquired (e.g. by way of inspections, measurements, calculations, or simulations) for each investigated room and are compared to the respective reference values. The differences, weighted as in the previous step, provide a final score, which expresses the quality of the lighting in the investigated room.

2.2. Step 1: definition of lighting criteria, sub-criteria, indicators and deviations from the reference values

The proposed method is based on the selection of a set of relevant criteria and sub-criteria able to evaluate the quality of the lighting systems of educational rooms. The set of relevant criteria must be sufficiently concise (a limited number to allow a practical application) and significant (able to allow an adequate characterization of the lighting quality in the investigated room). Based on the scientific literature [11, 21–24,52–55] and international technical standards [56–60], a set of five different lighting criteria (LC) was selected, each of them split into three lighting sub-criteria (LSC), as indicated in Table 1.

Some of the LSC can be analysed through field measurements and simple analytical calculations (quantitative evaluation), other through field visual checks (qualitative evaluation). The indicators considered for the analysis of each single LSC are also reported in Table 1. The choice of the LSC indicators was carried out taking into account the possibility to obtain a direct evaluation using only portable measurement instruments (i.e. illuminance meter, luminance meter, flicker meter).

The lighting quality of an environment is evaluated by assigning a deviation indicator (DI), variable in the 0–1 range to each LSC. The closer the indicator is to 0, the better the lighting quality is with respect to the considered LSC; the more the indicator approaches 1, the more urgent is the need for improvement with respect to the considered LSC. The DI is assigned by comparing the value obtained for the indicator with the reference one, for the investigated room with specific visual tasks. DI can be assigned by using Table 2, after calculating the deviation (D) from the reference value with the equation:

$$D = (P - P_R)/P_R \quad (1)$$

Table 1
Proposed LQAM: list of lighting criteria (LC), sub-criteria (LSC) and related evaluation indicators.

Lighting Criterion	Lighting Sub-Criterion	Type of evaluation	Evaluation indicator	Unit
LC1 Amount of light	LSC1.1 Illuminance	QT	Average illuminance over the task area (E_m)	lx
	LSC1.2 Illuminance uniformity	QT	Illuminance uniformity over the task area (U_0)	–
	LSC1.3 Luminance distribution	QT	Luminance ratio (LR)	–
LC2 Glare	LSC2.1 Discomfort glare	QT	CIE flux code (2nd number)	–
	LSC2.2 Overhead glare	QT	Overhead luminance (OL)	cd/m^2
	LSC2.3 Daylight glare	QL	Presence and type of shading system	–
LC3 Colour appearance	LSC3.1 Colour rendition	QT	Colour rendering index (Ra)	–
	LSC3.2 Colour temperature	QT	Correlated colour temperature (CCT)	K
	LSC3.3 Surface treatments	QT	Walls luminance (WL)	cd/m^2
LC4 Flexibility	LSC4.1 Lighting scenes	QL	Presence of switching device	–
	LSC4.2 Adjustment of luminous flux	QL	Presence of dimming device	–
	LSC4.3 Adjustment of CCT	QL	Presence of CCT control device	–
LC5 Healthiness	LSC5.1 Daylight availability	QT	Daylight factor (DF)	–
	LSC5.2 Flicker effects	QT	Flicker index (f_{FI})	–
	LSC5.3 Circadian effects	QT	Circadian stimulus (CS)	–

Legend: QT = quantitative evaluation; QL = qualitative evaluation.

where: P is the value obtained for the indicator of the considered LSC in the actual conditions and P_R is the corresponding reference value. By way of example, when evaluating LSC1.1 (illuminance) in a classroom, an average value on the worktop (school desks) of 100 lx is measured (P = 100) and the value suggested by the technical standard is 300 lx (P_R = 300), $|D|$ = 66% is obtained. Therefore, according to Table 2, DI = 1. It is important to notice that the D ranges shown in Table 2 were defined by the Authors (as starting point), and they could be modified based on the expertise of the personnel that performs the evaluation.

2.3. Step 2: determination of lighting criteria and sub-criteria weights using AHP

To take into proper consideration the weight of each LC (and LSC) on the overall lighting quality, a questionnaire (added as *Supplementary Materials*) was distributed to a sample of experts. The sample consisted of 12 experts in different technical fields related to the building physics, with at least an experience of three years, as found in other studies [27]. A summary of the main characteristics of the sample is shown in Table 3, where for each expert are reported current position, academic degree, field of expertise, and years of experience.

The questionnaire is composed of 25 pairwise comparisons, 10 of which are related to the LC and 15 to the LSC. Experts had to express their preferences, on a 9 point scale, by evaluating the relative importance among the compared LC or LSC for the visual comfort achievement in educational rooms. The questionnaire was electronically administered, with the specification of completing the pairwise comparisons referring to educational rooms in general, without reference to a specific case study, but based on their experience. The results of the pairwise comparisons were analysed according to AHP, in order to obtain the weights of each LC and LSC with respect to the lighting quality. Since the experts were asked to judge conceptual criteria (lighting criteria and sub-criteria, see Table 1) without reference to a specific case study, and not directly the physical quantities used for their quantification (evaluation indicators, see Table 1), the sub-criteria were treated as independent variables, in analogy to other studies related to the indoor environmental quality [44,47]. The weights obtained for each lighting criterion (LC weight) are reported in Table 4, together with the local (LSC local weight, normalized on single LC) and global (LSC global weight, normalized on all the LC) weights obtained for each lighting sub-criterion. It should be noticed that the obtained weights are the expression of the sensitivity and experience of a sample of 12 experts (see Table 3) and are strictly referred to educational rooms. The specific values of the weights are therefore a proposal made in this study and could be adjusted in the future, even with the extension of the sample of experts, without compromising the validity of the proposed assessing method.

In order to adequately justify the data shown in Table 4, the results obtained from LC and LSC comparisons are reported in detail in Tables 5 and 6. The consistency ratios (CR) of the obtained weights are in the range 0.001–0.04 (see Tables 5 and 6), which is considered adequate [51] in order to guarantee a high consistency of the results. Using the collected data, the five lighting criteria can be organized, according to their global relevance, as follows (see Table 4): Glare (LC2), Amount of light (LC1), Healthiness (LC5), Flexibility (LC4), Colour appearance (LC3). Moreover, from the collected data it is possible to highlight that (see Table 4): Luminance distribution (LSC1.3), Daylight glare (LSC2.3), Surface treatments (LSC3.3), Lighting scenes (LSC4.1) and Daylight availability (LSC5.1) represent the most important lighting sub-criteria inside the respective LC. In order to simplify the data interpretation, the LC weights are shown in the radar chart of Fig. 1, while the LSC global weights are shown in the bar chart of Fig. 2, sorted in descending order of relevance. It is possible to observe that the Daylight glare (LSC2.3, global weight 0.199) represents the most relevant lighting sub-criterion among the all considered, while the Colour temperature of

Table 2
Deviation indicators (DI) for each LSC in function of Deviations (D) between the actual and the reference values.

LSC	Indicator	Type of evaluation	D or other reference range		DI
LSC1.1	Average illuminance over the task area (E_m)	Comparison with minimum value	$D \geq -15\%$		**0**
			$-30\% \leq D < -15\%$		**0.25**
			$-45\% \leq D < -30\%$		**0.50**
			$-60\% \leq D < -45\%$		**0.75**
			$D < -60\%$		**1**
LSC1.2	Illuminance uniformity over the task area (U_0)	Comparison with minimum value	$D \geq 0\%$		**0**
			$-15\% \leq D < 0\%$		**0.25**
			$-30\% \leq D < -15\%$		**0.50**
			$-45\% \leq D < -30\%$		**0.75**
			$D < -45\%$		**1**
LSC1.3	Luminance ratio (LR)	Comparison with range of acceptability	Static vision	Dynamic vision	
			$1/3 \leq LR \leq 3$	$1/10 \leq LR \leq 10$	**0**
			$1/10 \leq LR \leq 10$	$1/20 \leq LR \leq 20$	**0.25**
			$1/20 \leq LR \leq 20$	$1/40 \leq LR \leq 40$	**0.50**
			$1/40 \leq LR \leq 40$	$1/60 \leq LR \leq 60$	**0.75**
			$LR < 1/40$ or $LR > 40$	$LR < 1/60$ or $LR > 60$	**1**
LSC2.1	CIE flux code (2nd number)	Comparison with minimum value	$D \geq 0\%$		**0**
			$-15\% \leq D < 0\%$		**0.25**
			$-30\% \leq D < -15\%$		**0.50**
			$-45\% \leq D < -30\%$		**0.75**
			$D < -45\%$		**1**
LSC2.2	Overhead luminance (OL)	Comparison with maximum value	$D \leq 0\%$		**0**
			$0\% > D \geq 15\%$		**0.25**
			$15\% > D \geq 30\%$		**0.50**
			$30\% > D \geq 45\%$		**0.75**
			$D > 45\%$		**1**
LSC2.3	Presence and type of shading system	Qualitative evaluation	Manually or automatically adjustable/not necessary		**0**
			Automatically adjustable		**0.25**
			Manually adjustable		**0.50**
			Fixed		**0.75**
			Not present or not working		**1**
LSC3.1	Colour rendering index (Ra)	Comparison with minimum value	$D \geq 0\%$		**0**
			$-10\% \leq D < 0\%$		**0.25**
			$-20\% \leq D < -10\%$		**0.50**
			$-30\% \leq D < -20\%$		**0.75**
			$D < -30\%$		**1**
LSC3.2	Correlated colour temperature (CCT)	Comparison with range of acceptability		$D_{min} \geq 0\%$ and $D_{max} \leq 0\%$	**0**
				$-15\% \leq D_{min} < 0\%$ and $0\% < D_{max} \leq 15\%$	**0.25**
				$-30\% \leq D_{min} < -15\%$ and $15\% < D_{max} \leq 30\%$	**0.50**
				$-45\% \leq D_{min} < -30\%$ and $30\% < D_{max} \leq 45\%$	**0.75**
				$D_{min} < -45\%$ and $D_{max} > 45\%$	**1**
LSC3.3	Walls luminance (WL)	Comparison with range of acceptability		$D_{min} \geq 0\%$ and $D_{max} \leq 0\%$	**0**
				$-15\% \leq D_{min} < 0\%$ and $0\% < D_{max} \leq 15\%$	**0.25**
				$-30\% \leq D_{min} < -15\%$ and $15\% < D_{max} \leq 30\%$	**0.50**
				$-45\% \leq D_{min} < -30\%$ and $30\% < D_{max} \leq 45\%$	**0.75**
				$D_{min} < -45\%$ and $D_{max} > 45\%$	**1**
LSC4.1	Presence of switching device	Qualitative evaluation		Yes	**0**
				No	**1**
LSC4.2	Presence of dimming device	Qualitative evaluation		Yes	**0**
				No	**1**
LSC4.3	Presence of CCT control device	Qualitative evaluation		Yes	**0**
				No	**1**
LSC5.1	Daylight factor (DF)	Comparison with minimum value		$D \geq 0\%$	**0**
				$-25\% \leq D < 0\%$	**0.25**
				$-50\% \leq D < -25\%$	**0.50**
				$-75\% \leq D < -50\%$	**0.75**
				$D < -75\%$	**1**
LSC5.2	Flicker index (f_{FI})	Comparison with maximum value		$D \leq 0\%$	**0**
				$0\% > D \geq 15\%$	**0.25**
				$15\% > D \geq 30\%$	**0.50**
				$30\% > D \geq 45\%$	**0.75**

(*continued on next page*)

Table 2 (*continued*)

LSC	Indicator	Type of evaluation	D or other reference range	DI
			D >45%	**1**
LSC5.3	Circadian stimulus (CS)	Comparison with minimum value	D ≥ 0%	**0**
			−25% ≤ D <0%	**0.25**
			−50% ≤ D < −25%	**0.50**
			−75% ≤ D < −50%	**0.75**
			D < −75%	**1**

Table 3
Expertise overview of the subjects belonging to the sample of experts.

ID	Position	Academic degree	Field of expertise	Years of experience
1	Researcher	PhD MsME	Energy performance of buildings	25
2		PhD MsCE	Thermal, acoustic and visual comfort	15
3		PhD MsAE	Health and safety in work environments	15
4	PhD student	MsBE	IEQ	3
5		MsCE	Building design	3
6		MsArch	Daylight and interior design	3
7	Project engineer	MsArch	Lighting design and architecture	12
8		MsBE	Lighting systems design	5
9	Lighting manager	MsBEArch	Lighting design and architecture	10
10	R&D manager	MsBEArch	Lighting systems design	9
11	Technical consultant	MsBE	Human exposure to physical agents	5
12	Independent contractor	MsCE	Building design	5

Legend: Ms = Master Science Degree; ME = Mechanical Engineering; CE=Civil Engineering; AE = Aerospace Engineering; BE=Building Engineering; Arch = Architecture.

Table 4
Weights obtained using AHP for the lighting criteria (LC) and sub-criteria (LSC).

LC	LC weight	LSC	LSC local weight	LSC global weight
LC1	0.253	LSC1.1	0.123	0.031
		LSC1.2	0.320	0.081
		LSC1.3	0.557	0.141
LC2	0.351	LSC2.1	0.334	0.117
		LSC2.2	0.098	0.034
		LSC2.3	0.568	0.199
LC3	0.075	LSC3.1	0.286	0.021
		LSC3.2	0.143	0.011
		LSC3.3	0.571	0.043
LC4	0.153	LSC4.1	0.557	0.085
		LSC4.2	0.320	0.049
		LSC4.3	0.123	0.019
LC5	0.168	LSC5.1	0.581	0.098
		LSC5.2	0.309	0.052
		LSC5.3	0.110	0.018

the source (LSC3.2, global weight 0.011) represents the less relevant (Fig. 2).

2.4. Step 3: acquisition of the values for the evaluation indicators and calculation of the final score for the lighting criteria and sub-criteria

As previously reported, the values of some indicators used to

Table 5
Results of pairwise comparisons among the LC.

Lighting Criteria (obtained consistency ratio CR = 0.02)					
	LC1	LC2	LC3	LC4	LC5
LC1	1	1/2	3	2	2
LC2	2	1	4	2	2
LC3	1/3	1/4	1	1/2	1/3
LC4	1/2	1/2	2	1	1
LC5	1/2	1/2	3	1	1

Table 6
Results of pairwise comparisons among the LCS.

Amount of light (consistency ratio CR = 0.02)			
	LSC1.1	LSC1.2	LSC1.3
LSC1.1	1	1/3	1/4
LSC1.2	3	1	1/2
LSC1.3	4	2	1
Glare (consistency ratio CR = 0.02)			
	LSC2.1	LSC2.2	LSC2.3
LSC2.1	1	4	1/2
LSC2.2	1/4	1	1/5
LSC2.3	2	5	1
Colour Appearance (consistency ratio CR = 0.001)			
	LSC3.1	LSC3.2	LSC3.3
LSC3.1	1	2	1/2
LSC3.2	1/2	1	1/4
LSC3.3	2	4	1
Flexibility (consistency ratio CR = 0.02)			
	LSC4.1	LSC4.2	LSC4.3
LSC4.1	1	2	4
LSC4.2	1/2	1	3
LSC4.3	1/4	1/3	1
Healthiness (consistency ratio CR = 0.04)			
	LSC5.1	LSC5.2	LSC5.3
LSC5.1	1	2	5
LSC5.2	1/2	1	3
LSC5.3	1/5	1/3	1

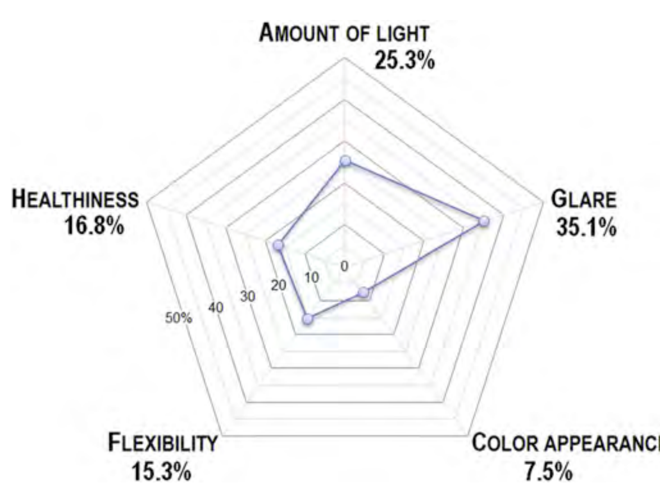

Fig. 1. AHP results: radar chart of the lighting criteria (LC) weights.

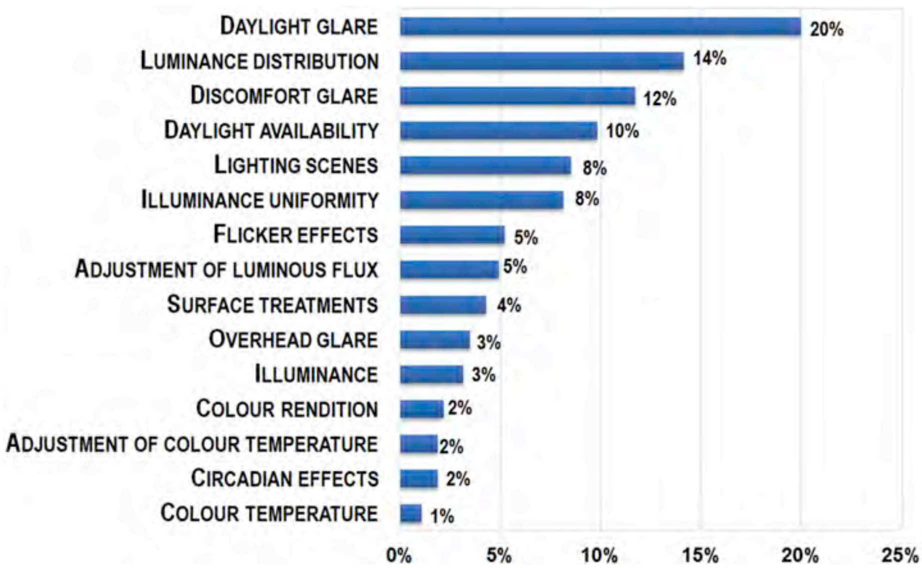

Fig. 2. AHP results: bar chart of the lighting sub-criteria (LSC) global weights.

evaluate LSC in the current situation can be obtained through field measurements and simple analytical calculations, other ones through field visual checks.

In this study a measurement campaign was carried out for the acquisition of the following parameters:

- horizontal illuminance on the floors and desks;
- vertical illuminance on the blackboard and at height of the observer's eye (students);
- luminance of the surfaces representing the main objects of vision (blackboard, desks, side walls);
- luminance above the area occupied by desks;
- spectral power distribution, flicker index, colour rendering index, and correlated colour temperature of the light sources in the room.

Measurement instruments available at the 'Lighting and Acoustics Laboratory' of the University of Pisa were used:

- illuminance meter *RadioLux 1111 PRC Krochmann* (operative range 0.001 ÷ 360,000 lx, accuracy $\leq$1.5%);
- luminance meter *Hagner S4* (operative range 0 ÷ 200,000 cd/m^2, accuracy $\leq$3%);
- illuminance spectrophotometer *Minolta CL-500A* (operative range 0.1 ÷ 100,000 lx, accuracy $\leq$2%);
- flicker meter *UPRtek MF250 N* (operative range 70 ÷ 70,000 lx, accuracy $\leq$5%).

The collected data were used for calculating the average illuminance values and the illuminance uniformity on the main work-place (student desks, teacher blackboard and floor), the luminance ratios on the main directions of view (student desks-blackboards for dynamic visual task, and blackboard-background and desks-floor for static visual task), and the daylight factor (average over the whole room). In order to guarantee repeatability of the measurements, they should be carried out following the prescriptions of technical standards or acknowledged guidelines. In this study grids with a minimum number of measurement points and minimum distance between them which are function of the task area size were used, according to European standards [60].

The Circadian Stimulus (CS) was determined by using the analytical model proposed by the Lighting Research Centre of the Rensselaer Polytechnic Institute [61,62], which allows the calculation of the CS value from the vertical illuminance detected to the eye of the observer and the spectral distribution of the light source. In order to apply the proposed method, the room analysis was completed with the survey of the luminaires and any devices for the control and regulation of the artificial lighting system and with the qualitative analysis of the shading systems for the solar radiation.

Once the values of the indicators are known and considering the weights shown in Table 4, determined using the AHP, for each LSC it is possible to calculate the final score (FS_i), using the equation:

$$FS_i = DI_i \cdot W_i \tag{2}$$

where: DI_i and W_i are respectively the deviation indicator and the weight for the i-th LSC. Summing the final scores of pertinent LSC, an overall score for each LC can be obtained; summing the final scores of all the LSC, an overall score for the investigated room can be finally found. Calculating the sum seems the most simple and logic approach in order to consider the degree of the criticalities (unfavourable deviations from the reference values) found in the various classrooms. Choosing the mean value as an alternative could be worst, because it could affect and misrepresent the results. In this way, the higher is the sum, the higher is the problem (even if the contribution to the sum is due to only one or a few classrooms). The described scores allow to directly compare the results obtained for different rooms and to point out the critical aspects of the rooms that need for more urgent interventions. Since DI and W vary in the 0–1 range, FS varies in the same range too. By ordering the FS from the largest to the smallest it is possible to obtain a ranking of the LSC in relation to the priority of improvement interventions.

2.5. Subjective survey

The aim of the LQAM method is to avoid to supply questionnaires to the occupants which are very time and money demanding. In addition, the perception of visual comfort is strongly influenced by the ability to adaptation and, especially in environments not continuously occupied, a conscious evaluation is difficult. However, in order to verify the reliability of the LQAM and to find the correspondence between LQAM results and the perception of the occupants, an evaluation by means of questionnaires was also carried out in 6 classrooms used as case study and detailed described in Section 3. The questionnaire was anonymous and it was prepared with questions as much as possible clear and unambiguous [1].

Apart from the initial information (gender and age), the questionnaire is composed of 14 closed-ended questions on a 11-point Likert

Table 7
Plan of the questionnaires surveys.

Classroom	Weather conditions	Date	Time	Administered questionnaires
C1	Clear sky	10/12/2018	10:30	33
	Partially overcast sky (clear clouds)	08/03/2019	12:30	20
	Clear sky (just veiled)	19/03/2019	15:30	19
C2	Uniformly covered sky (gray clouds)	06/12/2018	09:30	27
	Clear sky (just veiled)	06/03/2019	12:30	19
	Clear sky (just veiled)	12/03/2019	15:30	20
C3	Uniformly covered sky (gray clouds)	12/12/2018	10:30	31
	Clear sky (just veiled)	06/03/2019	12:30	21
	Clear sky	15/03/2019	14:30	21
C4	Clear sky	17/12/2018	15:30	23
	Partially overcast sky (clear clouds)	08/03/2019	12:30	17
	Uniformly covered sky (gray clouds and rain)	13/03/2019	10:30	20
C5	Uniformly covered sky (gray clouds)	17/12/2018	09:30	25
	Clear sky	22/03/2019	11:30	25
	Clear sky	15/03/2019	14:30	24
C6	Partially overcast sky (clear clouds)	13/12/2018	10:30	27
	Clear sky	22/03/2019	11:30	20
	Uniformly covered sky (gray clouds and rain)	13/03/2019	10:30	26

Note: Based on the analysis of different photos taken from the windows during the administration of the questionnaires, the sky conditions were mainly grouped as: 'Clear sky' (less than 10% of the sky occupied by cloud) and 'Uniformly covered sky' (less than 10% of the sky not occupied by cloud). All the intermediate conditions were considered as 'Partially overcast sky'.

scale (from 0 to 10), divided in five parts corresponding to the five lighting criteria proposed in the LQAM: LC1–Amount of light, LC2–Glare, LC3–Colour appearance, LC4–Flexibility, and LC5–Healthiness. Each question is referred to a specific LSC, in order to simplify the interpretation of the results and the comparison with the LQAM results. It was not possible to write questions for each LSC, because some issues were difficult to be evaluated by not specialist persons, therefore the 14 questions cover 10 of the 15 LSC. The questions related to the LSC1.1 and LSC1.2 are three for each LSC because referred to three different task areas (desks, blackboard, floor) and they are differentiated by numbering them alphabetically (i.e. LSC1.1A, LSC1.1B, LSC1.1C, LSC1.2A, LSC1.2B, LSC1.2C). The text of the questionnaire is showed in the *Supplementary materials*. The participants were students in part of the Bachelor degree in 'Civil Engineering' and in part of the Master degree in 'Building Engineering', who attended lectures of 'Building Physics', 'Lighting and Applied Acoustics', and 'HVAC Systems Design'. The questionnaire was supplied during the lectures, however the participation was voluntary and no pressure was made to push anyone to complete the questionnaire. The period of the surveys was December 2018–March 2019 and each one was repeated in each classroom on three different days, in order to evaluate the influence of the external weather conditions on the subjective evaluation. The detail of the plan of the questionnaire administration is reported in Table 7, in which the sky conditions, the date and time of each survey and the number of the filled questionnaires is showed.

3. Case study

A sample of six university classrooms of the School of Engineering at Pisa University was chosen as case study, in order to test the LQAM. The classrooms were selected considering geometric characteristics, number of seats, intended use, materials, and properties of the lighting system, so that the sample is representative of the overall 51 classrooms of the School. Some pictures of the classrooms are shown in Fig. 3; they are identified with the codes C1, C2, …, C6. Their main characteristics are summarized in Table 8, where the dimensions, the materials and the fixtures, the number of luminaires and lamps, the nominal power of lamps, and the presence of control systems for different lighting scenes are reported. The volume of the selected classrooms is in the 230–1450 m^3 range (C1 and C6 rooms respectively); they are mainly intended for the lectures, with the use of blackboard or video projection panel. Only one classroom (C3) is an educational laboratory set up with personal computers.

In Table 9 the reference values, defined for the assessment of the lighting quality of the sample, are shown for each LSC indicator (see Table 1). The reference values are taken from international technical standards, technical guidelines, or scientific literature, considering the visual tasks of blackboard reading, desk writing and reading, orientation for movements inside the classroom. In Table 9 the LSC for which qualitative evaluations are provided (LSC2.3, LSC4.1, LSC4.2, LSC4.3) are missing; in these cases reference values are not required and it is possible to check the related indicators (see Table 1) simply by visual inspections.

4. Results

4.1. Application of LQAM to a university classroom

The application of the LQAM to a single classroom provides an in-depth analysis of the room, with the aim of identifying the critical aspects. As an example, results related to classroom C1 are reported in Table 10, where: the measured values (P), the reference values (P_R), the

Fig. 3. Photos of the selected classrooms for the application of the LQAM.

Table 8
Main characteristics of the selected classrooms.

	C1	C2	C3	C4	C5	C6
Type	Teaching room	Teaching room	Computer room	Teaching room	Teaching room	Teaching room
Seats	88	139	84	216	142	208
Width (m)	7.6	10.6	11.5	10.3	14.0	13.7
Length (m)	11.7	14.7	18.7	21.0	13.3	17.8
Height max (m)	2.6	3.5	2.8	5.6	5.6	7
Volume (m^3)	231	512	613	745	910	1452
Floor area (m^2)	89	156	215	216	186	244
Ceiling material	Plaster	Panels	Panels	Panels	Plaster	Plaster
Floor material	Ceramic tiles	Rubber	Marble	Marble	Ceramic tiles	Rubber
Surface wall material	Plaster	Plaster	Plaster	Plaster	Plaster	Plaster
Average reflection coefficient	0.50	0.60	0.50	0.45	0.50	0.60
No. of window	2	3	9	16	6	3
Total window surface (m^2)	6.7	14.4	32	80	18	22
Material of window frame	Wood	Metal	Metal	Metal	Wood	Metal
Type of glass	Single glass	Double glass	Double glass	Double glass	Single glass	Double glass
No. of luminaires	15	20	22	15	16	30
Type of lamps	Fluorescent	Fluorescent	Fluorescent	Fluorescent	Fluorescent	Fluorescent
No. of lamps	30	80	44	30	32	60
Power of lamp	58	18	58	58	58	58
Shading system	Absent	Window films	Fixed sunblinds	Fixed sunblinds	Roller blinds	Roller blinds
Lighting scenes	Allowed	Allowed	Allowed	Allowed	Allowed	Allowed
Dimming device	NO	Yes	NO	NO	NO	Yes
CCT control device	NO	NO	NO	NO	NO	NO

Note: during the survey period, the roller blinds in C5 classroom were not fully functional.

Table 9
Reference values and related sources (Ref.) for the LSC indicators.

LSC	Indicator	Reference value	Ref.
LSC1.1	E_m (lx)	500 (blackboard), 300 (desk), 100 (corridor)	[60]
LSC1.2	U_0	0.7 (blackboard), 0.6 (desk and corridor)	[60]
LSC1.3	LR	1/3 ÷ 3 (static vision), 1/10 ÷ 10 (dynamic vision)	[58]
LSC2.1	CIE flux code (2nd number)	≤90	[57]
LSC2.2	OL (cd/m^2)	≤16000 cd/m^2	[59]
LSC3.1	Ra	≥80	[60]
LSC3.2	CCT (K)	4000 ÷ 6000 K	[63]
LSC3.3	WL (cd/m^2)	30 ÷ 40	[64, 65]
LSC5.1	DF	≥3%	[66]
LSC5.2	f_{FI}	≤0.1	[57]
LSC5.3	CS	≥0.2	[61]

DI, W, and FS values are shown for each LSC. The rank, obtained by ordering the values of FS from largest to smallest, is reported in the last column.

Results show that the absence of shading system for solar radiation represents the most relevant weakness (FS = 0.199, rank = 1). Furthermore, the choice of the artificial lighting system can be considered as suitable when taking into account static visual tasks. It is justified by the scores for average illuminance levels on teacher blackboard (FS = 0.031, rank = 10), illuminance uniformity on the desks and blackboard (FS = 0.041, rank = 6), colour rendering index (FS = 0.011, rank = 13), and correlated colour temperature (FS = 0.00, no rank). On the other hand, it is not possible to assert the same for dynamic visual tasks: the luminance ratios in the student's visual field are significantly outside the reference values, especially the one between the surfaces of desk and blackboard (FS = 0.106, rank = 2) typically observed by students for reading and writing. The illuminance uniformity on the floor is also poor (FS = 0.081, rank = 3), right along the paths used for moving around the classrooms.

Table 10
Results of LQAM for the classroom C1.

LC	LSC	Indicator	Surface/Element	P_R	P	DI	W	FS	Rank
LC1	**LSC1.1**	Average illuminance over the task area (E_m, lx)	Student Desks	300	847	0	0.031	0.000	–
			Teacher blackboard	500	175	1	0.031	0.031	**10**
			Floor	100	383	0	0.031	0.000	–
	LSC1.2	Illuminance uniformity over the task area (U_0)	Student Desks	0.60	0.42	0.5	0.081	0.041	**6**
			Teacher blackboard	0.70	0.50	0.5	0.081	0.041	**6**
			Floor	0.40	0.13	1	0.081	0.081	**3**
	LSC1.3	Luminance ratio (LR)	Desk–Blackboard (dynamic visual task)	1/10 ÷ 10	25	0.75	0.141	0.106	**2**
			Blackboard–Background (static visual task)	1/3 ÷ 3	0.26	0.25	0.141	0.035	**8**
			Desk–Floor (static visual task)	1/3 ÷ 3	3.80	0.25	0.141	0.035	**8**
LC2	**LSC2.1**	CIE flux code (2nd number)		90	97	0	0.117	0.000	–
	LSC2.2	Overhead luminance (OL, cd/m^2)		16,000	11,000	0	0.034	0.000	–
	LSC2.3	Presence and type of shading system		–	Absent	1	0.199	0.199	**1**
LC3	**LSC3.1**	Colour rendering index (Ra)		80	70	0.25	0.021	0.011	**13**
	LSC3.2	Correlated colour temperature (CCT, K)		4000 ÷ 6000	4100	0	0.011	0.000	–
	LSC3.3	Walls luminance (WL, cd/m^2)		30 ÷ 40	21.8	0	0.043	0.021	**11**
LC4	**LSC4.1**	Presence of switching device		Yes	Yes	0	0.085	0	–
	LSC4.2	Presence of dimming device		Yes	No	1	0.049	0.049	**5**
	LSC4.3	Presence of CCT control device		Yes	No	1	0.019	0.019	**12**
LC5	**LSC5.1**	Daylight factor (DF)		3%	2.2%	0.5	0.098	0.049	**4**
	LSC5.2	Flicker index (f_{FI})		0.1	0.015	0	0.052	0.000	–
	LSC5.3	Circadian stimulus (CS)		0.3	0.32	1	0.018	0.000	–

Note: The LSCs that do not have rank are those that meet the respective reference values and do not need improvement interventions.

4.2. Application of LQAM to a group of classrooms

The application of LQAM to several classrooms (or to the whole building) can be useful when it is necessary to manage the building and to guide the evaluation of improvement interventions. In this cases, the interest is focused on understanding the issues which occur most frequently in the whole building (or on a group of rooms) and how much each of them impacts negatively the comfort conditions, with the aim of giving a priority scale to the interventions. In order to facilitate the use of LQAM, by making quicker the determination of DI, charts using the deviation ranges indicated in Table 2 can be created, by inserting the actual values of the considered LSC in the abscissas and the reference values in the ordinates and by separating the DI bands. As an example, the chart for the LSC1.1, whose indicator is the average illuminance over the task area (E_m), is shown in Fig. 4. The chart can be quickly used by entering the reference value and the actual value (measured, calculated or simulated) of E_m and identifying the related DI. The results of the application of the charts to the 6 classrooms are summarized in Fig. 5, only for LSCs with quantitative evaluation (see Table 1).

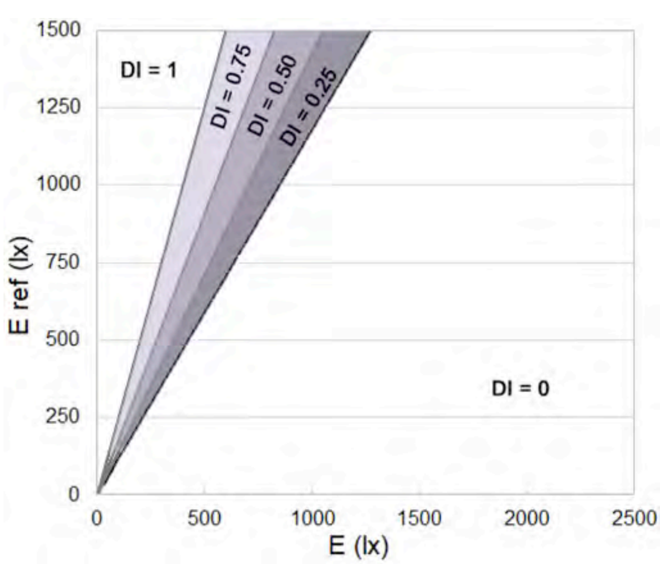

Fig. 4. Example of chart for the determination of DI: the case of LSC1.1 (illuminance).

The evaluated FS values, obtained for each LSC and for each investigated room, are shown in Table 11; when considering 21 LSCs and six classrooms, a grid of 126 FS values is obtained. Given a single LSC, by summing the FS values obtained for that LSC on all the classrooms, the total weighted score (FS_T) is obtained (see Table 11). Sorting the FS_T values from the higher to the lower, it is possible to identify which LSC introduces more stringent critical issues for the analysed building. This aspect can be very useful in guiding the choice of any interventions for improving the quality of lighting in the building.

For the investigated rooms the lighting issues, pointed out and described for the single classroom, are substantially confirmed. The main critical issues do not derive from the choice of lighting sources and illuminance levels, adequate for the visual tasks performed and the intended use of the investigated rooms. Rather, a criticism can be identified in the difficulty of a dynamic lighting control based, for example, on the type of teaching technique (i.e. writing on the blackboard, use of video projection): LSC4.2 results with rank = 3 (see Table 11). Another criticism is the ineffectiveness of the shading system for the direct solar radiation (LSC2.3, rank = 1, see Table 11). Moreover, the luminance distribution were not properly considered in the design phase (LSC1.3, rank = 2 or 5 if the blackboard is involved and LSC3.3, rank = 4, see Table 11). These results highlight inadequate lighting solutions when compared to current trends.

4.3. Surveys by means of questionnaires

A total of 420 questionnaires were filled, with a response rate of 98%. The overall sample is divided into 264 males (63%) and 156 females (37%), within the age range 20–32 years. In details, the sample is composed by 69% with students in the 20–24 years range, 28% in the 25–30 years, and 3% over 30 years. The average age of the participants is 23 years (S.D. 7.5 years). The questionnaires were collected in the period December 2018–March 2019 and the weather conditions during the surveys are reported in Table 7. The results were analysed at the scale of the single classroom and at the scale of the group of classrooms and the answers to the questions LSC1.1, LSC1.2, LSC2.1, LSC 2.3; LSC3.1, LSC3.3, LSC5.1; LSC5.2 were evaluated (Table 12). It should be

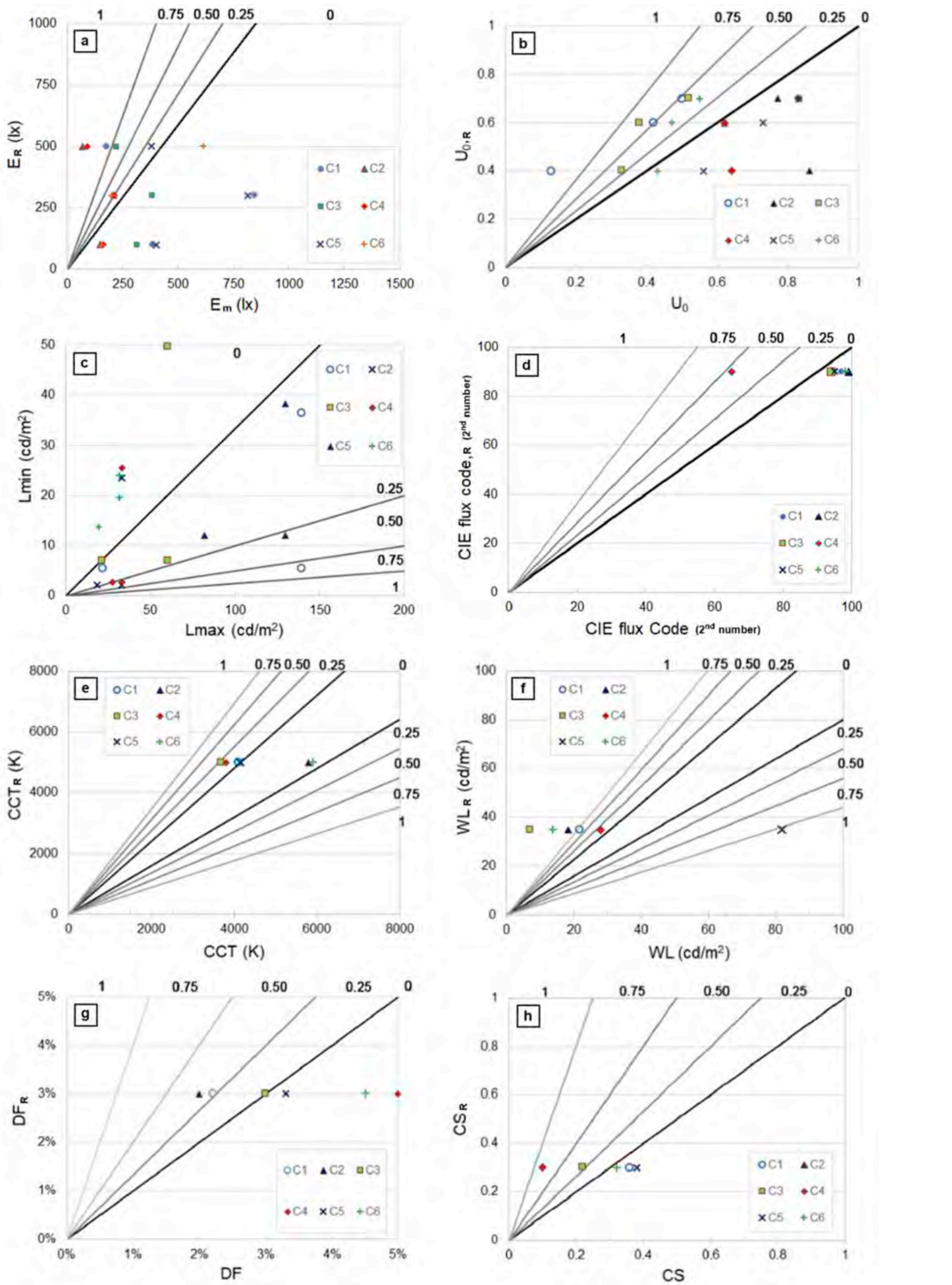

Fig. 5. DI determination charts for some LSC, using the results of the in situ evaluation activities (a–LSC1.1, b–LSC1.2, c–LSC1.3, d–LSC2.1, e–LSC3.2, f–LSC3.3, g–LSC5.1, h–LSC5.3).

Table 11
Weighted scores FS obtained for each LSC in each room, total weighted scores FS_T and rank of the found criticisms.

LC	LSC	Indicator	Surface/Element	FS ($x10^{-2}$)						FS_T ($x10^{-2}$)	Rank
				C1	C5	C3	C4	C2	C6		
LC1	**LSC1.1**	Average illuminance over the task area (E_m, lx)	Student Desks	0.00	0.00	0.00	0.78	1.55	1.55	3.88	**14**
			Teacher blackboard	3.11	0.78	2.33	3.11	3.11	0.00	12.44	**7**
			Floor	0.00	0.00	0.00	0.00	0.00	0.00	0.00	–
	LSC1.2	Illuminance uniformity over the task area (U_0)	Student Desks	4.06	0.00	6.08	0.00	0.00	4.06	14.20	**6**
			Teacher blackboard	4.06	0.00	4.06	0.00	0.00	4.06	12.18	**8**
			Floor	8.11	0.00	4.06	0.00	0.00	0.00	12.17	**8**
	LSC1.3	Luminance ratio (LR)	Desk–Blackboard (dynamic visual task)	10.58	7.06	3.53	7.06	7.06	0.00	35.29	**2**
			Blackboard–Background (static visual task)	3.53	3.53	3.53	3.53	3.53	0.00	17.65	**5**
			Desk–Floor (static visual task)	3.53	3.53	0.00	0.00	0.00	0.00	7.06	**13**
LC2	**LSC2.1**	CIE flux code (2nd number)		0.00	0.00	0.00	8.78	0.00	0.00	8.78	**12**
	LSC2.2	Overhead luminance (OL, cd/m^2)		0.00	0.00	0.00	0.00	0.00	0.00	0.00	–
	LSC2.3	Presence and type of shading system		19.94	19.94	14.96	14.96	14.96	4.98	89.74	**1**
LC3	**LSC3.1**	Colour rendering index (Ra)		1.07	0.00	0.53	0.53	0.53	0.00	2.66	**16**
	LSC3.2	Correlated colour temperature (CCT, K)		0.00	0.00	0.27	0.27	0.00	0.00	0.54	**18**
	LSC3.3	Walls luminance (WL, cd/m^2)		2.13	4.27	4.27	1.07	3.20	4.27	19.21	**4**
LC4	**LSC4.1**	Presence of switching device		0.00	0.00	0.00	0.00	0.00	0.00	0.00	–
	LSC4.2	Presence of dimming device		4.89	4.89	4.89	4.89	0.00	0.00	19.56	**3**
	LSC4.3	Presence of CCT control device		1.87	1.87	1.87	1.87	1.87	1.87	11.22	**10**
LC5	**LSC5.1**	Daylight factor (DF)		4.89	0.00	0.00	0.00	4.89	0.00	9.78	**11**
	LSC5.2	Flicker index (f_{FI})		0.00	0.00	0.00	0.00	0.00	0.00	0.00	–
	LSC5.3	Circadian stimulus (CS)		0.00	0.00	0.92	1.34	0.92	0.00	3.18	**15**

Table 12
Mean values and standard deviations (SD) of the questionnaires responses in the different campaigns.

		LC1						LC2		LC3		LC5		
		LSC 1.1A	LSC 11B	LSC 1.1C	LSC 1.2A	LSC 1.2B	LSC 1.2C	LSC 2.1	LSC 2.3	LSC 3.1	LSC 3.3	LSC 5.1	LSC 5.2	LSC 5.3
C1	Mean	7.93	7.41	7.26	7.8	6.87	6.92	8.03	7.96	7.38	6.69	6.76	8.1	4.75
	SD	1.17	1.16	1.42	1.37	1.44	1.38	1.59	1.15	1.43	1.62	1.69	1.49	2.82
C2	Mean	7.95	7.55	7.18	7.86	7.1	7.33	8.28	8.56	7.62	7.32	5.07	8.34	4.02
	SD	1.31	1.53	1.60	1.50	1.68	1.25	1.38	1.47	0.99	1.46	2.29	1.60	3.06
C3	Mean	7.46	6.77	6.57	7.33	6.17	6.19	7.53	8.06	6.49	6.03	5.45	7.37	5.27
	SD	1.06	1.55	1.56	1.27	1.79	1.60	1.74	1.89	2.07	2.08	2.45	1.89	2.72
C4	Mean	7.67	7.11	7.14	7.72	6.02	7.36	7.51	8.62	7.08	7.12	5.91	8.25	4.65
	SD	1.43	1.18	1.37	1.33	2.27	0.94	2.07	1.10	1.71	1.53	2.39	1.76	2.72
C5	Mean	7.68	6.98	6.74	7.20	6.55	6.61	7.96	7.66	6.98	6.72	6.07	7.99	5.04
	SD	1.30	1.55	1.54	1.53	1.65	1.49	1.61	1.96	1.55	1.50	2.08	1.68	2.73
C6	Mean	7.75	7.15	6.85	7.71	6.79	6.64	7.99	8.45	7.09	6.8	6.11	7.85	5.33
	SD	1.39	1.55	1.74	1.41	1.51	1.71	1.50	1.34	1.80	1.50	2.41	1.80	2.86

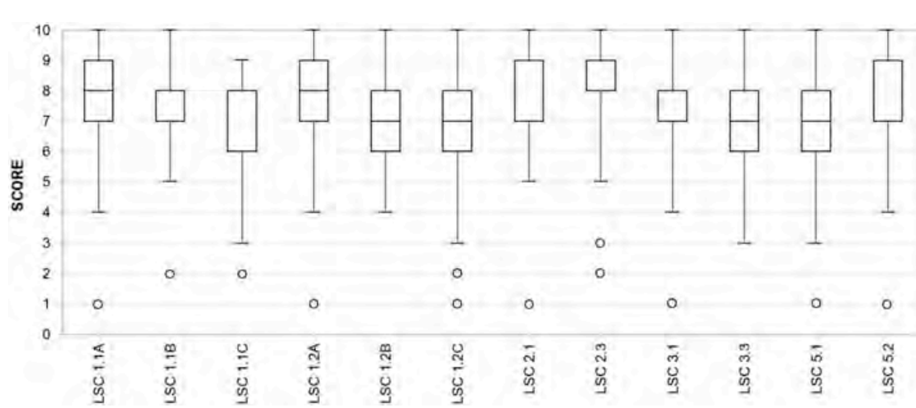

Fig. 6. Box plot of the responses obtained in the evaluation questionnaire in the C1 classroom during the three days of survey.

noticed that the analysis of the answers to the question LC4 (flexibility) was not considered because the students were not actually aware of the possible adjustments of the lighting systems. Table 12 shows the mean values and the standard deviations obtained from the responses given by the students in the different campaigns, taking into account different weather conditions. Additional data, about the results of the questionnaire for each day of the survey, are included in the *Supplementary materials*. Values which tend to 10 are the best for all the questions, except for the last one (LSC5.3).

The overall results on the three days of survey in the C1 classroom are shown in Fig. 6. From such results, it is possible to observe that students judged the lighting as positive. However, the attention should be paid not so much to the absolute value of the score obtained for each single LSC (lacking for the participants a direct comparison with optimal lighting conditions), but rather on the comparison among the relative scores of the different LSC, in order to identify those considered less favourable. In general the votes are high, for classrooms that present a high percentage of window surfaces with northern exposure (i.e. C1, C2); on the other hand, classroom C3 has the lowest values regardless the judged LSC (see Table 12).

More interesting comments can be obtained when comparing separately the sunny-days questionnaires and the cloudy-days ones. Therefore only the questionnaires of the clear-sky days and the ones of the cloudy days were compared. The most interesting results considering the illuminance distribution and uniformity can be observed in Fig. 7, for sunny (top) and cloudy (bottom) days, respectively. In sunny days the best behaviour is shown for classroom C1, which presents also the best lighting uniformity on the desk, on the blackboard, and on the pavement. In cloudy days, C2 can be considered the best one, especially for its uniform light distribution. Moreover, C3 is the worst classroom above all in cloudy days, and C4 shows a low score about illuminance uniformity on the board, especially in sunny days.

In general a good correlation between the LQAM and the questionnaires answers can be observed. As an example LQAM results could be compared with the questionnaires results for classroom C1. As for the LQAM, the questionnaires answers indicate that the artificial lighting system can be considered adequate if the static visual tasks are considered, but the illuminance uniformity is not very high on the floor and on the blackboard (scores lower than 7). Both methodologies lead to a positive evaluation of colour rendition.

The comparison between the results obtained by subjective evaluation and those obtained by the LQAM can be performed using the D_w parameter, defined as:

$$D_w = W_i \cdot (10 - S_j) \quad (3)$$

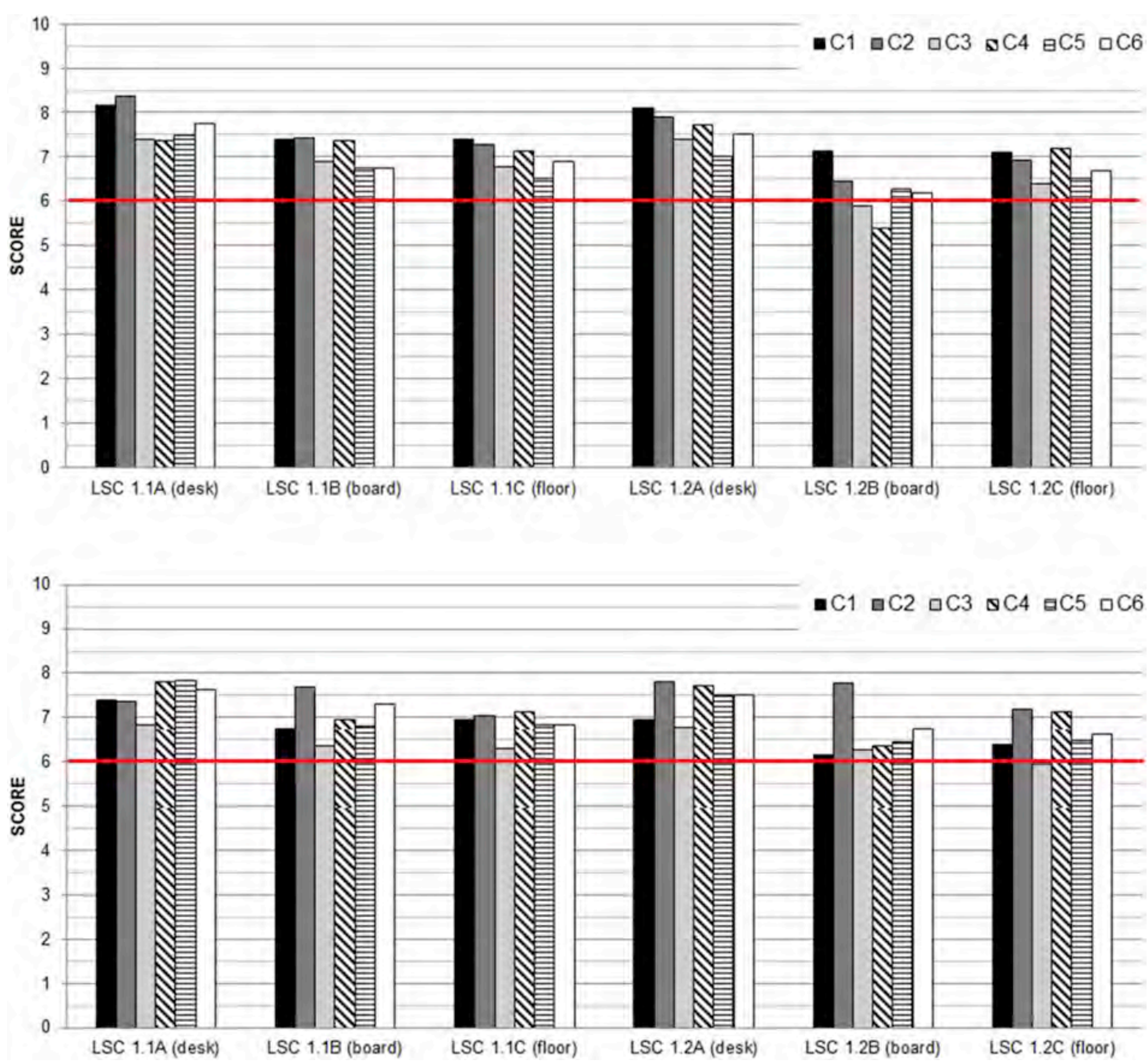

Fig. 7. Amount of light (LC1): mean values of the questionnaires responses in sunny days (top) and in cloudy days (bottom).

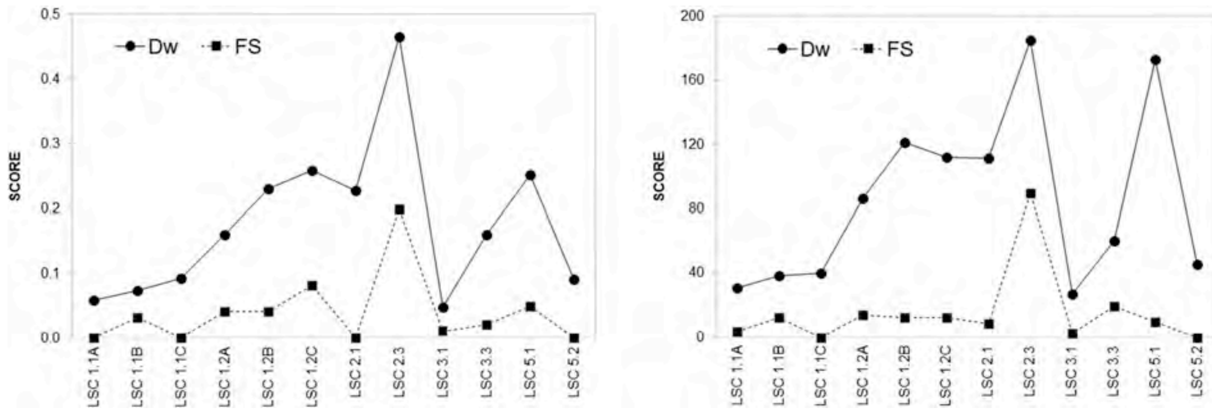

Fig. 8. Comparison between the results of D_w and FS for C1 classroom (left) and for the overall sample of classrooms (right).

where W_i is the weight of the i-th LSC, 10 is the maximum score of the used Likert scale, S_j is the average score obtained from the answer of the j-th question. The D_w values (obtained by subjective survey) can be similarly interpreted as FS values (obtained by the LQAM), even if the two parameters cannot be numerically compared.

Fig. 8 shows the trends of D_w and FS, evaluated for the C1 classroom with clear sky conditions and for all the investigated classrooms and weather conditions. For the classroom C1 (Fig. 8, left), it can be observed that LSC2.3 (daylight glare) represents the most critical aspect (maximum value for both D_w and FS), followed by LSC1.2C (illuminance uniformity on the floor), and LSC5.1 (daylight availability). The answers obtained for the LSC5.3 question, dealing with a particular aspect of light perception, showed a significant dispersion when compared to the others, so this question is not included in the discussion. A further comparison can be made between the values of D_w and FS obtained for the overall sample of the classrooms (Fig. 8, right). It reveals some correlations with C1 results: both investigations show that the daylight glare (LSC2.3) represents the main criticism, and in general similar trends are observed. It is also interesting to point out that, for the overall sample the greater difference between the values of D_w and FS is obtained for LSC5.1 (daylight availability).

5. Discussion

With reference to the results shown in the previous section, some interesting comments can be done to improve the discussion. It was observed how the daylight glare represents the main issue for all the analysed classrooms and that the maximum difference between users' perception and objective evaluations is related to the daylight availability. It could be due to the evaluation indicators used within the LQAM, which are not able to accurately predict the perception of the occupants in different weather conditions. Despite of different indicators are currently available for the evaluation of both daylight glare and daylight availability (e.g. daylight glare probability, useful daylight illuminance), in the proposed method the presence and type of shading system and the calculation of the daylight factor were chosen as indicators. The choice is mainly due to their easy evaluation, without the use of expensive continuous measurements or advanced dynamic software simulations, not very suited for a method designed to be applied with a series of simple and limited field inspections.

In order to verify the correspondence between the results of the subjective investigation and those of the LQAM, a linear least squares regression was applied to the collected data. The correlation between the FS and the D_W values is shown in Fig. 9. A reasonable value of R^2 (0.66) was obtained, that confirms the validity of the assessment method in relation of the occupants real perception. This correlation was

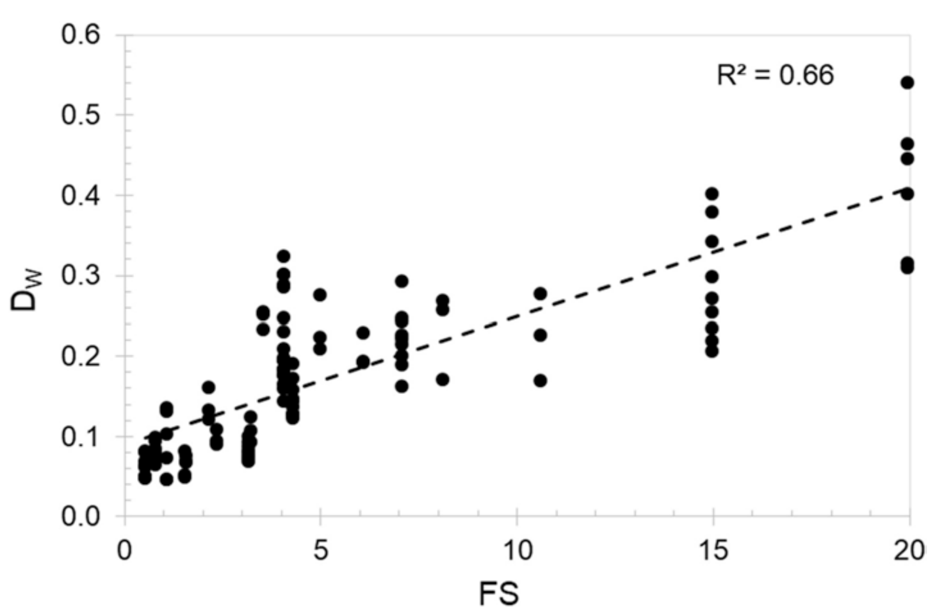

Fig. 9. Correlation analysis of FS and $D_{w.}$

calculated neglecting the values of FS equal to zero because the LQAM is designed to highlight any critical issues and provides a quantitative gradation, for each LSC, of situations of non-compliance with respect to the reference values. On the other hand, when the reference values are satisfied the LQAM does not provide any quantitative gradation and all the situations are evaluated with D = 0 and hence FS = 0. Furthermore, the correlation between D_W and FS was obtained also considering only the data related to the specific conditions of clear sky and overcast sky, which represent sky conditions commonly used in lighting analysis. In these two conditions the R^2 are equal to 0.78 and 0.64, respectively. The graphical representations of these two correlations are included as additional data in the *Supplementary materials*.

In the discussed results, the subjective investigation can be considered in reasonable agreement with those obtained by the LQAM and therefore the proposed method can be suitable for the evaluation of the lighting quality of the educational rooms. However, aiming to improve the method with further investigations, some limitations can be pointed out. The LQAM is based on the calculation of the deviation of the value of a certain lighting parameter with respect to a reference value (see Table 2). The reference values are mainly taken from international Technical Standards but the debate in the scientific community on these values is currently open. It means that the reference values could be adjusted in the future, according to the latest findings of the Literature, without the method losing its validity. The arbitrary choice of the fixed ranges chosen to calculate the deviation indicator D (see Table 2) could result in bias on the final assessment of the lighting quality. However the ranges could be modified based on the expertise of the personnel that performs the evaluation, also considering the type of assessment they are conducting (e.g. evaluation of the general state of the lighting conditions, assessment of potential risks due to the lighting, etc.). In order to avoid any conditioning, the D parameter could be evaluated exclusively by using the exact percentage deviation between the observed value and the reference value and not the defined fixed intervals.

Finally, the subjective judgment expressed on the quality of lighting for each classroom can be related to the specific conditions (e.g. time of day, weather conditions) in which the questionnaire was administered. For this reason, although the questionnaires were administered trying to cover different times and weather conditions (see Table 7), the possibility of having a sample extension may be useful to validate the meaning of the results obtained on a statistical basis.

6. Conclusions

The evaluation of lighting in indoor environments is often limited to the check of the illuminance levels of the main task areas. However, the lighting quality and the achievement of adequate levels of visual comfort strongly depend on other factors that cannot be neglected in a detailed analysis (e.g. luminance distribution, glare, colour rendition, daylight availability, circadian and flicker effects, etc.).

The lighting quality assessment method (LQAM) proposed in this paper aims to establish critical aspects and to create a ranking related to their impact on visual comfort. The LQAM is based on the selection of 5 lighting criteria, 15 lighting sub-criteria and 15 relative indicators, used to assess the lighting quality of educational rooms. Since each lighting criterion has a different impact on the lighting quality, an analytic hierarchy process was applied in order to assign a weight to each LCS. The weights were obtained as a result of a subjective survey involving a group of 12 experts in the field, with different careers and years of experience, to whom a pairwise questionnaire was administrated.

The LQAM was tested both on a single classroom and on a group of six classrooms of the School of Engineering of the University of Pisa, taken as case study. They were chosen with different characteristics, representative of the overall 51 classrooms of the School. In order to verify the reliability of the LQAM, an evaluation questionnaire was administered in the same classrooms used as case study, to different groups of students during the lectures; a total number of 420 questionnaires was filled.

The LQAM results show that the absence of a shading system for solar radiation represents the most relevant weakness, both for the single case and for the overall building. Moreover, the choice of the artificial lighting systems was assessed as suitable, when the static visual tasks are considered. On the other hand, it is not possible to assert the same for dynamic visual tasks, especially because the luminance distribution was not properly considered in the design phase. More in general,the LQAM results highlighted inadequate lighting solutions with respect to the current trends.

The attention to the average illuminance values and the illuminance uniformities on the desks, together with the lack of attention to the luminance ratios and to the daylight glare, characterize the lighting design of the recent past and can be observed in several schools of all levels in the Italian school buildings heritage. The new approaches to the design of lighting systems (both for new buildings or for renovation interventions) should consider, in particular, aspects related to dynamic visual tasks in order to guarantee adequate levels of lighting quality, as also highlighted by the methodology developed and applied in this paper.

The results of the subjective survey by means of questionnaires is in good agreement with the ones obtained by the LQAM method, confirming, the appropriateness of the last one when applied to the investigated university classrooms.

The LQAM could be used for educational buildings, in order to add important information before starting the classrooms renovations, but could be also easily adapted to other indoor working environments, varying (if necessary) the lighting criteria weights and the indicators reference values. The LQAM represents a useful tool for lighting design engineers, architects, and infrastructure decision makers for a better assessment of lighting quality in existing buildings, and for funding the improvement interventions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2019.106501.

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