A quality approach of the lighting installations

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KEYWORDS

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ABSTRACT

The paper is related to the evaluation of the interior lighting systems quality. A multi-criteria method provides the means to consider the lighting installation not only by its photometrics, but also by electric/economic parameters and human behavior. It is developed a working tool to analyse the quality of an interior lighting installation ILES - Interior Lighting Evaluation System -, with two components - an objective photometric and energetic analysis LQED - Lighting Quality & Economic Diagnose and a subjective survey ULCS - Users' Lighting Comfort Survey. The evaluation system ILES allows to estimate the degree on which the existing (or designed) lighting installation fulfills the required photometrical, electrical, economical and human standards, and to know whether the user's needs and preferences are satisfied, and in what extent. A computer program supports the analysis of energy efficiency and quality of lighting systems. Specific modules are related to the objectives of this study – the quality factor, the daylight availability, the energy savings expectations. A toolkit designed to allow the measurements or estimation of photometric parameters, electric energy metrics, energy savings opportunities and users' opinions. It is presented with its components and using recommendations. The survey of the user's opinions to assess the electrical lighting in their work office was designed to match the local knowledge and education in lighting topics and the technical needs and state of the facts. Part of this research is based on the [2, 3, 15, 16] works.

INTRODUCTION

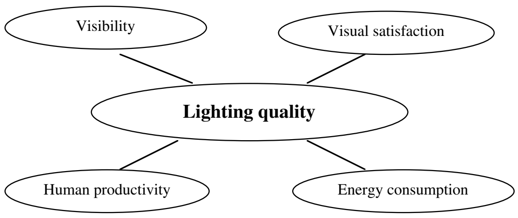
The primary function of an electric lighting installation is to enable people to see, in order to perform their tasks comfortably and safely. For avoiding an undesirable outcome from an electric lighting installation which achieves energy-efficiency at the cost of lighting but makes people uncomfortable and puts their safety at risk, it is necessary to consider lighting quality as well as energy-efficiency when designing or evaluating lighting.

It is necessary and useful to discuss lighting quality in context of both human productivity and energy. A link between an improved lighting quality and improved human productivity – not yet proved – should provide a powerful economic reason for acting towards a new quality in lighting, with the final recognition of the need to model the complexity of lighting quality and to distill the results to a form useful for designers. There are many methods of measuring the visibility and visual performance proposed or in use, each of them with some advantages and disadvantages, limitations or difficulties related to their field measurements.

VISIBILITY AND VISUAL PERFORMANCE

Visual task is very different related to the developed activity, from the reading of a book to the electronic component assembling. Its characteristics determine the conditions required to the lighting system. A proper design and accomplishment are a priori requirements for a good lighting. The main criteria of the lighting design for a cer-

Fig. 1 Components of the lighting quality concept



tain application are the *visibility and visual satisfaction*, linked with the *capital and running costs*.

The performance of a certain user for a specified task is determined necessarily both from its ability and devotion to the accomplishment of the task. The lighting, together with the other physical environmental factors may intensify this task. The *visual performance* is the term that evaluates the information processed by the visual system. The speed and accuracy of the accomplishment of the visual task (component of a complex task) measure it. The *visibility* of a visual task is mainly determined by the visibility of the most difficult component to be detected or recognised, named the *critical detail*. The detail visibility is depending of the several factors, such as: its angular dimension, its luminance and color, luminance and color contrasts between the detail and background, available time for observation, position of the detail in the visual field, and so on.

SYSTEMS AND METHODS FOR EVALUATING LIGHTING QUALITY

The quality of a lighting installation would be described by several parameters: illuminance level and uniformity; direct glare control or avoidance (luminance distribution); appearance color and color rendition; modeling. The qualitative parameters have different weight, related to the room destination and architecture. The accent should be on: *visual performance*, choosing the right illuminance level and the glare avoidance; *visual comfort*, by the colour rendering and the luminance distribution; *visual environment*, by the selection of the light colour and direction and modeling.

Lighting quality is a multi-faceted concept. We assess it *directly*, by measuring its photometrical parameters, and, *indirectly*, using behaviour measures – for instance, responses to semantic differential scales or Likert-scale responses to statements of opinion. There are also many research studies proposing new methods and surveys devoted to identify a proper modality to refine visual performance and comfort models. However, since there are yet no comprehensive and objective measures of visual comfort; occupant surveys remain the most accurate way to assess the lighting installation not only by its photometrics, but also by economic parameters and human behavior. It is useful to simultaneously estimate photometric and economic (cost and energy) parameters, maintenance program and subjective evaluation of visual comfort.

Energy efficiency and quality do not automatically go hand in hand. Greater lighting comfort for people in offices, for example, is often combined with a higher energy consumption. If a measurable (energy consumption) and a non-measurable (lighting comfort) parameter have to be weighted against each other, the non-measurable parameter comes under pressure [23].

Individual criteria for evaluation. A lighting installation with good quality is energy-efficient whether permits a high level of performance without creating discomfort. *The light quality is not directly measurable, but it is a state generated by the link between environment and users.* A lighting has a good quality when: (1) there is a good visual condition; (2) it permits the accomplishment of the task or determines the behaviour in accordance with the environment; (3) assures the availability of the interactions and desired communication between the participants; (4) contributes to the aesthetics of the space. The evaluation of the lighting quality has to be made by the evaluation of its effect on the people, having in mind all the characteristics of the room space and the users. To consider a good quality, the lighting has to be consider comfortable by the minimum 70% of its end-users - [3].

Global systems for evaluation. CIE, CIBSE and IESNA were developed several methods to assess the degree of the users visual comfort or discomfort glare - *Equivalent Sphere Illumination – ESI, Relative Visual Performance – RVP, Visual Comfort Probability – VCP, Glare Index - GI, Luminance Limit Curve, Unified Glare Rating – UGR.*

THE INTERIOR LIGHTING EVALUATION SYSTEM – ILES

In order to support the improvement of the existing lighting installations and to optimise the design of the new ones, there was developed a working tool to analyse the quality of an interior lighting installation ILES - Interior Lighting Evaluation System [18, 19]. Designed to be inexpensive, simple to administer, to score, and easy to interpret, the ILES covers a reduced number of parameters, but most important ones, and a rough scale of preferences. The system has two components - an objective photometric and energetic analysis LQED - Lighting Quality & Economic Diagnose and a subjective survey ULCS - Users' Lighting Comfort Survey.

The objective component – LQED – evaluates the photometric and energetic of the lighting system. This module may be used for in design to compare different variants and to offer an objective criterion to choose the better one.

Technical Audit

Questionnaire concept. It is proposed a questionnaire following the reference models and answering to the specific questions, presented below.

Room: Destination; Dimensions; Daylight factor – average value; Ceiling/walls reflectance

Equipment: Luminaires; Lamps - type, power, colour; Ballast; Installed power

Photometric measurement: Average illuminance - norm/measured (designed); Illuminance uniformity - minim/average; Lighting source luminance; Luminance contrast - source/ceiling

Electric measurement: Voltage

Technical state: Lighting source - clean/dirty/painted; Power density - W/m2 and/or W/(m2 ·100 lx); Switching control – wall mounted/local, manual/automatic control

Maintenance programme: Is there a scheduled activity? - Yes/No; Last date of the change of the lamps/luminaires; Cleaning period of the room/installation - Yes/No

Measurements

Electrical measurements: - voltage level; - harmonic analysis; - currents system simetry.

Photometrical measurements. The physical data collection includes a general space inventory as well as measures of lighting – illuminance, luminance, daylight factor, and surface reflectance following the CIE standards.

The Quality Value Method. The quality of the lighting installations is influenced by different parameters. They cover the lighting quality – referred by its photometric parameters -, the lighting energy-effectiveness – referred by its economic parameters -, and the benefit of final users – referred by their comfort, pleasantness and productivity. The importance of different parameters varies inside of each of these groups and also between them. Following the Krochmann study [15], there are proposed a method and a model for quantifying them into a final "quality value" number, by weighting the meaning of parameters and by evaluation of their levels.

Each of the parameters – noted with x – has a certain importance on the quality assembly, noticed by the *weighting factor w(x)*, valued from 1 (lowest) to 10 (highest importance). Each of the parameters is evaluated in function with its effective value, compared with the standard, recommended or optimum value by the *scaling factor s(x)*, valued from 1 to 10. Each of the parameters contribute to define the quality value of the lighting installation by the *quality factor q(x)*, product of both specific factors

$q(x)=w(x)\cdot s(x)$.

The effective quality factor of the installation is the sum of the quality factors of each component parameters $q_{ef}=\Sigma w(x)\cdot s(x)$, between the minimum - $\min q_{ef}=\Sigma w(x)$ -, and the maximum value - $\max q_{ef}=10\Sigma w(x)$.

The optimum quality factor of the installation is corresponding to the standard, recommended or optimum values, being the maximum value $q_{opt}=\max q_{ef}=10\Sigma w(x)$.

The Quality Value, describing the overall quality of the lighting installation, is the ratio:

$$Q=\frac{q_{ef}}{q_{opt}}\cdot 10=\frac{\sum w(x)\cdot s(x)}{\sum w(x)}$$

The scaling factor of each parameter x is defined by comparing the effective value, measured or designed, to the standard value, recommended or admissible, and introducing the minimal/maximal values ratio:

$$s(x)=10\cdot\frac{\min\left(x_{effective},x_{standard}\right)}{\max\left(x_{effective},x_{standard}\right)}$$

Photometric parameters. The photometric parameters targeted to the lighting quality are: average illuminance, illuminance uniformity, modeling (cylindrical illuminance), lighting source luminance, luminance distribution (contrast) on the visual field, reflectance of the room surfaces – walls, ceiling, ground, luminaire protection angle, correlated colour temperature, colour rendering index and a lot of many others.

For example, for *the illuminance level on the working plane*,

$$s(E)=10\cdot\frac{\min\left(E_{effective},E_{standard}\right)}{\max\left(E_{effective},E_{standard}\right)}$$

By using the ratio of the two illuminances, we take into account the following aspects: on one side, an installation which assures an illuminance level lower than the standard value is under norm, but the rules concerning the illuminance are, as we all know, very elastic and conjectural (there are many working installations with illuminance levels well under the standard values, accepted by the users); on the other side, an installation which assures an illuminance level higher than the standard value does this by consuming extra electrical energy over the right balance. In both cases, the lighting installation will be qualitatively under-marked due to the involvement either of the photometrical aspect, or of the energetical aspect. The illuminance measured in a new installation is 600 lx, designed for a standard level $E_{standard}$=400 lx. Introducing the maintenance factor 0,8, the effective illuminance is considered $E_{effective}$=0,8·600=480 lx. The scaling factor becomes *s(E)*=10·400/480=8,3.

Of course, we may suppose that an installation is designed, executed or maintained so that its characteristically parameters should conform to the admissible/reasonable specific limits. For example, for offices it is recommended the use of some electrical (fluorescent) lamps with a colour rendering index of at least 80; it is absolutely improbable to design or keep in working state an installation equipped with lamps with an index of 50...60, because someone may easily obtain the necessary lighting sources.

Energy efficiency. The power density of a lighting installation is estimated following the identification and counting of lamps type. It is reported to the area of the room/space - W/m2 and, eventually, to the effective illuminance, as hundreds lux, - W/(m2·100 lx). The reference value is represented by norms - [7, 14] – or by the recommendations of the UE programs - Thermie, Save – 4 W/(m2·100 lx) for offices, at the years '90 level. The present value obtained with efficient lighting systems - 2 W/(m2·100 lx) for offices is difficult to be reached in the economic conditions of this period in our country.

Harmonic analysis. The impact of the lighting sources on both customer and utility distribution systems is of great importance. Indeed, the up-to-date lighting systems widely use new classes of sources commonly known as energy saving lamps: compact fluorescent lamp (CFLs) and electronically ballasted fluorescent lights. The success and proliferation of these new solutions is mainly due to [10]: (1) the retrofit that utility customers are doing to save some money by means of the energy saving these devices provide, (2) the energy rebate programs electric utilities are offering, and (3) to the massive campaigns carried on by both producers and utility companies.

Unfortunately, the above mentioned devices are nonlinear and therefore, producers of harmonics. CFLs and electronically ballasted fluorescent lights with highly distorted currents may jeopardize the reliability of the distribution systems and the quality of the electric power delivered. On the other hand, harmonic currents do not upset the end-use electronic equipment as much as they overload neutral conductors and transformers and, in general, cause additional losses and reduced power factor for electrical power system components transporting the real power along with the added harmonic component [4].

Both laboratory and field experimental results reported in [5, 6, 9, 10] have highlighted the following:

- relatively reduced harmonic distortion (THDi < 20%) for fluorescent lamps with magnetic ballast;
- harmonic current distortion up to 140% for CFLs with high distortion electronic ballast and up to 30% for electronic ballast with harmonic control;
- harmonic current distortion less then 7% for fluorescent lamps ballasted with modern electronic devices;
- neutral currents up to 150% of phase current;
- high current distortion can result in unacceptable voltage distortion levels on the distribution system; this it is true even when the effects of cancellation between various devices is considered.

In conclusion, the study of harmonic distortion produced by different lighting sources can be used in lighting systems design in order to compare different variants and to choose the best one. It is important to verify that: (1) harmonic current limits of lighting equipment do not exceed the relative limits given in [9b]; (2) harmonic voltages at the PCC do not exceed the imposed relative limits; (3) the harmonic spectrum does not produce resonance phenomena in the distribution system.

Evaluation of the weighting factors. The importance of different parameters is variable. The ILES user, according to the particular data of the room and the importance of the relevant component has to decide by himself the quality parameters and their values of the weighting factors for the lighting system analysed.

A survey with 150 people (during the last five years) revealed the following values for the weighting factors of the quality parameters submitted to their attention:

1) Illuminance level on the working plane	9
2) Illuminance uniformity on the working plane	8
3) Space modeling	7
4) Luminance contrast - light source/ceiling	7
5) Luminance contrast - visual task/background	8
6) Distribution of illuminances in the visual field	8
7) Reflectance of the room surfaces (average weighted value)	6
8) (Correlated) Colour temperature of the lighting sources	8
9) Colour rendering index	7
10) Energy efficiency	9

A simple computer program allows us to obtain quickly the information necessary to evaluate the analysed lighting installation and its energetic balance.

We would like to identify how lighting condition affect lighting economics and visual comfort of the users. The LQED module will be used to evaluate different variants of designed installations, to compare them on multiple aspects for having an objective criterion for choosing the best one.

The subjective component – ULCS – must be simple to administer and score. For this a large number of former proposals have been analysed (some of them are presented in the mentioned bibliography) to identify the most important questions for defining a visual performance and comfort model. The complexity level of the corresponding parameters, and, implicitly, of the questions asked to the users, are determined by the knowledge level and, respectively, of education. It is useless to ask an uninformed user about certain aspects related to illuminance contrasts, colour rendering or interior space modeling.

The fulfillment of the comfort from a lighting installation is determined by parameter values that affect the visual task, visual comfort and environment. Some of them may be accurately measured, but others should be very subjective. *The visual satisfaction* describes on which measure the real visual conditions of the lighting are accepted by the users; it is determined the easiness which the work is performed and the pleasantness of the environment, both in the period when the attention is targeted to the visual task, and in the relax time. Of course, the luminous environment and the individual preferences affect the visual satisfaction.

To obtain the subjective opinions of the users there were selected the following questions. The answers are included in five options: improper, poor, fair, good, excellent or with two options: Yes/No, Comfortable/Uncomfortable, Disagree with/Agree with:

Is the day-light sufficient?

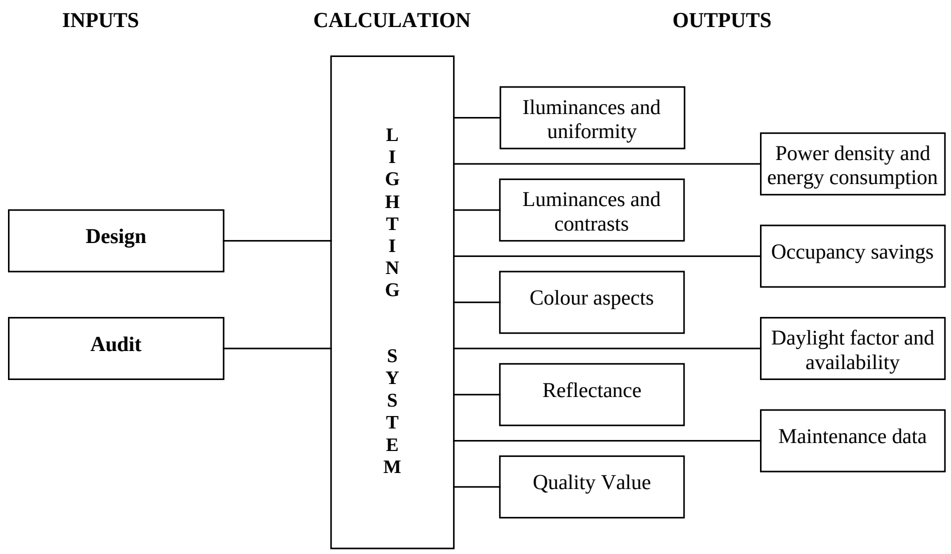
Is the electric light sufficient?

The illuminance (light) is uniform on the working room surface?

Are you satisfied by the switching on/off modality?

Is the light appearance (brightness) of the luminaires adequate?

Fig 2. The block-structure of the computer program LQE – Lighting Quality Evaluation



How do you appreciate the maintenance schedule of the lighting installation (cleaning, replacement of the failed equipment)?

Is the available light sufficient to read/write by hand/computer use/draw?

How do you appreciate the light environment of the room?

How do you appreciate the work lighting at your place (stand, desk)?

How do you appreciate the lighting in your working room comparing with the others?

Please notify on which room would you like to work/do you like the lighting installation?

EVALUATION TOOLKIT OF THE INTERIOR LIGHTING QUALITY

The evaluation toolkit of the quality of an interior lighting installation proposed for producing is developed following the models presented in [5, 6, 12, 18]. This is conceived to be comprehensive and flexible, to be multidimensional, to consider the users' opinion and to be convergent.

The toolkit made of a plastic or cardboard box consists of (1) a notebook with sets of four pages (differently coloured) containing the Form of energy and photometric audit (technical characteristics of the installation and the results of the photometric and electrical measurements), the Subjective evaluation questionnaire (users' opinions), the Recording form of the measurements in different points over the analysed surfaces and the Presentation form of the evaluation results; (2) a magnetic support (diskette, CD) with software for processing the collected data and assessment the analysed quality indicators; (3) a simple, but qualitative illuminance meter that could have attached a black tube to convert it into a luminance meter; (4) a toolkit with necessary tools for opening (closing) and cleaning the luminaires; (5) a users manual.

The Form of energy and photometric audit is presented in Annex. The photometric measurements shall be performed in accordance with the regulations mentioned in [7, 8, 14].

The Subjective evaluation questionnaire, presented in Annex, contains a series of declarations with a view to expressing the users' agreement - satisfaction or disagreement – dissatisfaction concerning the analysed lighting installation.

The Diskette with the evaluation software of the lighting quality. The computer program LQE - Lighting Quality Evaluation is a component of the program package LSD - Lighting Systems Design – achieved within the research activity of the "Lighting Engineering Centre" Group [17].

From the initial program there are used: (a) the calculation of the average illuminance and uniformity; (b) the graphic presentation of the illuminance distribution, and (c) estimation of the direct glare limitation degree using the CIE Method of the Limit Luminance Curves.

The computer program allows: (a) to establish the daylight factor (by calculation or based on the photometric measurements) and on this basis, (b) to estimate the electric energy savings by correlation of the electric lighting with the daylight availability, (c) to establish the Quality Value of the analysed installation and (d) to perform an optimised design of an interior lighting installation targeted to the qualitative aspects.

The Illuminance-meter equipped with a luminance-tube adapter. The illuminance-meter is simple with a satisfied degree of accuracy (5%) for obtaining the accurate enough results available for an overall photometric evaluation of the lighting system. The illuminance-meter is equipped with a black cylindrical luminance tube adapter that could be attached on the photocell, allowing the luminance measurement. The tube adapter dimension limits the luminance measurements to the average values on the small surfaces, having a measuring angle of 12-13 degrees

– [3, 16]. The illuminance/luminance meter shall have a reduced cost in order to make attractive the evaluation toolkit.

The measurements that could be performed are direct: (a) the illuminances of the room surfaces or on the working plane, (b) the luminances of the room surfaces, furniture and light sources, and indirect: (c) the daylight factor; (d) the reflection factors of the room surfaces or furniture; (e) the depreciation of the lighting equipment – luminaires, light sources.

COMPUTER PROGRAM FOR THE OPTIMISED DESIGN OF AN INTERIOR LIGHTING INSTALLATION TARGETED TO THE QUALITATIVE ASPECTS

The designing of an interior lighting installation follows the simultaneously fulfilling of some multiple requirements, i.e. photometric, ambient, ergonomic, economic, energy and maintenance requirements. On the first stage the room and equipment technical data are established and than the interior lighting are pre-dimensioned using the method of utilisation factor. After the choosing of the colour temperature and the colour rendering index the installation luminaires layout is completed.

The quality verification concerning the illuminance level is performed by checking the average illuminance $E_{av} \geq E_{standard}$, where a deviation of 10% is allowed, by checking the uniformity minimum-average ration $E_{min}/_{Eav}>0,1$ for industrial halls and combined lighting and ≥0,8 for general uniform lighting, and by checking the minimum-maximum ration $E_{min}/E_{max} \geq 0,25$ for common activities and ≥0,65 for intellectual job and accuracy works.

The luminance verification could be accomplished by one of the well-known methods: Visual Comfort Probability – VCP, Glare Index - GI, Luminance Limit Curve, Unified Glare Rating – UGR.

The modelling verification involves the calculation of the horizontal E_H, vertical E_V, scalar E_{sc}, vectorial _, cylindrical E_{cl}, and semi-cylindrical $_{Escl}$ illuminances, and the checking of the following ratios:

$$E_V / E_H > 0,25 \; ; \; \overline{E} / E_{sc} = 0 \div 4 \; ; \; E_{cl} / E_H = 0,3 \pm 3 \; ;$$
$$E_V / E_{scl} = 0,3 \div 1,3$$

CONCLUSIONS

The proposed method to analyse the quality of an interior lighting installation allows us to estimate the degree on which the existing (or designed) lighting installation fulfills the required photometrical, economical and human standards. The evaluation system IELS is the basis of the analysis of a new and existing lighting installation, to know whether the user's needs and preferences are satisfied, and in what extent. Thus, one may adjust the possible unfavorable aspects of the lighting installation. A computer program supports the analysis of energy efficiency and quality of lighting systems. Specific modules are related to the objectives of this research study.

The evaluation of the lighting quality is analysed by the provided information related to many specific parameters. For having an comparative indicator of an installation faced to other different variants, it is proposed to consider a single number index. It is well known that various single number indices have been proposed, and, a criticism position has been concerned with them. The Lighting Quality Value has to be use with prudence, and it is considered being absolutely a subjective value, specific for each evaluator, for his own use. A multi-dimensional approach, together with the consideration of the single number quality index, is an optimum modality to analyse the quality of a lighting installation.

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ANNEX QUESTIONNAIRE CONCERNING THE QUALITY ESTIMATION OF THE INTERIOR LIGHTING INSTALLATIONS

A. Technical characteristics

Room:	Destination
	Dimensions
	Daylight factor – average value d%
	Ceiling/walls reflectances
Lighting equipment:	Luminaires
	Electric lamps – type, power and colour
	Ballasts
	Installed power = No. of lamps x (lamp power + ballast loses)
Photometric data:	Set/measured average illuminance
	Minimum/average ratio of illuminance
	Luminance of light sources
	Sources/ceiling luminance contrast
Electric data:	Voltage
	Light sources are clean/dirty with dust/ painted with lime
	Power density - W/m2 ;- W/(m2 ·100 lx);
	Switching control – wall mounted/local (infrared)
	Automatic control – daylight, occupancy sensors, time
Maintenance data:	Is there a scheduled activity? – Yes/No
	Last date of the change of the lamps/ luminaires
	Cleaning period

B. Users' Opinion

Please mark with a circle the correct answer and with "x" the cell that you consider it appropriate!

Age <30 31-50 >51

Sex F M

Seeing With/without glasses

Education Elementary-Technical-High schoolTechnicianBachelor/M.Sc. (engineer, economist, other)

Quality criteria		Improper	Poor	Fair	Good	Excellent
How do you appreciate the light environment of the room?						
Is the day-light sufficient?						
Is the electric light sufficient?						
Is the illuminance (light) uniform on the working/room surface?						
Are you satisfied by the switching on/off modality?						
How is the light appearance (brightness) of the luminaires?						
How do you appreciate the maintenance schedule of the lighting installation (cleaning, replacement of the failed equipment)?						
Is the available light sufficient to	read					
	write by hand					
	use the computer					
	draw					

	Comfortable	Uncomfortable
How do you appreciate the lighting in your room?	The room is bright	The room is dark
	The lighting is uniform over the entire room	The lighting is not uniform over the entire room
	The room reflections do not disturb me	The room reflections disturb me
	The available light is sufficient	The available light is not sufficient
	The colours of different surfaces are proper rending to the electric light	The colours of different surfaces appear changed to the electric light
	The lighting equipment are properly maintained	Lighting equipment are not properly maintained
	The lighting installation is aesthetic	The lighting installation is not aesthetic (I do not like it)
How do you appreciate the work lighting at your place (stand, desk)?	The available light is sufficient	The available light is not sufficient
	The work place has no shadows	The work place has shadows that disturb me

How do you appreciate the lighting in your working room comparing with the others?	Worse	Same	Better
Please notify on which room would you like to work or do you like the lighting installation?			