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COMMISSION INTERNATIONALE DE L'ECLAIRAGE
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TECHNICAL REPORT

TEST CASES TO ASSESS THE ACCURACY OF LIGHTING COMPUTER PROGRAMS

CIE 171:2006

UDC: 628.931

Descriptor: Artificial lighting: Design and calculation

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This Technical Report has been prepared by a CIE Technical Committee 3-33 of Division 3 "Interior Environment and Lighting Design" and has been approved by the Board of Administration of the Commission Internationale de l'Eclairage for study and application. The document reports on current knowledge and experience within the specific field of light and lighting described, and is intended to be used by the CIE membership and other interested parties. It should be noted, however, that the status of this document is advisory and not mandatory. The latest CIE proceedings or CIE NEWS should be consulted regarding possible subsequent amendments.

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TEST CASES TO ASSESS THE ACCURACY OF LIGHTING COMPUTER PROGRAMS

SUMMARY

The objective of this report is to help lighting program users and developers assess the accuracy of lighting computer programs and to identify their weaknesses. A validation approach is therefore presented based on the concept of separately testing the different aspects of light propagation. To apply this approach, a suite of test cases has been designed where each test case highlights a given aspect of the lighting simulation domain and is associated with the related reference data.

Two types of reference data are used: data based on analytical calculation and data based on experimental measurements. The first is associated with theoretical scenarios that avoid uncertainties in the reference values. The second type is obtained through experimental measurements, where the scenario and the protocol are defined in a manner that minimizes the uncertainties associated with the measurements.

A set of recommendations is also presented in order to achieve reliable experimental data for validation purposes. These recommendations address the choice and description of the scenarios, to the experimental protocol precautions, to the estimation of the error sources and to the presentation of the reference data.

CAS-TESTS POUR VERIFIER LA PRECISION DES LOGICIELS DE SIMULATION DE L'ECLAIRAGE

RESUME

Ce rapport est destiné aux développeurs ainsi qu'aux utilisateurs de logiciels d'éclairage afin de leur permettre d'évaluer la précision de ces logiciels et d'identifier d'éventuelles faiblesses. Le protocole de validation proposé consiste à tester séparément les différents aspects de la propagation de la lumière. Ainsi, un ensemble de cas-tests a été conçu par les auteurs. Chaque cas-test met en exergue un aspect donné des problèmes de simulation, et un ensemble de valeurs de référence lui est associé.

Deux types de références sont proposés : des données obtenues par calcul analytique, et des données recueillies par expérimentation. Le premier groupe est associé à des scénarii théoriques et permet d'évacuer le problème d'incertitude sur les valeurs proposées. Pour le second groupe, les scénarios et les protocoles sont définis de manière à réduire les incertitudes associées aux mesures.

Nous présentons également dans ce rapport un ensemble de recommandations destinées à obtenir des données expérimentales avec la fiabilité suffisante pour être utilisée comme références dans les tâches de validation. Ces recommandations portent sur le choix et la sélection des scénarii, les précautions à prendre dans les protocoles expérimentaux, la manière d'estimer les sources d'erreurs et le mode de présentation des données de référence.

TESTDATEN ZUR BEURTEILUNG DER GENAUIGKEIT LICHTTECHNISCHER COMPUTERPROGRAMME

ZUSAMMENFASSUNG

Der vorliegende Bericht stellt eine Anleitung für Entwickler und Nutzer lichttechnischer Programme zur Beurteilung der Genauigkeit lichttechnischer Computerprogramme und zur Ermittlung eventueller Schwächen dar. Hierzu wird ein Bewertungsverfahren vorgeschlagen, das auf der getrennten Prüfung der einzelnen Aspekte der Lichtausbreitung beruht. Zur Anwendung des Bewertungsverfahrens sind eine Reihe von Prüfungen entwickelt worden; hierbei beschreibt jede Prüfung einen einzelnen Aspekt der Lichtberechnung im Zusammenhang mit den entsprechenden Referenzdaten.

Als Referenzdaten werden sowohl Daten benutzt, die aufgrund analytischer Berechnungen ermittelt wurden, als auch solche, die aus Messungen in Versuchsräumen stammen. Die berechneten Referenzdaten beruhen auf theoretischen Szenarien und sind somit frei von Ungenauigkeiten. Für die aus Messungen gewonnenen Referenzdaten darf angenommen werden, dass bei der Ermittlung der Daten versucht wurde, die Ungenauigkeiten so klein wie möglich zu halten.

Im Bericht werden auch Empfehlungen zur Erlangung verlässlicher experimenteller Daten gegeben, wie sie für den Validierungsprozess benötigt werden. Diese Empfehlungen sind abhängig von der Wahl des in Betracht stehenden Versuchsaufbaus, von den experimentellen Bedingungen, von der Abschätzung möglicher Fehlerquellen und der Darstellung der Referenzwerte.

DEFINITIONS

- Test case:** A given building design scenario associated with reference data, to be used for assessing a given aspect of a lighting simulation.
- Reference data:** A set of values (calculated or measured) to be used as a reference when assessing the results of a simulation.
- Experimental test case:** A real-world case study where the reference data is based on experimental measurements inside a scale model or a test room.
- Analytical test case:** A theoretical building design scenario wherein the reference data can be analytically calculated based on given assumptions (e.g. light source and surface photometry) and physical laws.

1. INTRODUCTION AND SCOPE OF THE REPORT

CIE Technical Committee 3-33 was established based on the following terms of reference:

"To develop a set of validation benchmarks to assess the accuracy of lighting computer programs. The benchmarks consist of a set of test cases produced using analytical solutions and measurements with scale models, including 1:1 scale. Sensitivity studies will be carried out and software examples produced."

The need for this committee is related to the lack of independent information about the accuracy of the computer lighting programs that are increasing in number over the international market of lighting and engineering design. This lack of information can lead to potential users not having sufficient information to choose the proper tool adapted to their needs, and it can also lead to a lack of trust (or unwarranted trust) in the tool they are using.

The objective of the committee was to address this problem by offering a suite of reference test cases against which users can assess the accuracy of a lighting program. The test cases address different aspects of light propagation. These test cases also allow objective comparisons between different programs with respect to the different domains of lighting simulation.

The present Technical Report is mainly concerned with the development of the validation benchmarks (reference test cases). A large fraction of these test cases were developed in the framework of a Ph.D thesis (Maamari, 2004) at ENTPE, France. Applications of these test cases can be conducted separately. Some of them are presented as separate papers (Maamari, Fontoynt et al., 2003; Maamari, Jongewaard, et al., 2003). In addition, some recommendations are given for the use of the test cases and also for the development of additional and useful test cases.

Although the primary target of the proposed test cases is physically based computer simulation using for example radiosity and ray tracing algorithms, they are also applicable to verification of the accuracy of empirical or equation-based tools.

The test cases are designed with respect to a validation methodology based on the concept of separately testing the different aspects of light propagation. Therefore, each test case is designed in a way to highlight the influence of a given aspect of light propagation.

Two types of test cases are provided: 1) experimental cases; and 2) analytical test cases. The former are based on experimental references. A set of recommendations is also provided to minimize the uncertainty in the reference values developed from experimental measurements, complete with an objective presentation method for this experimental reference data. This presentation method is based on a detailed estimation of the error sources associated with the measurements. A suite of experimental test cases is presented where the reference data were obtained in the manner recommended.

In addition to these experimental test cases, a special focus of this report is on the use of test cases with analytical references. Such test cases have the advantage of minimizing if not eliminating the uncertainties in their reference values. A large suite of test cases with analytical reference is therefore provided.

This report, including the proposed test case suite, should be considered as a first step toward an efficient validation methodology. It is expected that additional test cases will be developed to cover larger domains of lighting simulation than have been possible thus far. We suggest parameters for the design of further test cases complementary to those provided in the report.

2. PROPOSED VALIDATION APPROACH

One of the major handicaps in existing validation work is related to the number of potential error sources in the same scenario that make it difficult to determine the weaknesses of a program from deductions based on the results of the validation work. It is therefore recommended that scenarios for test cases be designed with a very limited number of independent parameters.

Each scenario should preferably be able to highlight a particular aspect of the light propagation and simulation. This should make it easier to identify the strengths and weaknesses of a program being tested.

These considerations can be divided into three main groups:

1. the light source description (luminaire or daylight) and direct lighting calculations;
2. the light transfer through openings and window components or around obstructions; and
3. the inter-reflections between different types of materials with different photometric properties.

Based on this approach, this report presents a test case suite dealing with simple lighting scenarios where one specific aspect of the light propagation is isolated or highlighted for each case.

The description of these test cases includes the geometry, the light source, and a set of values to be used as a reference to assess the accuracy of a lighting simulation. These reference values have been obtained by simple theoretical calculation for the analytical scenarios or by measurement in the experimental cases where the theory is not enough to assess a given aspect.

These test cases should be used as a complete package rather than individually to assess a lighting program. A general overview of the comparisons between the tested lighting program results and the corresponding reference values should give a clear idea of the domains where the program respects physical laws and where it does not. The goal is to help users to verify if a program is compatible with their intended domain of application of the software. (See also Section 7.)

3. RECOMMENDATIONS TO ACHIEVE RELIABLE EXPERIMENTAL DATA FOR VALIDATION

Prior attempts to develop lighting software validation protocols have been based on experimental data. The problem with this type of validation is mainly related to the uncertainties in the reference values.

Because it is costly to conduct experimental measurements for both scale models and in real-world scenarios, it is important to enhance the usefulness of any experiment. This requires minimizing the error sources in number and in magnitude, and to clearly document the scenarios and related references.

Within this context, we define below a set of recommendations related to: 1) the choice of experimental protocols; 2) description of the scenarios; 3) estimation of the potential error sources; and 4) presentation of the reference values based on measurements and estimated errors. The sources of these recommendations are (CIE, 1996; IESNA, 2000a; Slater and Graves, 2002; Maamari, Jongewaard, et al., 2003). The key features of these recommendations are:

- simple scenarios to highlight a given aspect of lighting simulation;
- robust protocols to minimize potential error sources; and
- identification of these error sources for objective presentation.

3.1 Recommendations related to the choice and the description of the scenarios

To achieve reliable validation data, it is important not only to choose the appropriate test scenario, but also to make a complete and accurate description of this scenario.

Careful design of the test scenario optimizes the usefulness of the experiment mainly by avoiding independent and potentially interfering parameters. In other words, test cases

should limit their physical complexity to the extent required only to accomplish their defined goal, which is to assess a given aspect of the light simulation.

An accurate description of the scenario minimizes the potential for error when the scenario is simulated. Making available a complete description of the scenario helps testers create the numerical models without ambiguity. The description should include room dimensions, surface photometry, light source position, photometry and all other relevant parameters. Providing a CAD drawing illustrating the pertinent information is recommended.

Below is a list of recommendations for the type and quality of geometry, materials, light sources and measurement points in the scenarios.

a. Geometry

- Use simple geometrical configurations (e.g., rectangular rooms with no internal obstructions).
- When assessing daylight calculations, use only one aperture.
- When assessing artificial lighting, minimize the number of luminaires.
- Try to include a sensitivity study in an experimental scenario such that it highlights the influence of a given parameter (e.g. the aperture dimensions or the luminaire flux output).
- Room dimensions should be measured accurately (tolerance < 1%).
- Include a detailed description of the geometry to eliminate any ambiguity when a numeric model is to be created by a third party. This description should include for example the exact position and thickness of the daylight aperture and the exact positions of luminaires.
- Make available a CAD file for the geometric description wherever possible.

b. Materials

- Use scale models or test rooms with black surfaces (reflectance < 5%) in order to limit the test case to direct lighting and to minimize errors due to indirect light propagation within the room.
- If needed, include a sensitivity study on the influence of the internal surface reflection. Associating this study to a scenario with black surfaces would allow the separation of errors due to direct lighting from those due to inter-reflections.
- When using surfaces that are not black, spectrally neutral surfaces are preferred in order to avoid errors related to spectrally selective absorption.
- If the surfaces are not spectrally neutral, spectral reflectance measurements should be conducted. This will allow the assessment of programs modelling spectral calculations.
- Surfaces with perfectly diffuse reflection are preferred.
- Where appropriate, the bi-directional reflectance distribution functions (BRDFs) of the room surface materials should be measured or otherwise characterized as accurately as possible, and should be included in the description of the scenario. This will permit the assessment of programs that model bi-directional reflectance calculations.
- The surface reflectances should be measured in an integrating sphere or by luminance comparison with two reflectance cards of known reflectances (CIE, 1998). The accuracy of the integrating sphere or the reflectance card should be documented. Note that the reflectance card method relies on an accurate card reflectance being known and an accurate luminance meter. If the card colour is significantly different from that of the room surface being tested then the spectral response of the meter is another source of potential error. If the reference cards are not in pristine condition, then their reflectance should be measured again.
- When a simulation assumes that the reflections from surfaces are ideally diffuse, this assumption should be verified and justified through luminance measurements (in different directions) over a sample of the surface material. The luminance measured at different viewing angles should not vary by more than 10%. Above this level, the error introduced by this assumption can become considerable.

c. Light sources

In case of artificial lighting scenarios:

- Use a limited number of luminaires.
- The distance between measurement points and luminaires should respect the five-times law to minimize errors related to near-field light distribution. This law states that for considering a luminaire as a point light source, the distance from the luminaire to the measurement point should be greater than five times the largest projected dimension of the luminaire (IESNA, 2000a).
- Luminaire selection should be done with care, taking into account the goal of the particular test case. For example, if the goal is to test the ability of the simulation to model distribution in a room of direct illuminance from a small luminaire, then it is better to select a broad distribution luminaire so that the exact aiming of the luminaire is not as critical as it would be for a narrowly focused luminaire.
- Use a luminaire with semi-specular or diffuse optical surfaces rather than one with highly specular surfaces because the latter's distribution will be more sensitive to exact lamp position that might vary between the photometric test and the installed conditions.
- Each luminaire used in a room should have its photometry individually measured. To minimize interpolation errors, the angular resolution of the photometric data should be chosen to represent accurately the particular luminaire being tested. Vertical angles should be measured in steps of 1° to 5° and horizontal angles in steps of 5° to 15°. Higher angular resolution might be necessary in rapidly changing candela distributions. No symmetry should be assumed in the photometric data.
- Luminaire photometry should be done at a certified laboratory according to the recommended practices of the region (e.g. CIE, IESNA, CIBSE, etc.). General guidelines include an environmentally controlled test chamber, a regulated power supply, and accurate angular position tracking and calibrated photocells (CIE, 1987, 1996; IESNA, 1998, 1999, 2000a).
- The luminaire photometry should be provided in at least one of the standard photometric file formats, such as IESNA LM-63, CIBSE TM-14, EULUMDAT or CIE 102 (IESNA, 2002; CIBSE, 1988; Stockmar, 2000; CIE, 1993). In case the photometric measurements are given relative to a reference flux (1000 lm is usually used), the absolute flux to be associated with the luminaire in the simulation should also be known. In case of electrical current fluctuation, the variation of the absolute output should be known accordingly.
- The position and the orientation of each luminaire should be clearly identified to eliminate any confusion when preparing the simulation. The correlation between the photometric measurements and the geometric position should be stated in terms of the centre point position and position of C_0 plane, and if necessary the lamp or luminaire tilt angle. An illustration of this information would be useful (CIE, 1996).

In case of daylighting scenarios:

- It should be verified that the external luminance distribution is within the far field hypothesis. This can be assured with a sufficient scale ratio between a scale model and the artificial sky dimensions or between the room opening and the external environment. A ratio of 10 should reduce this error to a satisfactory level (Mardaljevic, 2002; Maamari, 2004).
- In real-world scenarios (i.e. external sky and physical environment), it is preferable to avoid complex luminance distributions such as shading vegetation, irregular shading masks, and so forth.
- Where necessary, obtain an accurate description of the external luminance distribution (as seen from the opening) at the time of the internal illuminance measurements.

d. Measurement points

For illuminance measurements:

- The measurement test points should be selected with care taking into account the goal of the particular test case. The position should be selected in a way to highlight the aspect

to be tested. For example, measurement points positioned perpendicular to the opening would allow the checking of the daylight entry in the room and assessment of the influence of a glazing material.

- To minimize errors related to cosine corrections, avoid exposing sensors to primary light sources with an incidence angle greater than 85° .
- Avoid positioning the measurement points close to shadow lines, where any slight variation in the position of the sensor can involve a significant variation of the received illuminance.
- The measurement test points should receive adequate levels of illumination so that the quoted error of the meter is relevant to that level. For example, if a meter loses accuracy at low light levels then test points with low light levels should be avoided or else separately reported with respect to their expected error.
- A sufficient number of measurement points should be used to enable the calculation of the average illuminance of the room. A regular rectangular grid of measurement points must be used in this case.
- The positioning of the sensors should be stable and accurate to minimize errors due to orientation or to the exact position of these sensors.
- The position of the sensors should be measured and described in detail including the height of the upper surface of the sensors. The position measurements should be made with a tolerance of 1% or less.

For luminance measurements:

- It is preferable to use a luminance meter with a precise description of the position and the opening angle used.
- Room surface areas with uncontrolled specular reflections should be avoided.
- It is important to describe the accurate position of the luminance meter as well as the measurement point, particularly when any specular component of the surface reflection is to be assessed.

3.2 Recommendations and precautions related to the experimental protocol

The following recommendations aim to enhance the accuracy of the experimental protocol and to minimize the importance of the error sources. This is of great importance for the reduction of the uncertainty associated with any measured data.

a. General precautions

- All photocells should be calibrated by their manufacturer or an accredited test laboratory. The date of the last calibration on the photocell should be not more than 6 months from the date the testing is done.
- The absolute error of the photocell as quoted by the manufacturer should be documented as well as the range of lux through which the error is applicable.
- If an array of photocells is used, then each one should be checked against a calibrated photocell and their variation by percentage should be documented. The data collected by each photocell can then be adjusted at the end of the test so that it can all be referenced to a single photocell of known calibration.
- Illuminance measurements should be collected to at least 3 significant figures.
- It is important to maintain the internal surfaces in a condition close to the one used to measure the photometric characteristics of these surfaces (reflectance and specularity). If a considerable variation is observed, the surfaces should be restored or the new photometric values (reflectance in particular) should be recorded.

b. Artificial lighting scenarios

- Conduct the experiment under conditions close to those of the laboratory where the photometric measurements of the luminaires were done.

- Luminaire power should be provided via a regulated power supply, preferably with a constant voltage level equal to the power condition used in the laboratory for the luminaire characterization.
- If the room power is provided via standard line voltage then any variation of the luminaire output should be monitored during the test. Luminaire output can be monitored via one photocell fixed at some position in the room with readings taken at the same time as the readings at the grid data points.
- Luminaire assembly should be done with care so as to match the measured performance after it is installed in the room. Lamp position and the cleanliness of optics are two areas of concern.
- Lamps should be allowed to stabilize before data collection begins. A single illuminance reading under the luminaire(s) should be checked at intervals of 10 minutes until the value changes less than 2% between readings.
- Temperature in the environment should be controlled to be the same as that used in the testing laboratory. The standard testing temperature is generally 25° Celsius.
- The lamps and ballasts should be seasoned (aged) for the appropriate amount of time, which depends on the lamp type. Typical lamp seasoning times are 0,5% to 1% of rated lamp life (Ashdown, 2001; IESNA, 1998, 1999, 2000b).

c. Daylighting scenarios

- For daylighting scenarios, it is important to observe variations of the external luminance distribution at the same time as the internal measurements. For an accurate description of this luminance distribution sky scanners or imaging luminance meters with hemispherical field of view can be used.
- It is important to verify the absence of a near-field problem between the external luminance distribution and the tested geometry. One way to confirm the presence of a near-field configuration is to observe the variation of the external illuminance over the daylight opening. If this variation is bigger than 5% to 10%, assuming that an external luminance distribution measured from a given position over the aperture surface applies to the whole surface, it would introduce a considerable error source.
- With glazed daylight openings, conduct measurements with and without glass materials over the opening in order to separate the error due to the glass directional transmission from the one related to the direct illuminance and surface inter-reflections.

3.3 Error estimation

No matter how accurate the experimental protocol, there will always be potential sources of error when collecting physical measurements. Errors can be generally classified into two categories:

- errors due to limitations of instrumentation and hardware (objective errors); and
- errors due to the measurement process (subjective errors).

Each of the above categories can also be subdivided in two sub-categories:

- errors related to the measured values; and
- errors related to the simulation and in particular the accuracy of the scenario description.

All efforts should be made to obtain accurate estimates for each source of error. The estimation of each error should be reported as +/- percentage compared to the measured value. The global estimated error can then be calculated using the following equation (standard deviation metrics for uncorrelated data) (Slater and Graves, 2002):

$$E_M(\text{or } E_G) = \sqrt{\sum_{i=1}^N (\text{error}_{(i)})^2} \quad (1)$$

where:

- E_M = estimated total measurement errors;
- E_G = estimated global errors including both measurement and simulation errors;
- N = number of error sources.

Below is presented a description of the potential error sources, and where possible, of methods for estimating the magnitude of these errors.

a. Measurement related, objective errors

- Photocell calibration: the error estimation is obtained from the quoted accuracy of the photocell after calibration. Generally, use photocells with an estimated uncertainty less than 3%.
- Photocell cosine correction: estimation should be based on the accuracy quoted by the manufacturer. Generally, the related error is less than 3% for point measurements and 1% for average illuminance. This error can become considerable if a major part of the incoming flux is arriving with an incident angle higher than 80° (i.e., close to the photocell surface).
- Photocell spectral sensitivity (how well the photocell response matches the visual response curve): should be estimated from the quoted accuracy by the manufacturer. Spectral sensitivity errors are light source dependent and are usually close to 1%.
- Lumen output variation due to temperature or power fluctuations: this error can be removed if the procedure listed above (Section 3.2b) is followed to track the changes in absolute light output during the test. If the recommendations are not followed, then this error can be quantified by measuring temperature variations at the level of the luminaire during the test as well as power fluctuations during the test. Given this data, the lamp output characteristics must be known over the ranges measured.

b. Measurement related, subjective errors

- Measurement apparatus intrusions: this is the error introduced due to the equipment that is placed in the room for measurement purposes. Taking two measurements at a certain point in the room, before and after the instruments are installed, can give an idea about the influence of these instruments on the data collected.
- The stability and the accuracy of the photocell position and orientation: the related error can be estimated through repeated data collection at the same point (moving and replacing the sensor under the same external conditions). Using accurate positioning systems can minimize this error. The importance of the error can vary from one point to another according to the position of the light source and to the variation of the illuminance around the measurement point. Under good conditions, the error can approach 3% for point measurements, but will probably be closer to 1% for averaged illuminance measurements.

c. Simulation related, objective errors

- Near-field related errors: in both artificial and daylighting scenarios, the source photometry is generally obtained in a far-field configuration. This introduces a potential error source, especially in the cases of luminaires of large dimensions (linear or rectangular), artificial sky scenarios or close masks such as shading systems and facing buildings.
- Photometric measurements of luminaires: there are always some uncertainties related to the difference between laboratory measurements and the real performance of the luminaire after installation (absolute output flux and intensity distribution). The error related to the flux difference can be 5% or more. The error related to the directional distribution of the flux is usually negligible for averaged illuminance measurements (<1%), but can go above 5% for point measurements.
- The interpolation of the measured intensities: laboratory photometric measurements of luminaires are conducted at given angular steps. In a lighting simulation, the measured values at the given angles are interpolated to determine a calculated value for the other directions of space. The error related to this interpolation depends on the algorithm used for interpolation, the angular resolution and the complexity of the real distribution.
- Room surface reflectance: the related error is due to the difference between the simulated and measured values. It depends therefore on the accuracy of the method and the instruments used to measure the reflectance. The influence of the error in the

measured reflectance on the simulation accuracy can be calculated with the following equation (Maamari, 2004):

$$\Delta E_m = \frac{\Delta \rho}{(1 - \rho) \cdot (1 - (\rho + \Delta \rho))} \cdot \frac{\phi_0}{S_T} \quad (2)$$

where:

ΔE_m = error in the average indirect illuminance due to the inaccuracy in the measured reflectance (ρ);

$\Delta \rho$ = error in the measured ρ value = ($\rho_{\text{measured}} - \rho_{\text{real}}$);

ϕ_0 = luminous flux entering the room;

S_T = total area of internal surfaces.

- Variable reflectance across a surface. One other source of room surface reflectance error is variable reflectance across a given surface. To quantify this, several points (at least three) should be sampled from different parts of each room surface. The variation of the measured reflectance should be taken into consideration as an additional error source to be estimated as described above.
- Room surface spatial reflectance: the related error is introduced due to the assumption that the room surfaces are perfectly diffuse, despite existing directionality in the real reflections. The more significant the directionality, the more difficult it is to quantify the related error. In general, this error will increase with the participation of the luminous flux received through specular reflections to the illuminance on the measurement point. For example, the related error will increase for points closer to room surfaces. If the main point of the test case is to characterize indirect lighting conditions then the test should be done in a room with surfaces that are close to being ideal diffuse reflectors, with directional luminance variations not exceeding 10%.

d. Simulation related, subjective errors

- Dimensional errors: this error is related to the accuracy of the measured dimensions of the room. It can be minimized by repeating all dimensional measurements for the room configuration and luminaire placements. This error can be estimated via the lighting software with comparative analyses of changes in dimensions equal to the expected tolerance in physical measurement.
- Luminaire position accuracy: this is the same as for the position of the measurement points, the related error depends on the luminaire photometry and on unambiguous documentation of the measurement points.

3.4 Data presentation

The collected data set should be organized into its key components making it as convenient as possible to define the test case in the lighting software and summarize the comparison between the calculated and measured values.

The recommended organization for a given test case should include, in addition to an accurate description of the scenario (as mentioned in Section 3.1), a clear description of the reference values with the associated uncertainties to be calculated as mentioned in Section 3.3. The description of the reference values can be organized as follows:

- Describe the measurement grid locations and illustrate the grid with a CAD drawing.
- Summarize the error analysis addressing each of the potential errors listed above. Provide an estimation of the global error to be associated to the reference values, including if relevant the simulation errors.
- If necessary, segregate the total error expected for various parts of the grid. This can be justified where a given number of the measurement points are less exposed to a number of error sources than other points.
- Reference values should be given for each measurement point. It is recommended to present them with a tolerance (i.e. a range of acceptable values) for the simulation

results. This range is equal to the measured value plus or minus the total estimated error (with or without the errors related to the simulation).

- Normally the grid data should be provided in electronic format, such as a tabulated text file or spreadsheet, with an allocated space for the simulation results so that the comparison can be easily done between the simulation and the reference data.

Table 1. Example of recommended presentation for experimental measurements.

	<i>E</i> (lx) on measurement points			
	A1	A2	A3	A4
Measurement upper limit including global error	296	574	606	388
Measurement upper limit	278	539	569	364
Simulation				
Measurement lower limit	237	459	484	310
Measurement lower limit including global error	219	424	448	287

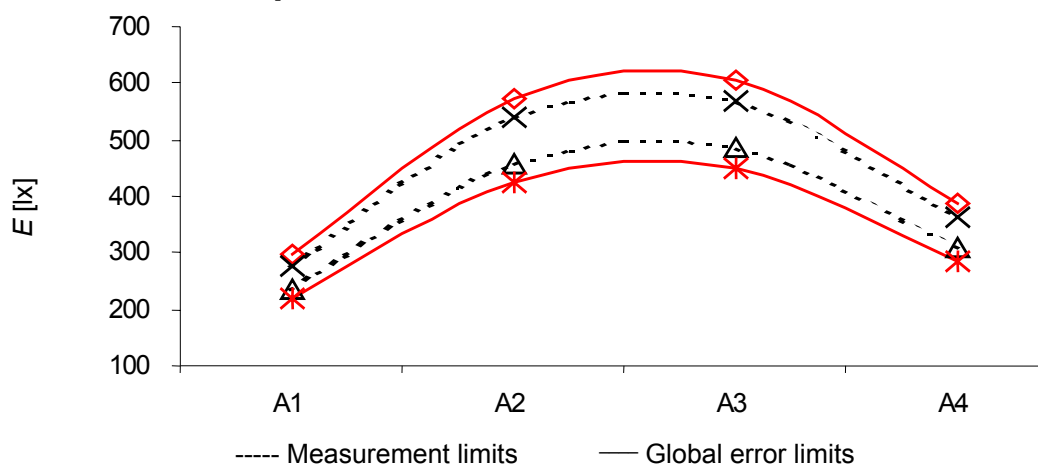


Fig. 1. Recommended graphical presentation of experimental measurements.

3.5 Standard description for experimental test cases

Based on the above recommendations, the description of an experimental scenario used for validation should be presented using the following structure:

a. Scope of the test (Introduction)

- the light propagation aspect to be tested;
- presentation of the conducted protocol.

b. Geometric description:

- dimensions;
- materials photometry (reflectance, transmittance, BT(R)DF characterization, etc.).

c. Light source description:

- position (luminaire or aperture);
- photometry (goniophotometric measurements for luminaires, external luminance map for daylight scenario, near-field analyses, etc.).

d. Reference values:

- measurement points description;
- error sources and global error estimation;
- data presentation (measurements +/- estimated error).

4. PROPOSED EXPERIMENTAL TEST CASES

4.1 Artificial lighting scenario - CFL, grey wall

4.1.1 Protocol description

This test case is based on of the CIBSE TM 28/00 (Slater and Graves, 2002), a report describing the experimental protocol that has been used in a measurement campaign under artificial lighting scenarios. The report includes the results of this campaign as benchmark data to be used for assessing lighting computer programs in artificial lighting predictions.

The quality of this data is mainly due to the efforts invested to minimize the potential errors through a rigorous experimental protocol and to the objective analysis of these errors.

The description of the scenario includes the luminaire photometric files in CIBSE TM 14 format (CIBSE, 1988), where each luminaire was photometered separately. The directions of the C_0 axes in the room were also given.

The protocol included a control on the light output through the control and the monitoring of the power fluctuations and the room temperature. The lamps and ballasts were properly aged. Lamps were warmed up for one hour before measurements. The photometers were calibrated and positioned on a trolley to guarantee repeatable position. Six measurements were taken for the same point with two different photometers and average values were used. Probably the only significant inaccuracy in the protocol was related to the floor colour, which was not spectrally neutral (dark brown), as no spectral measurements or chromaticity coordinates were given. However, due to the low reflectance of the floor, the related error source was likely negligible with respect to the illuminance measurements, but it could be significant for spectral and luminance values (which were not assessed in this test case). An alternative study that avoided this problem was performed by DiLaura et al. (1998).

Both the measurement and the simulation errors were estimated. The results were presented as two bands of values, the first for the measurement errors and the second for the total expected errors, including simulation errors.

The scenario of this test case is one of six total scenarios defined with different luminaires and/or with different surface reflectances. These scenarios include compact fluorescent lamps as light sources and grey painted walls. Therefore, the inter-reflections are taken into consideration.

4.1.2 Geometric description

The test room measures 6,78 m in the X-direction and 6,72 m in the Y-direction as shown in Fig. 2. The ceiling height is 3,24 m.

4.1.3 Materials photometry

No BRDF measurements are available for different surfaces.

- the ceiling consists of white acoustic tiles ($R = 0,70 \pm 0,01$);
- the floor is dark brown ($R = 0,06 \pm 0,01$);
- the walls are matte grey ($R = 0,41 \pm 0,02$).

4.1.4 Luminaire position

Four luminaires are positioned in a regular 2 x 2 grid with a spacing of 3,39 m in the X-direction and 3,36 m in the Y-direction.

- Luminaire 1 is positioned at the top left with respect to Fig. 2 ($X=1,695$ m, $Y=1,680$ m);
- Luminaire 2 is at the bottom left ($X=1,695$ m, $Y=5,040$ m);
- Luminaire 3 is at the top right ($X=5,085$ m, $Y=1,680$ m);
- Luminaire 4 is at the bottom right ($X=5,085$ m, $Y=5,040$ m).

The height of the luminaires is 3,14 m.

All luminaire C_0 axes are parallel with the Y-axis, and point towards the wall nearest to luminaires 2 and 4 ($Y=6,72$ m).

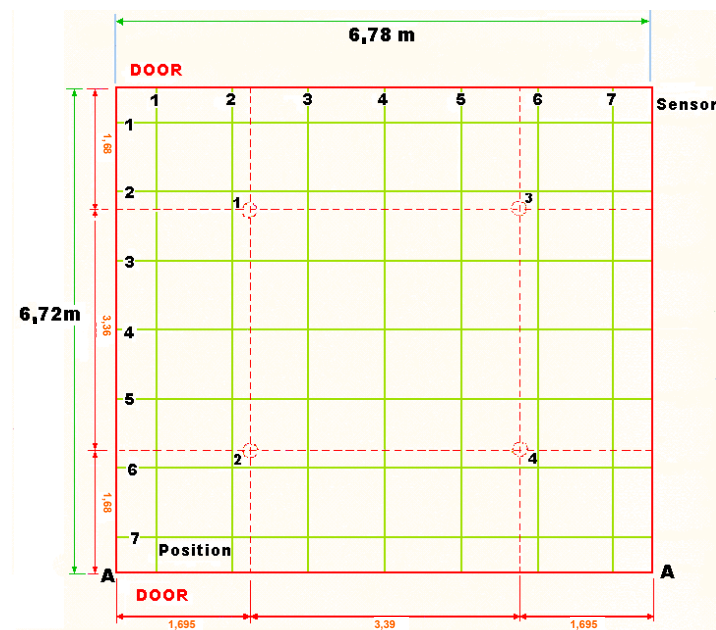


Fig. 2. Plan of the test room with lamp/luminaire and measurement positions.

4.1.5 Luminaire photometry

The luminaires used in this test consist of bare compact fluorescent lamps (32W Philips PL-T/ 840/ 4P) with Huco 32W TC-T electronic ballasts.

The total lumen output from each luminaire was measured as:

- Luminaire 1: 2182 lm;
- Luminaire 2: 2196 lm;
- Luminaire 3: 2203 lm;
- Luminaire 4: 2182 lm.

The photometric data for the lamps is given in CIBSE TM14 format (see Appendix A.1). The same photometry applies to all four luminaires.

4.1.6 Measurement points

The measurement points are defined on a regular 7 x 7 grid with half spacing at the edges (see Fig. 2).

The measurement plane is 0,80 m above the floor level.

4.1.7 Prediction of errors

The estimation of the different errors is described in Tables 2 and 3. The total error (total measurement error and total expectation of error) is estimated based on the different interfering errors using Equation 1.

The estimated total measurements error is:

- +/- 6,7% for point illuminance;
- +/- 3,8% for average illuminance.

Table 2. Measurement error estimates.

Measurement errors	Effect on average illuminance %	Effect on direct point illuminance %
Sensors		
Cosine correction	0,5	2
Colour correction	1	1
Calibration	2	3
Repeatability of position	0	3
Leveling	0	2
Photometry factors affecting measurement		
Lumen output - temp	2	2
Lumen output - power	1	1
Room factors		
Dimensions and irregular features	0,5	0,5
Luminaire positions	0	2
Measurement positions	0	2
Surface reflectances	2	2
Total measurement error	3,8	6,7

The estimated total expectation of error including the potential simulation errors is:

- +/- 10,5% for point illuminance;
- +/- 6,3% for average illuminance.

Table 3. Total expectation of error.

Simulation errors	Effect on average illuminance %	Effect on direct point illuminance %
Photometry factors affecting simulations		
Output distribution	0	5
Lumen output	5	5
Output photometry v. real situation		
Intervals in TM14 format	0	4
Total expectation of error	6,3	10,5

4.1.8 Reference values - point illuminance

For point illuminance measurements, the reference values are presented in Table A.1 of Appendix A.1 by means of two pairs of upper and lower limits, where the first pair (measurement $\pm 2 \times 6,7\%$) defines a band of values including the measurement errors and the second pair (measurement $\pm 2 \times 10,5\%$) defines a band including both measurement and simulation errors.

4.1.9 Reference values - room average illuminance

For the room average illuminance at the measurement plane, the reference values are presented in Table 4 by means of upper and lower limits (measurement $\pm 2 \times 6,3\%$) defining a band of values that include the total expectation errors.

Table 4. Upper and lower limits for mean room illuminance with grey wall-CFL lamp.

Upper limit	112,0
Simulated mean room illuminance	
Lower limit	88,0

4.2 Artificial lighting scenario - opal luminaire, grey wall

4.2.1 Protocol description

As described in 4.1.1.

4.2.2 Geometric description

As described in 4.1.2.

4.2.3 Materials photometry

As described in 4.1.3 except for the wall reflectance, which is 0,52 $\pm$ 0,02 instead of 0,41 $\pm$ 0,02.

4.2.4 Luminaire position

As described in 4.1.4 except for the luminaire height, which is 3,20 m instead of 3,14 m.

4.2.5 Luminaire photometry

The luminaires used in this test were opal luminaires (Opaline 450 mm luminaires, Cat. No. 2045T381 with 38W TC-DD Amalgam compact fluorescent lamps and Tridonic EC40 A50 ballasts).

The total lumen output from each luminaire was measured as:

- Luminaire 1: 1850 lm;
- Luminaire 2: 1830 lm;
- Luminaire 3: 1870 lm;
- Luminaire 4: 2110 lm.

The photometric data for the luminaires is given in CIBSE TM14 format (see Appendix A.2). The same photometry applies to all four luminaires.

4.2.6 Measurement points

As described in 4.1.6.

4.2.7 Prediction of errors

As described in 4.1.7.

4.2.8 Reference values - point illuminance

For the point illuminance measurements, the reference values are presented in Table A.2 of Appendix A.2.

4.2.9 Reference values - room average illuminance

For the room average illuminance at the measurement plane, the reference values are presented in Table 5 below.

Table 5. Upper and lower limits for mean room illuminance with grey wall-opal lamp.

Upper limit	67,5
Simulated mean room illuminance	
Lower limit	53,1

4.3 Artificial lighting scenario - semi-specular reflector (SSR) luminaire, grey wall

4.3.1 Protocol description

As described in 4.1.1.

4.3.2 Geometric description

As described in 4.1.2.

4.3.3 Materials photometry

As described in 4.1.3 except for the walls reflectance, which is 0,52 +/- 0,02 instead of 0,41 +/- 0,02

4.3.4 Luminaire position

As described in 4.1.4 except for the luminaire height, which is 3,20 m instead of 3,14 m.

4.3.5 Luminaire photometry

The luminaires used in this test are semi-specular reflector luminaires (Category 2, 600 mm x 600 mm square luminaires, Cat. No. U1701/318 P1 with three Philips New Generation TL-18 W, colour 840 lamps and Philips HF-Performer, warm-start 3 x 18 W high frequency ballasts).

The total lumen output from each luminaire was measured as:

- Luminaire 1: 4087,7 lm;
- Luminaire 2: 4174,7 lm;
- Luminaire 3: 4135,0 lm;
- Luminaire 4: 4114,3 lm.

The photometric data for each luminaire is given in CIBSE TM14 format (see Appendix A.3).

4.3.6 Measurement points

As described in 4.1.6.

4.3.7 Prediction of errors

As described in 4.1.7.

4.3.8 Reference values - point illuminance

For the point illuminance, the reference values are presented in Table A.3 of Appendix A.3.

4.3.9 Reference values - room average illuminance

For the room average illuminance at the measurement plane, the reference values are presented in Table 6 below.

Table 6. Upper and lower limits for mean room illuminance with grey wall-SSR luminaire.

Upper limit	254,2
Simulated mean room illuminance	
Lower limit	199,8

4.4 Artificial lighting scenario - CFL, black wall

4.4.1 Protocol description

As described in 4.1.1, except for the walls, which are black in order to avoid errors related to inter-reflections.

4.4.2 Geometric description

As described in 4.1.2.

4.4.3 Materials photometry

No BRDF measurements are available for different surfaces.

- the ceiling is covered with black velvet ($R = 0,03 \pm 0,01$);
- the floor is dark brown ($R = 0,06 \pm 0,01$);
- the walls are painted matt black ($R = 0,04 \pm 0,01$).

4.4.4 Luminaire position

As described in 4.1.4.

4.4.5 Luminaire photometry

As described in 4.1.5.

4.4.6 Measurement points

As described in 4.1.6.

4.4.7 Prediction of errors

As described in 4.1.7.

4.4.8 Reference values - point illuminance

For the point illuminance, the reference values are presented in Table A.4 of Appendix A.4.

4.4.9 Reference values - room average illuminance

For the room average illuminance at the measurement plane the reference values are presented in Table 7 below.

Table 7. Upper and lower limits for mean room illuminance with black wall-CFL lamp.

Upper limit	37,5
Simulated mean room illuminance	
Lower limit	29,5

4.5 Artificial lighting scenario - opal luminaire, black wall

4.5.1 Protocol description

As described in 4.1.

4.5.2 Geometric description

As described in 4.1.2.

4.5.3 Materials photometry

As described in 4.4.3.

4.5.4 Luminaire position

As described in 4.1.4 except for the luminaire height, which is 3,20 m instead of 3,14 m.

4.5.5 Luminaire photometry

As described in 4.2.3.

4.5.6 Measurement points

As described in 4.1.6.

4.5.7 Prediction of errors

As described in 4.1.7.

4.5.8 Reference values - point illuminance

For the point illuminance, the reference values are presented in Table A.5 of Appendix A.5.

4.5.9 Reference values - room average illuminance

For the room average illuminance at the measurement plane, the reference values are presented in Table 8 below.

Table 8. Upper and lower limits for mean room illuminance with black wall-opal lamp.

Upper limit	51,1
Simulated mean room illuminance	
Lower limit	40,1

4.6 Artificial lighting scenario - semi-specular reflector luminaire, black wall

4.6.1 Protocol description

As described in 4.1.1.

4.6.2 Geometric description

As described in 4.1.2.

4.6.3 *Materials photometry*

As described in 4.4.3.

4.6.4 *Luminaire position*

As described in 4.1.4 except for the luminaire height, which is 3,20 m instead of 3,14 m.

4.6.5 *Luminaire photometry*

As described in 4.3.5.

4.6.6 *Measurement points*

As described in 4.1.6.

4.6.7 *Prediction of errors*

As described in 4.1.7.

4.6.8 *Reference values - point illuminance*

For the point illuminance, the reference values are presented in Table A.6 of Appendix A.6.

4.6.9 *Reference values - room average illuminance*

For the room average illuminance at the measurement plane, the reference values are presented in Table 9.

Table 9. Upper and lower limits for mean room illuminance with black wall-SSR luminaire.

Upper limit	228,5
Simulated mean room illuminance	
Lower limit	179,5

4.7 Conclusions

The above experimental test cases show how difficult it is to minimize the uncertainties in an experimental reference data. Therefore, the use of analytical test cases can be considered as an adequate answer to this problem where they can be used to complete experimental validation data.

5. PROPOSED TEST CASES WITH ANALYTICAL REFERENCES

Since lighting simulations are usually based on theoretical laws based on physical observations, we propose a test case suite where the reference values are calculated based on these laws. The advantage of this type of test cases is the possibility to isolate a given aspect of the light propagation and to minimize or eliminate the uncertainty in the reference values.

5.1 Standard description for analytical test cases

As for the experimental test cases, it is recommended to provide a complete and unambiguous description of each analytical test case to be proposed for lighting software validation.

The description of an analytical scenario should be presented as per the following structure:

a.1 Scope of the test (Introduction)

- the light propagation aspect to be tested.

a.2 Analytical reference

- description of the theoretical law related to the tested aspect.

b. Geometric description

- dimensions;
- materials photometry (reflectance, transmittance, BRDF characterization, etc.).

c. Light source description

- position (luminaire or aperture);
- photometry (luminous flux and intensity distribution for luminaires, external luminance map for daylight scenarios, sky model, zenith luminance, horizontal illuminance, mask position and luminance, etc.).

d. Reference values

- measurement points description;
- presentation of the calculated reference values (based on the analytical reference). The reference values are usually absolute values. The difference between the simulation results and these values can be estimated and presented as relative errors.

Table 10. Example of comparison between analytical references and simulation results.

Illuminance					
Points	1	2	3	4	5
E analytic (lx)	341	324	280	224	169
E simulation (lx)	344	321	283	226	171
Error (%)	0,72	-0,94	1,13	1,17	1,17

5.2 Simulation of point light sources

The objective of this test case is to assess the capability of software to calculate the direct illuminance under a point light source described by a photometric distribution file.

Actually, most lighting programs simulate artificial lighting luminaires by using a photometric file representing the intensity distribution of this luminaire. Some of the commonly used formats for photometric intensity distribution files are the IESNA LM-63 format used internationally (IESNA, 2002), the EULUMDAT format commonly used in Europe (Stockmar, 2000) and the CIBSE TM14 (CIBSE, 1988).

The first source of error in the simulation of a luminaire with a photometric distribution file is related to the difference between the photometry described by the file (measured or given by the manufacturer) and the on-site performance. To avoid this error, we propose to use analytical intensity distributions in this test case.

The second source of error is related to interpolation, where the given intensity values at the measurement steps are used to calculate the intensity at other directions in space. This test case can be used to assess the interpolation method of the tested program, since the photometry is normally described by using vertical angular steps of 10° or less. It is understood however, that all interpolation methods provide only an estimate of the real data between measured data points, the amount of error due to interpolation methods depends upon the particular distribution of the luminaire. Therefore, to minimize the error due to the interpolation, the vertical angular steps used should be of 5° or smaller and the horizontal angular steps should be 15° or smaller.