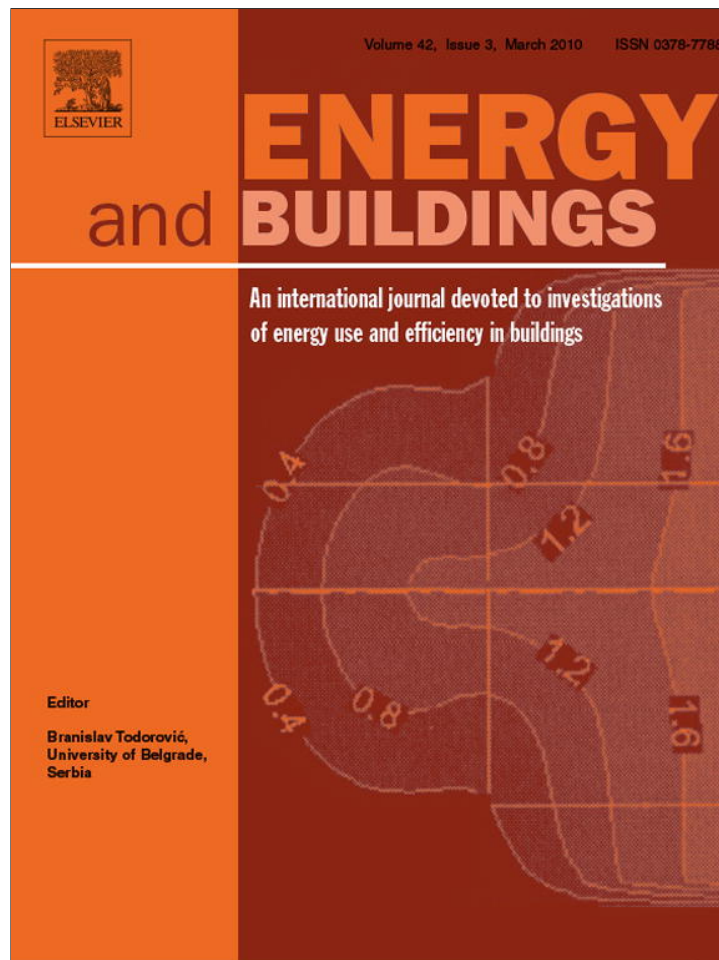


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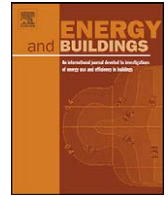
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Energy and Buildings

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Criteria for energy efficient lighting in buildings

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ARTICLE INFO

Article history:

Received 11 August 2009

Received in revised form 4 September 2009

Accepted 17 September 2009

Keywords:

Utilance

Energy efficient lighting

Normalized power density

Lighting

ABSTRACT

In order to assess the energy efficiency of an indoor lighting installation, a criterion for the installed electrical power is proposed which is broadly applicable and easy to use. Introducing target values for lamps and gear and taking into account some basic lighting comfort requirements, the maximum electrical power to be installed can be predicted for any kind of application. Herewith, one or more task areas with appropriate target illuminance values may be defined. The key parameter of the criterion is the analytical expression for the target utilance as a function of common lighting design parameters.

Two practical examples illustrate the validity of the criterion. In a first example, a general case where the task area is coincident with a reference plane parallel with the floor has been studied. The values obtained converge to actual target values in current practice. In a second example, the lighting design of a store with many vertical task areas is explained. These cases illustrate the advantages of the criterion as compared to energy evaluation criteria based on the normalized power density.

From 2010 on, the proposed criterion will be used in Flanders to assign grants for a re- or newlighting.

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1. Introduction

Lighting is an important issue in minimizing overall energy consumption [1]. For the industrialized countries, lighting accounts for 5–15% of the total electric energy consumption. Besides direct savings, indirect energy savings can be realized due to a reduced consumption for air conditioning.

The energy consumption of a lighting installation is strongly dependent on lighting controls (daylight, presence detection, dimming, etc.) [2,3]. Nevertheless, the electrical power load of a lighting installation is often a first and significant measure for the energy consumption. In this paper, only the installed power load will be considered.

In many countries, the government allocates grants to companies or local authorities choosing for energy efficient lighting solutions. To get a subsidy for a re- or newlighting in Flanders, the normalized power density *NPD* has been used as the evaluation criterion. The *NPD* of a lighting installation relates the electrical power for lighting to the mean maintained illuminance on a reference plane and to the overall floor area and is typically expressed in $W/(m^2 \cdot 100 \text{ lx})$. As an example, the maximum *NPD*

value to receive grants for relighting an office is $2 W/(m^2 \cdot 100 \text{ lx})$. The limit values have been based on everyday experience.

In fact, *NPD* values are only applicable for areas where a uniform illuminance is required over a task area approximately equal in area to the floor, such as in open plan offices. It is obvious that in shops, storehouses, classrooms and many other situations, the task areas can be completely different from the floor area. In these cases, *NPD* values referenced to the floor area are by no means relevant any more. For this reason, a lot of energy efficient lighting solutions are not considered for grant.

In [4,5], a new general criterion for energy efficient lighting installations has been proposed, taking into account basic lighting comfort requirements. The criterion is suitable for any interior task areas (not restricted to standard task areas) and is valid for a wide range of applications as may occur in offices, shops, storehouses, work areas, classrooms, etc.

Nevertheless, there are still some difficulties with this calculation method hampering its general use. Only one target illuminance value for all the task areas is allowed, which is a severe restriction. Furthermore, the assumption of a mean reflectance of 0.50 and a very basic estimation of the indirect illumination limits its accuracy. Moreover, the criterion seems to be too flexible for rooms where the task area is very small compared to the total area.

In this paper, this former criterion is adapted and refined to overcome the shortcomings listed above. Some examples illustrate the usability of the criterion for standard as well as for non-standard task areas.

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From 2010 on, the assignment of grants in Flanders will be based on the criterion described in this paper.

2. Installed lighting load

The power load P of an interior lighting installation is dependent on

- The efficiency of the gear η_{gear} .
- The efficacy of the light sources η_{lamp} , expressed in lumen per Watt.
- The efficiency of the luminaires which relates the luminous flux released by the luminaires to the luminous flux of the light source(s). This efficiency is called the Light Output Ratio and is abbreviated as LOR .
- The utilisation U is the efficiency of directing the luminous flux from the luminaires to the task area(s) TA . It is defined as the ratio of the total initial luminous flux reaching the task area(s) to the initial luminous flux released by the luminaires.
- The maintenance factor MF is defined as the ratio of the illuminance on a given area at the end of the maintenance cycle to the initial illuminance on the same area. The factor includes among others the effects of the depreciation of lamps, the deposition of dirt on luminaires and room surfaces and the applied maintenance procedure. In this paper, final values of illumination quantities at the end of the maintenance cycle are denoted with the suffix 'fin', whereas no suffix is used for initial values.

The total luminous flux on the task area(s) at the end of the maintenance cycle Φ_{TA}^{fin} can be written as [4]:

$$\Phi_{TA}^{fin} = MF \cdot U \cdot LOR \cdot \eta_{lamp} \cdot \eta_{gear} \cdot P \quad (1)$$

When a variety of luminaires, lamps and ballast types are used, (1) remains valid if weighted mean values are used.

On the other hand, Φ_{TA}^{fin} can also be written as

$$\Phi_{TA}^{fin} = \sum_i \bar{E}_{TA,i}^{fin} \cdot A_{TA,i} \quad (2)$$

with $\bar{E}_{TA,i}^{fin}$ and $A_{TA,i}$ the maintained mean illuminance value and the surface of the i th task area, respectively.

From (1) and (2), an expression for the power load P becomes:

$$P = \frac{\sum_i \bar{E}_{TA,i}^{fin} \cdot A_{TA,i}}{MF \cdot U \cdot LOR \cdot \eta_{lamp} \cdot \eta_{gear}} \quad (3)$$

In order to classify a lighting installation as being energy efficient, a maximum target value for the power has to be formulated. Therefore, minimum values for each parameter appearing in the denominator of (3) have to be chosen. In this proposal, it is not required to meet all individual target values and mutual compensation is allowed.

The basic assumption is to get a criterion which is suitable for any interior task area or combination of task areas, which is simple and easy-to-use while being accurate and reproducible. Only surface areas, reflectance and illuminance values of task areas can be considered as input which can easily be provided by the lighting designer.

3. Target values

The main goal of this study is to trace the most inefficient lighting installations. Hence, minimal target values for each individual parameter are proposed in this section.

Because a gear can have a considerable impact on the lamp efficacy and lamp power (e.g. a magnetic versus an electronic ballast for T8 fluorescent lamps), the efficiency of the gear and the efficacy of the lamp are combined in the system efficiency η_{sys} . The target value proposed is

$$\eta_{sys} = \eta_{gear} \cdot \eta_{lamp} > 75 \text{ lm/W} \quad (4)$$

In this way, the use of incandescent and halogen lamps is strongly penalized while, in general, T5 or T8 fluorescent lamps or the most efficient high pressure (metal halide) lamp types meet the requirement easily. Although this individual target is not reached by most compact fluorescent lamps, the overall power target may still be reached.

By using high reflective materials and smart reflector geometries, LOR values of 80% and higher can certainly be obtained. Inspecting catalogues of luminaire manufactures justifies that a realistic target value for the LOR is

$$LOR > 0.80 \quad (5)$$

For an interior installation with high polluting industrial activities, a maintenance factor MF lower than 0.6 may be realistic. On the other hand, in rooms such as office buildings, maintenance factors of 0.8 or higher are possible. Because MF is strongly dependent on the type of activities, MF will be considered as an input parameter

$$MF : \text{input parameter} \quad (6)$$

The target value for the utilisation U is more difficult to define and is considered in a separate section.

4. Utilisation target value

The key parameter to evaluate a lighting design is the utilisation U defined as:

$$U = \frac{\Phi_{TA}}{\Phi_{lum}} \quad (7)$$

with Φ_{TA} the total initial luminous flux reaching the task area(s) and Φ_{lum} the total initial luminous flux released by all luminaires.

The utilisation depends mainly on [6,7]:

- the arrangement of the luminaires in the room in relation to the position of the task area;
- the luminous intensity distribution of the luminaires and the spacing to height ratio;
- the reflectance values of the surroundings, which determine the indirect contribution.

The higher the utilisation, the more efficient the lighting installation will be. On the other hand, to guarantee lighting comfort [8], non-task areas have to be sufficiently illuminated to reach a minimal luminance. For this reason, extremely high values of U are not encouraged.

4.1. Classification of task areas

In order to formulate an analytical expression for the utilisation in a very simple but general way, a classification of the task areas is needed. A task area is any surface for which a minimal illuminance has to be guaranteed. The lighting designer, in consensus with the client, determines the task area(s) and the corresponding illuminance values. The determination can be inspired on the European standard EN12464-1 [9] in which specific task areas and corresponding illuminance values are defined for many indoor applications.

In light planning software, designers make often use of *transparent* calculation surfaces in order to compute main lighting

parameters such as maintained mean illuminance and uniformity. A typical example is an open plan office in which the desks are not integrated and only one transparent calculation surface at a particular height is considered.

In order to bring the criterion in line with standard calculation practice, the use of transparent calculation surfaces must be included.

One can distinguish three classes of task areas:

- Task area(s) *type a*: a task area coincident with the floor or a transparent calculation surface parallel with the floor (e.g. open plan office).
- Task area(s) *type b*: a task area coincident with the wall(s) or a transparent calculation surface parallel with the wall(s). A typical example is a wall in a museum.
- Task area(s) *type c*: a task area coincident with *additional furniture*. A typical example are the many vertical task areas in a storehouse.

The total surface area of task area types *a*, *b* and *c* is A_a , A_b , A_c , respectively. The reflectance for task areas type *a* and *b* equals the reflectance of the floor and walls, respectively. For a task area type *c*, the reflectance ρ_c has to be defined.

The total task area A_{TA} equals

$$A_{TA} = \sum_i A_{TA,i} = A_a + A_b + A_c \quad (8)$$

The total room area A_{tot} interacting with the light is approximated by

$$A_{tot} = A_{floor} + A_{wall} + A_{ceiling} + A_c \quad (9)$$

The introduction of type *c* task areas associated with furniture on one hand adds some additional non-task area, but on the other hand will hide some of the floor or wall area. Both effects, which can partially compensate each other, have been neglected in (9).

4.2. General utilisation estimation

The initial luminous flux which is incident on the total room area Φ can be separated into the flux received by all task area(s) Φ_{TA} and the flux received by all non-task area(s) Φ_{nTA} :

$$\Phi = \Phi_{TA} + \Phi_{nTA} \quad (10)$$

With $\bar{E}_{TA,i}$ and $\bar{E}_{nTA,i}$ the initial mean illuminance value of the *i*th task and *i*th non-task area, one finds:

$$\Phi = \sum_i \bar{E}_{TA,i} \cdot A_{TA,i} + \sum_i \bar{E}_{nTA,i} \cdot A_{nTA,i} \quad (11)$$

Introducing the weighted mean illuminance of all task areas $\langle \bar{E}_{TA} \rangle$ and all non-task areas $\langle \bar{E}_{nTA} \rangle$ (11) can be rewritten as:

$$\Phi = \langle \bar{E}_{TA} \rangle \cdot A_{TA} + \langle \bar{E}_{nTA} \rangle \cdot A_{nTA} \quad (12)$$

$$\Phi = \langle \bar{E}_{TA} \rangle \cdot A_{TA} \left(1 + \frac{\langle \bar{E}_{nTA} \rangle \cdot A_{nTA}}{\langle \bar{E}_{TA} \rangle \cdot A_{TA}} \right) \quad (13)$$

$$\Phi = \Phi_{TA} \left(1 + \frac{\langle \bar{E}_{nTA} \rangle \cdot A_{nTA}}{\langle \bar{E}_{TA} \rangle \cdot A_{TA}} \right) \quad (14)$$

On the other hand, the luminous flux from the luminaires Φ_{lum} gives rise to a direct and an indirect contribution to the illuminance values. Because the surfaces in the room are not totally absorbing, a part of the luminous flux is reflected and redirected into the room, giving rise to an indirect contribution of the illuminance. For this

reason, Φ can also be written as:

$$\Phi = \Phi_{lum} + \langle \rho_1 \rangle \cdot \Phi_{lum} + \langle \rho_1 \rangle \cdot \langle \rho_\infty \rangle \cdot \Phi_{lum} + \langle \rho_1 \rangle \cdot \langle \rho_\infty \rangle^2 \cdot \Phi_{lum} + \dots \quad (15)$$

and (15) can be simplified by series expansion:

$$\Phi = \Phi_{lum} \cdot \left(1 + \langle \rho_1 \rangle \cdot \frac{1}{1 - \langle \rho_\infty \rangle} \right) \quad (16)$$

The luminous flux from the luminaires Φ_{lum} represents the direct contribution to the flux. The second term represents the indirect flux after the first reflection with mean reflectance $\langle \rho_1 \rangle$. The following terms represent the contributions of each subsequent reflection for which the same reflection $\langle \rho_\infty \rangle$ was adopted. The first reflection has to be treated separately in order to improve the accuracy.

In calculating $\langle \rho_1 \rangle$, part of the luminous flux from the luminaires Φ_{lum} reaches the task area(s) and is reflected according to the mean reflectance of the task areas whereas the remaining part reaches the non-task areas. Therefore, $\langle \rho_1 \rangle$ can be calculated as:

$$\langle \rho_1 \rangle = U_{dir} \cdot \langle \rho_{TA} \rangle + (1 - U_{dir}) \cdot \langle \rho'_{nTA} \rangle \quad (17)$$

U_{dir} is the direct utilisation, in according to (7) defined as

$$U_{dir} = \frac{\Phi_{TA,dir}}{\Phi_{lum}} \quad (18)$$

$\langle \rho_{TA} \rangle$ is the weighted mean reflectance of the task areas:

$$\langle \rho_{TA} \rangle = \frac{A_a \cdot \rho_{floor} + A_b \cdot \rho_{wall} + A_c \cdot \rho_c}{A_{TA}} \quad (19)$$

$\langle \rho'_{nTA} \rangle$ is the weighted mean reflectance of the non-task areas with exception of the ceiling:

$$\langle \rho'_{nTA} \rangle = \frac{(A_{floor} - A_a) \cdot \rho_{floor} + (A_{wall} - A_b) \cdot \rho_{wall}}{(A_{floor} - A_a) + (A_{wall} - A_b)} \quad (20)$$

The contribution of the ceiling is excluded because direct illumination of the ceiling is assumed to be rather limited.

The weighted mean reflectance $\langle \rho_\infty \rangle$ is calculated as:

$$\langle \rho_\infty \rangle = \frac{A_{floor} \cdot \rho_{floor} + A_{wall} \cdot \rho_{wall} + A_{ceiling} \cdot \rho_{ceiling} + A_c \cdot \rho_c}{A_{tot}} \quad (21)$$

Combining (14), (16) and (21), one finds

$$\Phi_{TA} \left(1 + \frac{\langle \bar{E}_{nTA} \rangle \cdot A_{nTA}}{\langle \bar{E}_{TA} \rangle \cdot A_{TA}} \right) = \Phi_{lum} \cdot \left(1 + \frac{U_{dir} \cdot \langle \rho_{TA} \rangle + (1 - U_{dir}) \cdot \langle \rho'_{nTA} \rangle}{1 - \langle \rho_\infty \rangle} \right) \quad (22)$$

resulting in a general utilisation estimation:

$$U = \frac{\Phi_{TA}}{\Phi_{lum}} = \frac{1 + (U_{dir} \cdot \langle \rho_{TA} \rangle + (1 - U_{dir}) \cdot \langle \rho'_{nTA} \rangle) / (1 - \langle \rho_\infty \rangle)}{1 + (\langle \bar{E}_{nTA} \rangle / \langle \bar{E}_{TA} \rangle) \cdot (A_{nTA} / A_{TA})} \quad (23)$$

4.3. Target utilisation value

To calculate a target value for the utilisation, target values for the illuminance ratio $\langle \bar{E}_{nTA} \rangle / \langle \bar{E}_{TA} \rangle$ and for U_{dir} have to be proposed.

4.3.1. Illuminance ratio

The lower the illuminance of the non-task areas, the higher the utilisation and the more efficient the lighting installation will be (23). On the other hand, non-task areas have to reach a minimal luminance to maintain lighting comfort [8]. As explained in [4], it

seems reasonable that the weighted mean illuminance value of the non-task areas does not exceed the half of the weighted mean illuminance value of the task areas:

$$\frac{\langle \bar{E}_{nTA} \rangle}{\langle \bar{E}_{TA} \rangle} < 0.5 \quad (24)$$

4.3.2. Direct utilance

The direct utilance is determined by the luminous intensity distribution and the position of the luminaire towards the task area. The larger the distance between luminaire and task area, the narrower the luminous intensity irradiation pattern required. Typical intensity distributions can be modeled as

$$I(\vartheta) = I(0) \cdot \cos^n(\vartheta) \quad (25)$$

With ϑ the viewing angle referenced to the first axis. The value of n determines the full width at half maximum (*FWHM*) of the distribution.

For an energy efficient installation, it seems reasonable that at least the luminous flux within the *FWHM* of the luminaire reaches the task area. As shown in Appendix A, at least 50% of the luminous flux is emitted within the *FWHM*, whatever the value of n . Consequently, the target value for the direct utilance can be formulated:

$$U_{dir} > 0.5 \quad (26)$$

4.3.3. Target utilance value in function of known parameters

Combining (23), (24) and (26), a realistic utilance target value can be formulated:

$$U > \frac{1 + (0.5 \cdot \langle \rho_{TA} \rangle + 0.5 \cdot \langle \rho'_{nTA} \rangle) / (1 - \langle \rho_{\infty} \rangle)}{1 + 0.5 \cdot (A_{nTA} / A_{TA})} \quad (27)$$

This target value can be directly calculated from known parameters such as surface areas and corresponding reflectance values.

The target utilance value as a function of A_{nTA} / A_{TA} is plotted in Fig. 1 (full line).

As shown in Fig. 1, the utilance target value becomes very small for high values of A_{nTA} / A_{TA} . Indeed, due to the lighting comfort requirement (24), a major part of the luminous flux released by the luminaires is allowed to reach the non-task areas, and this part could become the main part if the task area surface A_{TA} is much smaller than the non-task area surface A_{nTA} .

To avoid unrealistic low target values for the power load, a lower limit for the utilance target value is proposed. As explained

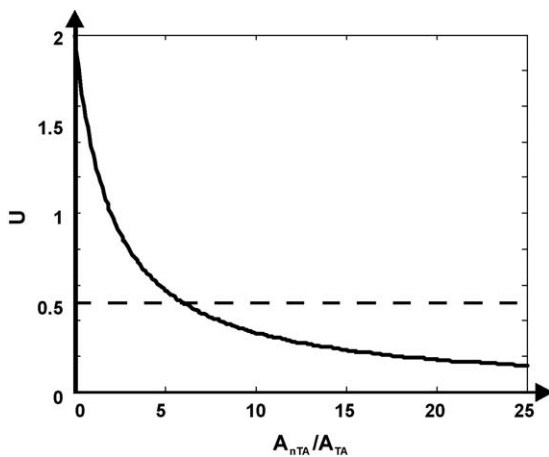


Fig. 1. Target utilance as function of A_{nTA} / A_{TA} . All reflectance values are equal to 0.5.

in Section 4.3.2, the target value for the direct utilance is chosen to be 0.5 and this value can be considered as the ultimate lower limit of the utilance:

$$U_T = \text{maximum} \left(\frac{1 + (0.5 \cdot \langle \rho_{TA} \rangle + 0.5 \cdot \langle \rho'_{nTA} \rangle) / (1 - \langle \rho_{\infty} \rangle)}{1 + 0.5 \cdot (A_{nTA} / A_{TA})}; 0.5 \right) \quad (28)$$

5. Target value for the installed power load

If all target values from (4)–(6) and (28) are gathered together and substituted in (3), the target value for the power load P_T can be formulated:

$$P_T = \frac{\sum_i E_{TA,i}^{fin} \cdot A_{TA,i}}{MF \cdot U_T \cdot 80 \cdot 0.75} \quad (29)$$

The target value P_T can be calculated with known parameters such as surface areas, reflectance and illuminance values of task areas and also the maintenance factor:

- A list of different task areas reporting the surface areas, type of the task area (type *a*, type *b* or type *c*), the maintained illuminance values (as output of light planning software) and the reflectance ρ_c in case of a type *c* task areas.
- Surface areas and reflectance of walls, ceiling and floor.
- The maintenance factor used in the light planning software to compute the maintained illuminance values.

A format for the required input data is shown in Section 6.2 (Table 2).

With these data, the target value P_T can be calculated using a spreadsheet and is compared to the installed power load P_{inst} . Installations which do not fulfil the condition for P_T can certainly be classified as inefficient.

6. Validation

The criterion has been tested for several practical examples. To illustrate the usability of the criterion, the lighting design of an office room and a storehouse are considered in detail as typical applications of standard and non-standard task areas.

6.1. Office rooms

6.1.1. Description

In a first validation, the proposed criterion has been applied to an office. An office is a typical example of a standard task area where the task area is parallel with and approximately equal to the floor area. We consider an office of 30 m by 30 m with a height of 3 m. The reflectance of the ceiling, walls and floor are 0.7, 0.5 and 0.2, respectively. As in most lighting design studies, a transparent calculation surface is used in order to calculate the mean illuminance on the working plane. In this example, the working plane is at 0.75 m above the floor and a wall zone of 0.5 m is used. With a *MF* of 0.85, the maintained mean illuminance value on the task area is calculated using the light planning software DIALux [10] to be 582 lx for an installed power load of 7722 W.

To evaluate the energy efficiency of the proposed lighting installation, the target value P_T is calculated. As the task area is a transparent calculation surface parallel with the floor, the task area is of type *a* with a surface area of 841 m² (29 m by 29 m). By using (29), the target value P_T can be calculated and equals 10,654 W. The proposed lighting of the office room can be classified as energy efficient.

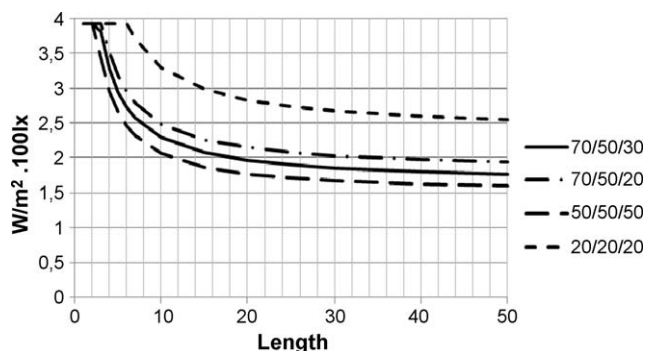


Fig. 2. NPD values in function of the length (MF = 0.85).

6.1.2. Comparison with traditional NPD values

When the task area equals the floor area, it is meaningful to calculate the target NPD value and to compare this value with traditional NPD target values based on current good practice, which range from 1.5 to 2.2 W/(m² 100 lx) for medium to large size offices. The target value is calculated to be 2.17 W/(m² 100 lx) which fits nicely into this range.

In Fig. 2, we calculated the target NPD values as a function of the length of the office for several combinations of the reflectances (no wall zone).

The decrease of the target values with increasing lengths and increasing floor reflectance is in accordance with literature [6,7]. The maximum value of 4 for small rooms is due to the lower limit for the utilization target value (28).

6.2. Storehouse

Storehouses are typical applications where the task areas are completely different from the floor area.

6.2.1. Description of the storehouse

The floor plan of the storehouse is shown in Fig. 3. A 3D view of the storehouse is given in Fig. 4. The length, width and height of the storehouse are 127.84 m, 65 m and 11 m, respectively. There are 36 racks, shown as gray rectangles, with a length of 45 m each. The rack height is 7.2 m. The floor areas between the racks are indicated in Fig. 3 as floor area 1. In addition, there are two load areas transversal to the racks, indicated as floor areas 2 in Fig. 3.

6.2.2. Description of the lighting installation

The total installed power load for the lighting installation P_{inst} is 64.0 kW. The characteristics of the luminaires are given in Table 1. The location of the luminaires are shown in Fig. 3 (dashes).

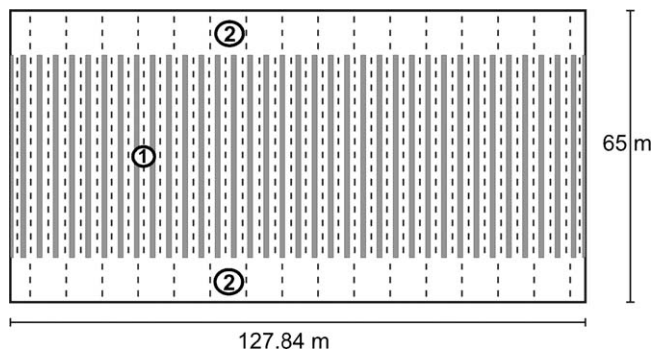


Fig. 3. Floor plan of the storehouse and indication of floor areas: gray filled rectangles represent the racks; dashed lines represent the luminaires.

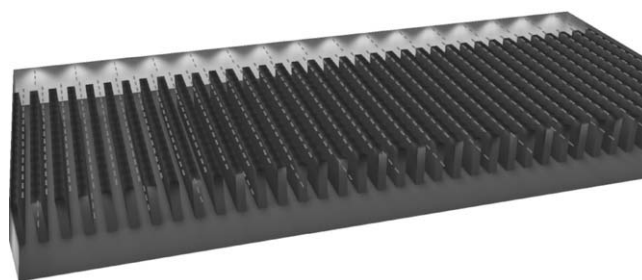


Fig. 4. 3D view of the storehouse.

The mounting height of the luminaires is 8.1 m, which is 0.6 m above the top of the racks. Narrow beam intensity distributions have been chosen for the luminaires between the racks.

6.2.3. Assessing energy efficiency

In order to calculate the power load target value P_T according to the proposed criterion, the task areas have to be defined. In this example, the lighting designer has defined, in consultation with the customer, three different task areas: floor areas 1 and 2 (Fig. 3) and all racks (72 vertical task areas, both sides of each rack).

The input parameters needed to assess the energy efficiency of the lighting installation are summarized in Table 2 (all racks combined). Indeed, both floor areas are type a task areas while the racks are of type c (vertical surfaces which are part of additional furniture). Illuminance values are calculated with DIALux. The reflectance values are mentioned below.

Using (29), one finds

$$P_T = 76.7 \text{ kW} \tag{30}$$

As the installed power load P_{inst} is 64.0 kW, the lighting installation of this storehouse can be classified as energy efficient. However, the NPD value referenced to the floor area – which is completely irrelevant – is 2.58 W/(m² 100 lx). In the past, this store would not be considered for grants because the value is higher than 2.5 W/(m² 100 lx).

Although not required in practice, the different parameters influencing the target power load are considered separately:

$$\begin{aligned} \eta_{sys} &= 70.3 \text{ lm/W} < 75 \text{ lm/W} \\ LOR &= 104\% > 80\% \\ U &= 0.94 \approx U_T = 0.95 \end{aligned} \tag{31}$$

The utilization is in accordance with the target value. The system efficiency is too low but is compensated by the high actual LOR.

6.2.3.1. Utilance. The real utilization value is slightly lower than the utilization target value. However, the weighted mean illuminance values of the task and non-task areas are about 120 lx and 50 lx, respectively. As the condition described in (24) is fulfilled, we expect an actual utilization value higher than the target utilization value, which is not the case. This can be explained as follows.

The estimation of the flux on the total area, given by (16) is calculated to be 5.40×10^6 lm. Using DIALux, the actual initial luminous flux incident on each surface was calculated and

Table 1
Luminaire characteristics.

Location	Lamp type	LOR #	$\Phi_{lum,i}$
Racks and floor area 1	Fluorescent T5: 1 × 80 W	105%	540
	Total power (incl. ballast): 88 W		6,150 lm
Floor area 2	Fluorescent T5: 2 × 80 W	102%	96
	Total power (incl. ballast): 172 W		12,300 lm

Table 2
Required input parameters to calculate the target value for the installed power load.

General room characteristics				
A_{floor}	8309.6	ρ_{floor}	10	
A_{ceiling}	8309.6	ρ_{ceiling}	50	
A_{wall}	4281	ρ_{wall}	30	
MF	0.8			
Task area data			Illuminance, $E_{TA,i}^{\text{fin}}$	Reflectance, $\rho_{TA,i}$
Nr.	Type (a–c)	Surface, $A_{TA,i}$		
1	Floor area 1	a	3,240	315
2	Floor area 2	a	2,557	273
3	Racks	c	23,328	77

summed over the total room area, reaching a value of 5.17×10^6 lm. Although the theoretical estimation for this rather complex geometry of task areas is very close to this value, the slight overestimation does explain why the utilisation value obtained from the lighting calculations is yet slightly lower than the target utilisation value.

7. Conclusions

In order to assess the energy efficiency of a lighting installation, normalized power density values are often used. Traditionally, these values are referenced to the overall floor area and target values, expressed in units $W/(m^2 \cdot 100 \text{ lx})$, exist for typical applications such as open plan offices.

In cases where the task areas are totally different from the floor area, normalized power density figures referenced to the floor area are by no means relevant. Applications with a lot of vertical task areas as can be found in storehouses or shops are typical examples.

This paper presents an alternative approach to obtain an indication of the energy efficiency of an interior space. Taking into account basic lighting comfort requirements, the maximum allowable lighting load for a given application can be predicted. This alternative criterion for energy efficient lighting installations is broadly applicable and easy to use as only quite common parameters of the lighting design have to be known. The criterion permits a variety of luminaire types and different illuminance values for different task areas. The key parameter of the criterion is the analytical expression for the utilisation as a function of known parameters such as task areas, room dimensions and reflectance values.

Some practical examples illustrate the usability of the criterion for standard as well as for non-standard task areas. From 2010 on, the proposed methodology to determine the target power load for a lighting installation will be used in Flanders as the evaluation criterion to assign grants for a re- or newlighting.

Acknowledgements

The authors appreciate the financial support from the Flemish Energy Agency (VEA) and the Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT-Vlaanderen) http://www.iwt.be/iwt_engels/general.html for financial support (IWT 030724, IWT 040575, IWT 60163 and IWT 80163).

We thank ETAP Lighting for providing the practical example of the storehouse.

Appendix A

In order to make a reasonable estimation of the direct utilisation U_{dir} , theoretical irradiation patterns are considered, fulfilling the condi-

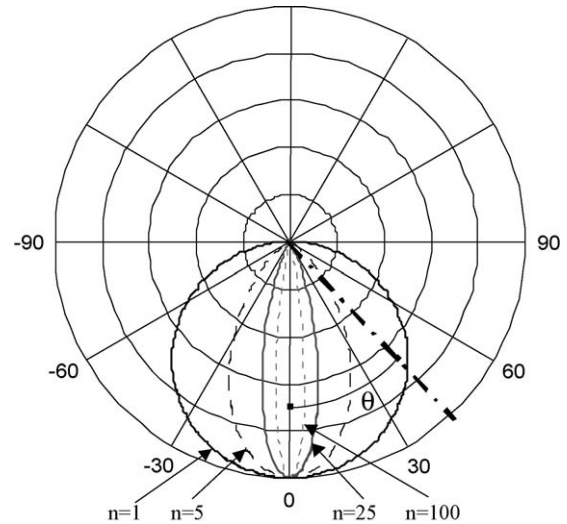


Fig. A.1. Irradiation pattern $I(\vartheta) = I(0) \cdot \cos^n(\vartheta)$; $n = 1, 5, 25, 100$.

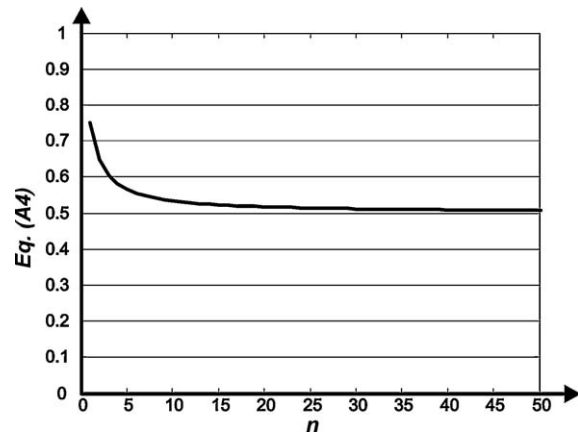


Fig. A.2. Eq. (A4) as a function of n .

tion:

$$I(\vartheta) = I(0) \cdot \cos^n(\vartheta) \tag{A1}$$

In Fig. A.1, irradiation patterns for different values of n are shown. The higher the power n , the smaller the pattern. Many practical irradiation patterns can be approximated by (A1).

To describe the directivity of a source, the FWHM angle σ_{FWHM} is often used. Consider a distribution curve of Fig. A.1. The angle $\vartheta = \gamma$ is the angle where the intensity has dropped to 50% of the maximum intensity. The angle σ_{FWHM} is given by

$$\sigma_{FWHM} = 2\gamma \tag{A2}$$

where γ fulfils the condition

$$\frac{1}{2} = \cos^n(\gamma) \tag{A3}$$

The angle σ_{FWHM} corresponds with the full top angle of a cone where the intensity is at least 50% of the maximum value.

The luminous flux within σ_{FWHM} as a fraction of the total luminous flux can be calculated as:

$$\frac{\int_0^\gamma \cos^n(\vartheta) \cdot \sin(\vartheta) d\vartheta}{\int_0^{\pi/2} \cos^n(\vartheta) \cdot \sin(\vartheta) d\vartheta} = 1 - \cos^{n+1}(\gamma) = 1 - \left(\frac{1}{2}\right)^{n+1/n} \quad (\text{A4})$$

For a perfect lambertian pattern ($n = 1$), σ_{FWHM} equals 120° ($2\pi/3$) and 75% of the total luminous flux is within the *FWHM* (A4). Eq. (A4) is plotted in Fig. A.2 as a function of the power n .

As can be concluded from Fig. A.2, at least 50% of the luminous flux from the luminaire is emitted within the *FWHM*, under the assumption of (A1).

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