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Daylighting & Electric Lighting (Green Lighting)

Estimation methodology for the electricity consumption with daylight- and occupancy-controlled artificial lighting

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Abstract

Artificial lighting represents 15-30% of the total electricity consumption in buildings in Scandinavia. It is possible to avoid a large share of electricity use for lighting by application of daylight control systems for artificial lighting. Existing methodology for estimation of electricity consumption with application of such control systems in Norway is based on Norwegian standard NS 3031:2014 and can only provide results from a rough estimate. This paper aims to introduce a new estimation methodology for the electricity usage with the daylight- and occupancy-controlled artificial lighting in an office, which is both accurate and rapid. The method is validated for an office building in Oslo, Norway, using the experimentally obtained data and the data from the Building Management System.

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Keywords: CIE sky; occupancy profile; light armature; solar factor; daylight factor, illuminance; case-study; measurement.

1. Introduction

Buildings account for nearly 40 % of the total energy use in Europe [1]. In the meantime, the artificial lighting represents 15-30 % of the total electricity consumption in buildings in Scandinavia [2].

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Nomenclature

$I_{Ref.point}$	total interior illuminance level on the reference point, lux
I_{facade}	exterior vertical illuminance at the façade, lux
DF	daylight factor in the reference point, %
SF	solar light factor in the reference point, %

Artificial and daylight control systems can be an efficient solution to reduce the electricity consumption for lighting in office buildings. In fact, electric lighting is the area where energy savings are possible at reasonable cost in the new buildings as well as in retrofit projects [3]. Simulation analyses as well as field-monitoring studies have reported that control of artificial lighting according to daylight availability can result in significant electricity savings ranging from 30% to 77% [4]. More critical study of energy savings using lighting controls in commercial buildings is performed in [5], showing that published studies risk overstating savings potential.

Reduction of electricity use for lighting is often discussed in the scope of control and optimization of light-related technical installations and daylight harvesting [3]. Naturally, the design of artificial lighting according to daylight and occupancy controls requires an estimation of expected energy use and/or savings. A lack of tools and methods for this task is clearly stated in the literature in [2,4–6]. This gap is particularly noticeable for the early design stage where no swift and accurate method exists for evaluation of electricity consumption for lighting with presence of daylight and occupancy control.

The existing methodology for calculating the electricity consumption with the daylight- and occupancy-controlled artificial lighting differs from country to country. In Norway, for example, it is based on NS 3031:2014 [7], which is described in the next paragraph and can only provide results from a rough estimate for electricity consumption for artificial lighting in buildings. This paper aims to introduce a new estimation methodology for the electricity consumption with the daylight- and occupancy-controlled artificial lighting in an office, which is both accurate and rapid.

2. Norwegian practice

According to Norwegian Standard NS 3031:2014 [7], a standard value for the energy demand for artificial lighting in an office building is set to 25 kWh/m2 per year. If daylight or occupancy control is used in the building, then the energy demand is reduced by 20% from the standard value. It is recommended that the average daylight factor should be at least 2 % if artificial lighting is used in combination with the daylight [8].

3. Methodology

For simplification purposes, it can be stated that the electricity consumption in an office building with the daylight- and occupancy-controlled artificial lighting is subjective to: occupancy profile, daylight availability, artificial light installations and their control settings. The methodology presented in this paper addresses all above-mentioned subjects and combines them into one method to calculate the electricity use for lighting on a room level. The method is then validated for a room in an office building in Oslo, Norway, using the experimental data and the data from the Building Management System (BMS).

3.1. Occupancy profiles

For occupancy controlled artificial lighting, the electricity use is logically dependent on the hours of occupancy. Therefore, the applicability and validity of presented methodology are sensitive to assumed occupancy profiles. Naturally, it is impossible to develop a generic occupancy profile for any building without losing the essentials of user behaviour. Generic profiles established according to the working hours are often used in the simplified calculations as a fair alternative to more complex and uncertain assumptions. In this work, the log data from the Building Management System (BMS) for two years of building operation is used in order to develop an occupancy profile specifically for the case-study building.

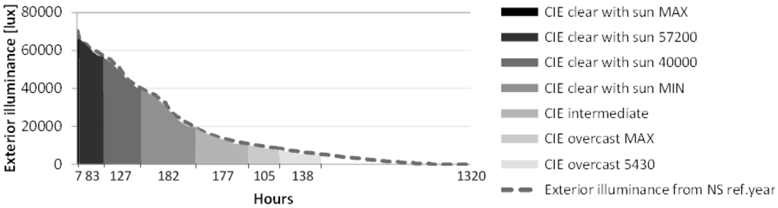

Fig. 1. Total vertical illuminance from the Norwegian reference year weather data divided into intervals of hours where different CIE sky conditions occur.

3.2. Daylight availability

Interior illuminance with absent artificial light represents the availability of daylight, while its determination, normally, requires knowledge of sky conditions. The luminance distribution of the sky changes due to the cloud thickness and scattering. As a result, the cloud cover holds an infinite number of combinations between thickness and the scattering of the clouds.

Simulation software for daylight analysis, such as RELUX, in this case, can only perform calculations for the specifically selected CIE sky conditions rather than for real weather data. Classifying the real sky conditions per day according to CIE sky definitions is difficult as the real sky is much more complex than the range of CIE skies.

For a generic building, a cell office for eight specific façade orientations is simulated in RELUX for the 21st of each month for every hour with the following three sky conditions: CIE Clear sky, CIE Intermediate sky and CIE Overcast sky. As a result, the incident exterior illuminance for eight specific façade orientations and three main CIE sky conditions are established. Next, the specific ranges of minimum and maximum exterior illuminance for the tested CIE sky conditions are identified.

Norwegian climate conditions are described by the Norwegian reference year. Thus the hourly exterior illuminance on a façade with specific orientation throughout a year in Norway can be calculated with the Norwegian reference year as a background. These hourly exterior illuminance values are sorted from highest to lowest value and assigned to earlier identified CIE illuminance ranges for a façade with the specific orientation, in Norwegian climate.

Fig. 1 shows the results of incident exterior illuminance on the example of South-Eastern façade including cumulative distribution of exterior illuminance from the Norwegian reference year, as well as ranges of the exterior illuminance obtained from three tested CIE sky conditions in RELUX. The black sloped line shows the hourly total vertical illuminance from the Norwegian reference year. It is evident that the exterior illuminance from the Norwegian reference year contains all of the illuminance levels from the tested CIE sky conditions. Furthermore, CIE sky with sunlight has a range from 19700 lux to 67000 lux, and CIE overcast sky has a range from 0 lux to 10800 lux, while CIE intermediate sky has a range from 10800 lux to 19700 lux. It is beneficial to divide the year into hours where different CIE sky conditions occur rather than divide into days, as the sky conditions usually change during the day. As seen in Fig. 1, the office is exposed to 399 hours of clear sky conditions, 177 hours of intermediate sky conditions, and 744 hours of overcast sky conditions during occupancy hours for a year, according to the CIE definition. Once the exterior illuminance from the reference year is linked to the CIE sky conditions, it can be further applied to calculate the interior illuminance value.

3.3. Artificial lighting

Obtained daylight availability and established occupancy profiles allow for calculation of the power on the light armature if the control settings for the light armature are known.

3.4. Overall procedure of the method

The method presented in this paper was along the way compared to the existing methodology described in NS 3031:2014 [7], which only requires the information about size of the office/building and type of lighting control. Contrary to that, the methodology introduced in this paper requires more detail inputs, these include:

- Geometry, which also includes orientation, surface properties, location of the reference point, etc.
- Occupancy profile
- Light armature, which includes set points, power properties of the armature, etc.

The overall procedure of this method is to:

1. Obtain a standardized set of total vertical exterior illuminance on the facade value intervals according to the definition of the CIE sky conditions, as described in section 3.2. The results of this step are applicable for any building within the same climate zone.
2. Obtain daylight factor for the specific room at the reference point using any light simulation software.
3. Obtain solar light factors for direct, diffuse and reflected light for the specific room at the reference point. Solar light factors can be determined using simulation software or by simple Excel calculation. These factors are included in the method as they allow addressing actual variation of the illuminance level in the room due to solar radiation.
4. Calculate total interior illuminance level on the reference point according to equation (1), which describes the relation between the solar light factor, daylight factor and interior, exterior illuminance.
   Estimate annual electricity use for the room of interest from the daylight availability and established occupancy profiles by establishing power of the light armature according to the control settings.

$$I_{Ref.point} = \frac{SF \cdot I_{facade}}{DF} \quad (1)$$

4. Experimental work

The experimental work is divided into two main objectives, which are explained in detail later in this chapter:

1. Measurement of the daylight availability and illuminance level in a cell office of a case-study building along with the power consumption on the light armature in the office and the outdoor conditions.
2. Analysis of user behavior in the building, and development of generic user profiles based on BMS data form the building.

Actual measurements of illuminance levels, daylight availability, power consumption, etc. are conducted from Friday, 13th of March to Thursday, 26th of March. Within this measurement period, one occupant was occasionally present in the office during the working hours.

4.1. Case-study building

The building was built in 1964 and renovated in 2011. This is a typical office building for Scandinavia, with common area, landscape- and cell- offices. Daylight related measurements are carried out for an average cell office in the building Fig. 2(a). The cell office is located on the third floor, facing East. The exact reflectance of the materials in the cell office was difficult to obtain from the manufacturer. Therefore, standard values of these properties are applied in this work according to colours and materials present in the office.

4.2. Measurement procedure

Interior illuminance in the office was measured in order to establish the illuminance distribution in the room under varying sky conditions. Exterior illuminance was measured simultaneously. The measurement was conducted on the days with and without the occupant in the office, to study the illuminance levels for combined natural and artificial lighting, but also for the daylight as standalone. In total, 11 luxmeters were installed in the office whereas 10 of them were installed at the height of the work plane (Fig. 2 (a)). The distribution of the daylight to the back of the room is always more difficult to estimate; accordingly, measurements of the illuminance level at the back of the room were prioritized. One luxmeter was placed right next to the daylight sensor of the armature for verification of the control settings and daylight conditions at the senor. Measurement frequency was 0.1 Hz.

Artificial lighting in the building is controlled according to available daylight (light sensors) and occupancy (presence detectors). The light armature does not allow an optimized dimming of artificial light according to the daylight availability. On the contrary, it allows dimming only for two levels: maximum (100 %) and minimum (27 %) of power. At maximum power, the armature uses 74.4 W while it uses 20.1 W at minimum.

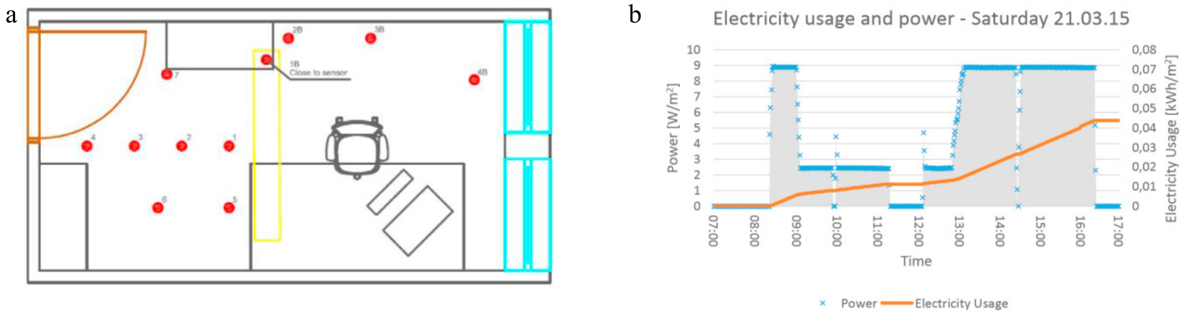

Fig. 2. (a) plan view of the cell office. Points of measurement: the illuminance (red), location of light armature (yellow); (b) the power and electricity usage of the armature in the cell office during Saturday the 21st of March.

Table 1. Established occupancy profiles for a cell office and an open landscape office on the 3rd floor of the case-building.

Occupancy	Cell office	Landscape office
Hours per day	6	9
Days per week	5days	5 and ½ days
Weeks per year	44	50 and ½ weeks

The power of the armature was measured simultaneously with the interior illuminance to find a relation between illuminance level on the working plane and the power of the armature.

Electricity consumption for artificial lighting is measured every minute simultaneously with the measurement of exterior irradiance and illuminance level on the working plane. An example of electricity consumption and power of the light armature during Saturday the 21st with clear sky condition is illustrated in Fig. 2(b).

4.3. Occupancy profile

The case building has presence detectors for the artificial lighting, which means the armature switches on when people arrive and turns off 10 minutes after people have left. In order to develop an occupancy profile on a room level, which is characteristic for the whole building, the data on occupancy presence from the BMS system for a significant number of rooms must be analyzed in order to be representative for the whole building.

A selection of offices on the third floor (same floor as the cell office where the measurements of the illuminance levels are conducted) are included in the investigation of the occupancy profile. In total, 6 cell offices and eight open landscape offices were analyzed according to two years of available data records.

One occupancy profile for cell office and one for open landscape office (from four to eight people) is shown in Table 1. Obtained occupancy profiles for the case building are significantly different from the profile definition for a corresponding building in NS 3031:2014 [7]. For further information on occupancy profiles, please see the original report on this work [10].

5. Results and discussions

Electricity consumption estimation methodology is applied on a case-study cell-office, using measured outdoor irradiance and the actual occupancy profile for the office during the measurement period of 6 days. Calculated electricity use in the period of measurements is estimated to 0.3 kWh/m^2(6 days). The measurement period is represented by 18 hours with clear sky, 9 hours of intermediate sky and 9 hours of overcast sky conditions occurring during the occupancy hours if compared against the CIE-sky illuminance ranges, explained in section 3.2. Only three hours out of 36 hours of sufficient daylight level in the cell office were obtained.

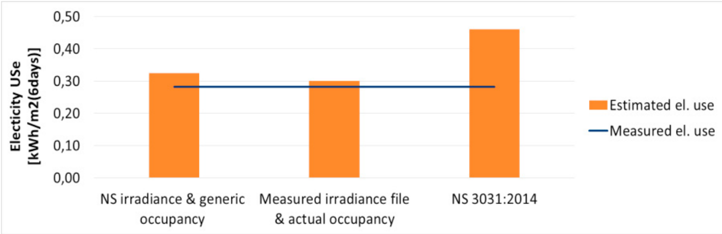

Fig. 3. Comparison of calculated use and measured electricity use in the case-study office.

For the case-study office, rough assessment of the electricity use can be carried out using the same methodology, but with the Norwegian reference year weather file instead of measured irradiance as a background. Furthermore, generic occupancy profile from the case-study building (section 3.1) must be used instead of actual occupancy record. In such case annual electricity use in the office corresponds to 10.5 kWh/m^2 year, which is approximately 0.32 kWh/m^2(6 days) for the period of measurements. Conversion from the annual value to 6 days is performed according to the number of working hours.

Fig. 3 shows a comparison between measured electricity consumption, calculated electricity consumption from the measured outdoor irradiance and finally calculated on the basis of Norwegian reference year. Additionally, this comparison also includes electricity use in the same cell office, estimated according to NS3031:2014. Good agreement is evident between the measured and the estimated consumption, using the methodology described in this paper. On one hand, the electricity use calculated with the method from NS 3031:2014 clearly overestimates the electricity use by up to 39 % compared to the actual electricity use, while it is very easy to use and requires very few inputs.

The aim of this paper was to introduce a new methodology for estimation of the electricity use, which is both rapid and accurate. Speaking of accuracy of the new method, it has been illustrated that it is able to provide fairly accurate results compared to the NS method. Nevertheless, the authors are aware of the limitations for validity of this methodology, as the documentation of validity of the method over longer time interval, supported by the experimental data is compulsory and more research is needed. Looking upon swiftness of the suggested methodology, it is proven to be true if the methodology is implemented using an excel sheet and all preliminary calculations are completed beforehand and integrated within the excel spreadsheet.

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