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Daylighting availability in a living laboratory single family house and implication on electric lighting energy demand

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Abstract

This study aims to analyze the correlation between daylight availability and the use of artificial light in a residential building in Nordic climate. Experimental data and numerical simulations are used to compare artificial light against daylighting availability. The use of electric lighting of six users' groups and outdoor environment conditions were recorded. The daylight availability during the occupation periods has been reconstructed, using as input data the outdoor environmental variable recorded in experimental analysis. The results show that the coefficient of correlation between daylight availability and artificial lighting is low, and the artificial lighting only marginally depends on daylight availability.

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Keywords: Daylighting; Electric lighting energy demand; Monitoring; Simulation; Living Laboratory

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1. Introduction

The design approach of a Zero Emission Buildings (ZEB) aims to harmonize the building volume with the climatic boundary conditions in which it is located by optimizing the use of the renewable energy sources to increase thermal and visual comfort for the users, and at the same time, by reducing the energy demand of the building. In this scenario, it is more and more important to develop a conscious use of natural light to guarantee an adequate indoor illuminance level with little use of energy for artificial lighting [1]. In that regard, the use of simulation tools for daylight analyses is fundamental during the entire design process to estimate the daily and seasonal indoor illuminance levels in buildings guaranteed by both natural and artificial light [2] [3]. While in office buildings there can be robust correlations between daylight availability and energy savings for artificial lighting due to the standardized users' behavior, in the case of residential buildings this relationship becomes more questionable. The aim of this study is to evaluate the correlation between the natural light availability and use of artificial light in a residential building located in the Nordic climate.

2. Methodology and materials

2.1. The ZEB Living Laboratory and the building use.

The ZEB Living Laboratory at Norwegian University of Science and Technology (NTNU) in Trondheim (Norway, latitude 63°25' N and longitude 10°27' E), is a test facility designed to be representative of the Norwegian residential building stock for detached, single family house typology. The surrounding area is dominated by residential buildings and University's blocks. The ZEB Living Laboratory is arranged on one floor with a heated surface of approximately of 100 m^2 and a volume of 500 m^3. It is organized in two main zones: the southern zone as a living space while the northern zone as a working or sleeping area. The inner space is organized to be flexible in order to host heterogeneous users' categories: from younger to elderly people, from students' couples to families. The ZEB Living Laboratory aims to reach the ZEB – O target which means that the building's renewable energy productions compensate for greenhouse gas emissions from operation of the building [4] [5]. The building is equipped with a monitoring system that records the electrical and thermal energy use in the building, with a degree of detail down to the individual power line, light source, and appliances. The system also records indoor environmental quantities and outdoor boundary conditions [6].

2.2. Monitoring experiment in the ZEB Living Laboratory and users' conditions

The study here presented is a part of a wider qualitative and quantitative monitoring experiment, which took place in the ZEB Living Laboratory from October 2015 to April 2016, when six different users' groups composed by two or four people, lived there for one month each. The experiment was designed and carried out in accordance to the regulation of the university and were granted permission by the Norwegian centre for research data (NSD, Norges Samfunnsvitenskapelig Datatjeneste) to use personally non-identifiable data for research activities.

In the overall qualitative and quantitative experiment, the complete users' behaviors (i.e. the entire set of interactions between user and the building) were monitored. In order to avoid any unusual users' behavior that might differ from the everyday habits, no detailed instructions were given to the users, which were therefore free to conduct their normal life according to their own habits and preferences.

Fig. 1. (on the left) View of the ZEB Living Lab; (on the right) Outside view through the south window of the ZEB Living Lab.

In this paper, the focus is placed exclusively on the use of artificial light. From the entire month of monitoring, only one typical week for each of five out of six users' groups was considered to investigate the correlation between natural light availability and use of artificial lighting, while some days of the selected typical weeks were further used to highlight relevant findings because of their representativeness of trends and recurrent situations.

2.3. Modeling and simulation tools

The ZEB Living Lab and its urban surrounding (i.e. nearby buildings and terrain profile) were modelled in NURBS modeler *Rhinoceros* environment [7], while advanced daylighting simulations were carried out with "Design Integrate Validate Adapt" *DIVA-for-Rhino*, an environmental analysis plugin for *Rhinoceros*. *DIVA-for-Rhino* is validated *Radiance*-based software that allows the annual amount of daylight in and around buildings to be simulated [8]. It is used as a calculation engine to obtain climate-based daylighting metrics [9], using typical weather data for a specific location. For the current work, the weather data file [10] for Trondheim was corrected to include actual measured values of the boundary conditions as explained below. The set of *Radiance* simulation parameters (Table 1) was chosen by referring to a similar example in literature [11], while *Radiance* primitives were set to simulate the indoor materials of the ZEB Living Laboratory (Table 2). In this study, the values of global indoor illuminance on the horizontal plane are calculated at a height of 0.85 m above the floor level.

Table 1. Set of 'rtrace' parameters used in the *Radiance*-based simulations.

ab (ambient bounces)	ad (ambient divisions)	as (ambient supersamples)	ar (ambient resolution)	aa (ambient accuracy)
5	1024	16	256	0.10

Table 2. Materials' properties used in the *Radiance*-based simulations for ceiling, floor, walls and glazing surfaces.

Description	Material/colors	Radiance material	RGB	Specularity	Roughness
Ceiling	Opaque/ clear brown	woodGenericCeiling_lightwood	0.5/0.3/0.2	0.02	0.05
Floor		woodGenericFloor_lightwood			
Wall		woodGenericInteriorWall_lightwood			
Single Glazing	Translucent	Glazing_SinglePane_88	0.96/0.96/0.96		
Triple Glazing	Translucent	Glazing_TriplePane_Krypton_47	0.5135/0.5135/0.5135		

2.4. Model validation and sensitivity analysis

The validation of the model was carried out by comparing the values from simulations performed in *DIVA-for-Rhino* with the experimental measurements collected by the sensors installed in the ceiling, and placed in the center of each room. The validation process was performed on four days in June, characterized by completely clear sky conditions, no occupancy by users and with all the artificial lights turned off. Two different sets of simulations were conducted in each day by (i) deactivating and (ii) activating the solar shading screens to control the natural light in the indoor environment. The analyses conducted for the validation of the model have demonstrated that in the analyzed days, the simulated values qualitatively and quantitatively approximate the real behavior of the natural light (Fig. 2). For daylight climate-based annual calculations, in *DIVA-for-Rhino* direct normal and diffuse horizontal solar radiation components are read as inputs data from the *.epw* data file. The two pyranometers by *Hukseflux* (model LP02), installed on the roof of the ZEB Living Laboratory with accuracy of ± 3%, measure only the global solar irradiance on the two different planes (horizontal and tilted roof plane), and a direct measurement of the different components of solar radiation (direct and global diffuse) was not implemented. Therefore, in order to obtain values of solar radiation in normal and diffuse horizontal components (as required by the *.epw* data file), it was considered that: (i) when the measured global solar radiation was lower than 100 W/m^2, it was assumed to be only diffuse solar radiation component, while (ii) when the measured global solar radiation was higher than 100 W/m^2, it was considered diffuse solar radiation until 100 W/m^2, and the excess part was equivalently divided in direct (50%) and diffuse (50%) solar radiation. A sensitivity analysis was conducted in order to validate this approach, running two different sets of simulations, in two reference periods (one week in April and one week in March), setting the following inputs:

- In the first set of simulations, the direct solar radiation component in the original *.epw* data file of Trondheim was increased by 20% and the diffuse solar radiation component was reduced accordingly to reach the total value of the global radiation measured by the pyranometers;
- In the second set of simulations, the direct solar radiation component in the *.epw* file was decreased by 20% and the diffuse solar radiation component was increased accordingly to reach the total value of the global radiation measured by the pyranometers.

The sensitivity analysis has showed that the model is not very sensitive to the differences between direct and diffuse solar radiation components replaced in the *.epw* data file (Fig. 3). Therefore, the proposed approach to split the global solar radiation measured by the pyranometers into direct and diffuse components and replace them as inputs data in the *.epw* data file, can be used with a satisfactory degree of reliability.

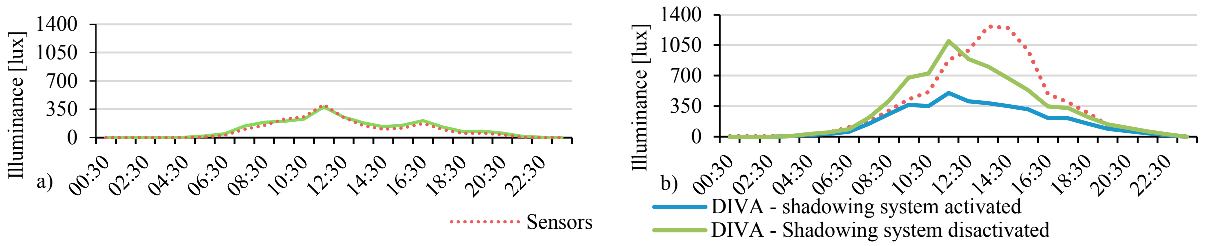

Fig. 2. (a) Comparison between the illuminance values carried out from the analysis of daylight autonomy and the values recorded by sensors installed on the ceiling of the bedroom on the 18th of June without the activation of the shading system; (b) The same comparison with and without the activation of the shading system in the south part of the living room for the 13th of June.

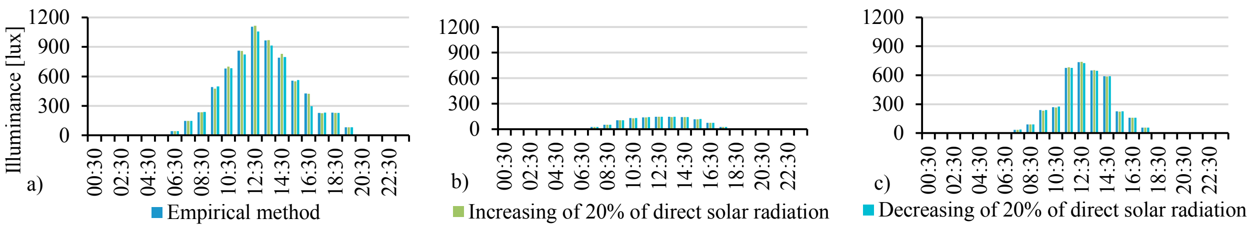

Fig. 3. Comparison between the illuminance values carried out from the analysis of daylight autonomy conducted in *DIVA-for-Rhino* for (a) 17th of April, (b) 13th and (c) 18th of March and for the three methods: empirical, increasing and decreasing of 20% of the direct solar radiation.

2.5. Experimental data processing: electric energy meter for lighting

In the ZEB Living Laboratory, the electric energy for artificial light is recorded at 30 seconds intervals throughout all the day. These values take into account the base-load power of 33 W for the system's operation of the power transformer 240 V to 12 V, which has been subtracted from the total energy used for the artificial lighting of the building for the sake of the correlation. The same procedure has been carried out for the energy needed for the light sources in the bathroom, given the fact that the correlation analysis only refers to the living areas of the ZEB Living Laboratory (sitting room, kitchen, studio, and bedrooms) and excludes the area of the bathroom and of the technical room. Continuous measurements were processed to obtain hourly data for electric energy use.

3. Results

The correlation between the values of daily average illuminance and energy for artificial light conducted on thirty-five analyzed days has been studied. In Fig. 4 the correlation on the 11th of February and on the 15th of March and the related level of illuminance and energy for artificial lighting are illustrated.

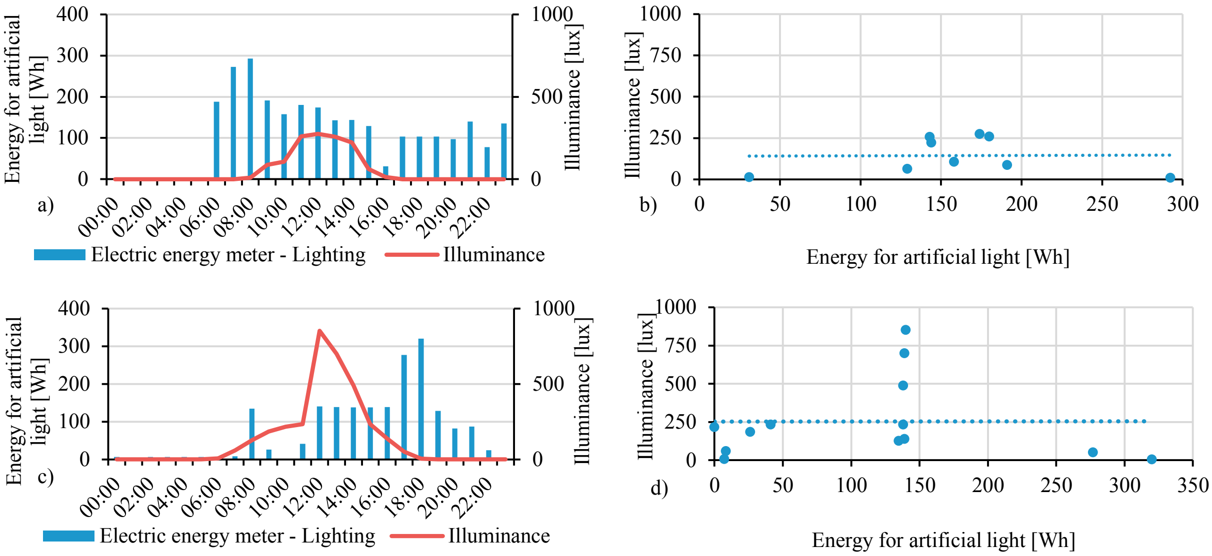

Fig. 4. The hourly illuminance values and energy for artificial light (a) and the correlation between illuminance level and energy for artificial light on the 11th of February (b) and for the 15th of March (c) and (d). The dotted line indicates the period considered for the correlation.

Table 3. The results of the correlations for the five groups of users in the different periods of the year.

Period	Users	Day	r	Period	Users	Day	r
Nov.2015	Two students − Gender: male/female − 20 < Age < 30 years old	Day 1	0.097	Jan.2016	Family with two children − Gender: male/female − Age parents: 30-40 years old − Age children: 0-6 years old	Day 1	-0.367
		Day 2	0.282			Day 2	0.331
		Day 3	0.388			Day 3	0.008
		Day 4	-0.398			Day 4	0.380
		Day 5	-0.279			Day 5	0.290
		Day 6	-0.317			Day 6	0.603
		Day 7	-0.470			Day 7	-0.490
Feb.2016	Retired couple − Gender: male/female − Age > 70 years old	Day 1	-0.531	Mar.2016	Family with two children − Gender: male/female − Parents: 30 < Age < 40 years old − Children: 0 < Age < 6 years old	Day 1	0.376
		Day 2	-0.589			Day 2	0.172
		Day 3	0.013			Day 3	-0.474
		Day 4	-0.786			Day 4	0.002
		Day 5	-0.796			Day 5	-0.490
		Day 6	-0.769			Day 6	-0.249
		Day 7	-0.476			Day 7	0.170
Apr.2016	Retired couple − Gender: male/female − 50 < Age < 60 years old	Day 1	0.079				
		Day 2	-0.085				
		Day 3	-0.441				
		Day 4	-0.650				
		Day 5	-0.439				
		Day 6	-0.348				
		Day 7	0.726				

The outcomes (Table 3) have shown that in eight days the Pearson Correlation Coefficient (r) is in the range of $\pm 0.5 \leq r \leq \pm 1.0$; in fifteen days, the correlation results within the range of $\pm 0.3 \leq r \leq \pm 0.5$; in other six days, the correlation is very small and it is include in the range of $\pm 0.1 \leq r \leq \pm 0.3$; and finally in other six the correlation ends out of the minimum range $r \leq \pm 0.1$. The week that presents a lower correlation is from 12th to 18th of March 2016, while the one that has a highest correlation results from 09th to 15th of February 2016 in which in five days out of seven r value is higher than -0.5. The correlation's values related to retired couple monitored in the period 9th - 15th of February 2016 were mostly negative, and quite often enough close to -1 (the value that represents a full, inverse correlation between daylight availability and energy use for lighting). The data show that for this specific group, the users' behavior was quite close to the expected one (an increase in daylight availability results in a decrease of energy use for artificial lighting). It is here useful to mention that this group was the one with an occupational behavior in general closest to that of and "ideal" user, and characterized by well-scheduled routines. This finding proved that it is quite difficult to make any prediction on the users' behavior. However, in general, from the obtained outcomes, it is clear that in most of the analyzed days, the correlation that exists between illuminance level and electricity requirement is quite low: it means that the use of artificial lighting is almost independent from the availability of natural light (Fig. 4).

4. Conclusions

The study demonstrated that in the use of a representative residential building located in a Nordic climate, occupied by different user groups and in different periods of the year, a particularly strong correlation between the availability of natural light and the energy for artificial light cannot be found. Indeed, it was confirms that is very difficult to obtain a robustness correlation in the context of a residential building than for office buildings. This occurs because users' behavior is often unpredictable when they interact with artificial lighting system in their everyday life at home. It is indeed not so straightforward to prove that this indirect relationship between daylighting and artificial light is actually real when users are in their home given that their behaviors are often influenced by culture and personal habits, as well as, by psychological aspects.

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