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Electric Lighting in a single family house in relation to daylight availability for real users

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1. Introduction

Daylight is an important component of the immense flux of short wave photonic energy that flows continuously onto the surface of Earth from the Sun (Kittle et al., 2012).

One of the current challenges for society is to discover how to make much more effective use of this free natural resource (Kittle et al., 2012). Concerning with building design, daylighting is the term used to express the control use of natural light in and around the buildings (Reinhart and Weissman, 2012).

The benefits of daylighting range from occupant's well being to energy savings. In fact, daylighting improves occupants' comfort and health, providing a view to the outside and improving the visual performance, since the spectrum of the Sun's solar radiation ensures an excellent colour rendering, and enhancing the aesthetics features of buildings. Daylighting strategies are also related to a reduction of the energy consumption of the building concerning with both electric lighting and thermal performances. Therefore it is important in the design stages to find a balance to enhance and maximize the amount of daylight in the interiors without generating glare and overheating that cause occupant's discomfort(Reinhart, 2014, p.9). Several factors concur to improve daylighting strategies in buildings. The two main driving factors are:

- The potential energy saving through effective daylighting;
- The emerging suggestion supported by new studies that daylight exposure has many benefits in human health and in the well-being of building occupants. (Mardaljevic, 2013).

The first driving factor originated from the growing concern about climate change and consequently the need to reduce carbon emissions from buildings (Mardaljevic, 2013).

In this scenario, it is important to take into consideration the building surroundings as well as its climatic boundary. Design considerations should aim to harmonize the building with its urban and climatic context to enhance a building's daylight utilization. One of the aims of daylighting strategies in buildings is to enhance visual comfort in order to reduce electric energy demand for lighting (Walkenhorst et al., 2002).

But, is it true that using more daylight to illuminate interiors leads to a reduction in the electric energy demand for artificial lighting?

Several studies proved that a strong anti-correlation between the electric lighting use and the daylight availability exists in office building when a proper range of illuminances is provided on the horizontal plane associated to the workstation. These studies are based on ideal model of user behaviour, which means that if the indoor illuminance on the work plane falls out of a certain range, the users' respond is to instantly switch on the lights; therefore they do not take into account the human component. In fact, it is common that users do not switch off the lights even if the indoor illuminance due to daylight is sufficient for the visual tasks. Furthermore, it is uncertain how these findings for users in office buildings can be relevant for user behaviour in domestic setting (Mardaljevic at al., 2001). In this context, it is important to investigate the actual users' behaviour towards artificial lighting in residential buildings. In particular, it is important to understand if the increasing of natural light available in the indoor environment is related to a decreasing in the electric energy use for lighting, in regard with actual user's behaviour.

1.2 Aim

The aim of this study is to investigate how users interact with electric lighting and, above all, if the availability of natural light during the day is related to low electric energy use for lighting. For the purpose of the study, the actual users' behaviour towards electric lighting in a residential building located in Trondheim (Norway) is taken into account.

The residential building taken into consideration is the ZEB Living Lab. It is a single family house, located in NTNU Gløshaugen Campus. It was designed by the architect Luca Finocchiaro and built by NTNU Faculty of Architecture and Fine Arts in cooperation with the ZEB Research Centre and its industrial partners. It is a test facility that was designed to carry out experimental investigations at different levels (Finocchiaro at al., 2014). For this reason, it is equipped with several sensors that measure the indoor environmental quantities, such as temperature, CO_2 concentration and relative humidity. Furthermore, the monitoring system keeps track of the electric energy meter concerning with each power line in the house. This information is useful because it allows knowing the actual energy use of the house, when it is occupied. It is also equipped with outdoor sensors that measure the outdoor climatic conditions that define the boundary conditions of the system.

In addition, the ZEB Living Lab hosted alternatively different groups of people during the winter of 2015-2016. This experience provides the data about the real use of electric lighting in the house, since the use of electric lighting was recorded (down to the single light source) during the whole occupation period. At the same time, the outdoor environmental conditions were also recorded, allowing reconstructing the indoor daylight availability occurring at the same time.

1.3 Research Question

This study's aim is to assess if the indoor daylight availability is related to the electric energy use for lighting in residential context, analysing the actual energy use for lighting in a single family house. The statistic relationship between the indoor daylight availability and the electric energy use is assessed by means of correlation that indicates any association or dependency between the two variables.

Therefore, the aim of this work can be summarized in a research question:

> **Is there a correlation between daylight availability and the use of artificial lighting in residential building?**

For assessing this question, the electric energy use for lighting and the indoor illuminance in the ZEB Living Lab were considered. In fact, another study carried out last year on the same topic took into consideration the whole house. Therefore, the overall electric energy use for lighting, measured by the monitoring system, was related to the average daylight availability on the horizontal plane placed at 0.85 cm from the floor level. From these findings, the current work aims at investigating if a higher degree of detail in simulation and experimental data (down to individual room) can instead show a higher correlation between the lack of natural light and use of electricity for lighting. Therefore, observing if, increasing the level of detail, there are significant differences in occupants' behaviour towards lighting in rooms that are characterized by different orientations, shape and intended use. In particular, the investigation is addressed to the users' behaviour in the two bedrooms and the open space in the living area facing south that included the living room and the kitchen.

Therefore the main question can be further detailed in:

> Does a correlation between the electric energy use for lighting and the daylight availability exist in each of the considered room?
>
> Regarding rooms with different shape, orientation and intended use, are there significant differences in the outcomes of the correlation?

2. Background

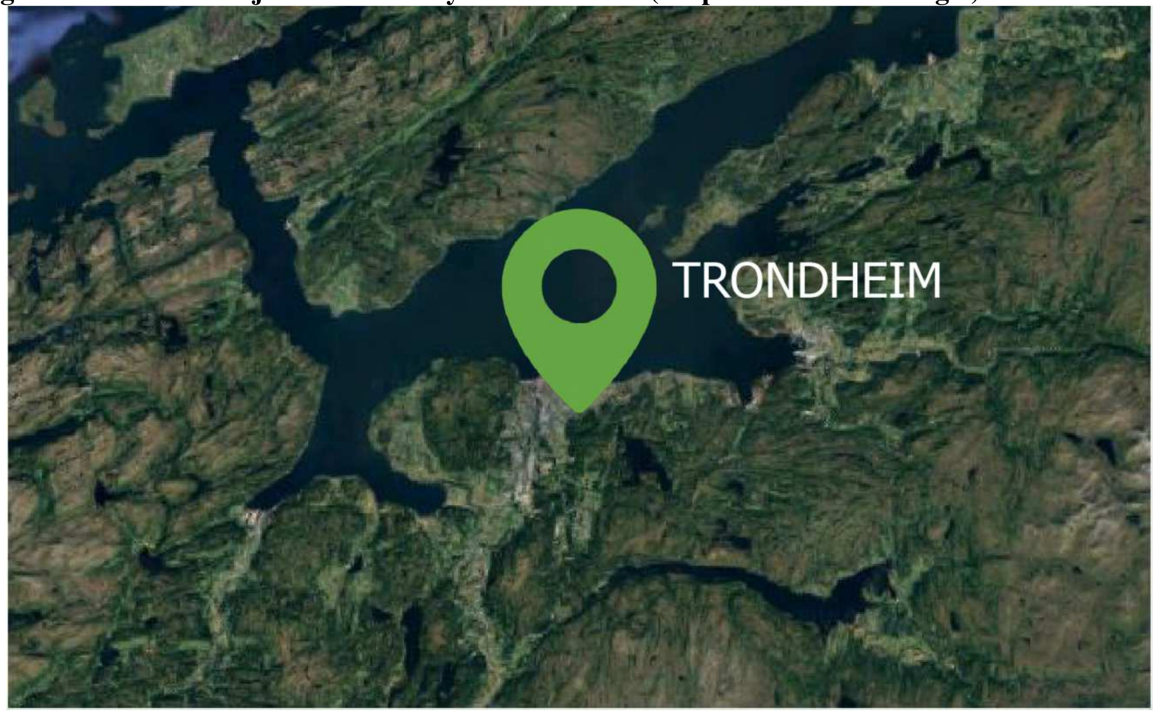
This chapter aims to introduce the boundary conditions of this study as well as to provide an insight about the daylight metrics referred to.

2.1 Trondheim Climate and Daylight condition

The ZEB Living Lab, the house used as case study, is located in Trondheim, which is a city and municipality in Trøndelag County, the region in the central part of Norway.

Figure 1 View of the Scandinavian countries (Map data © 2018 Google)

Figure 2 Trondheim Fjord and the city of Trondheim (Map data © 2018 Google)

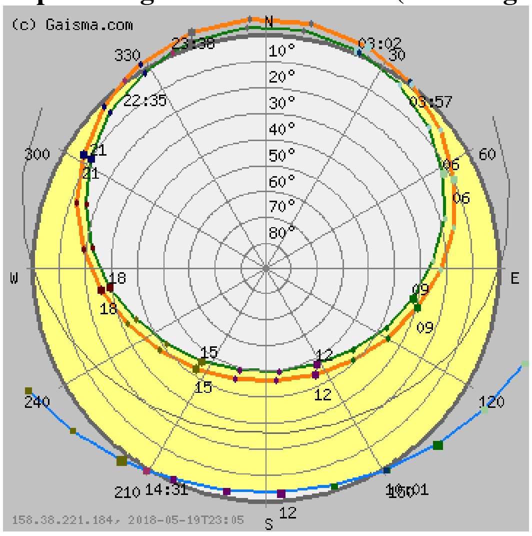


According to the Köpper-Geiger Climate Classification, Trondheim's climate is defined as "Dfc", i.e. Continental Subarctic Climate, which is characterized by long and cold winters and short and mild summers. Although, because of global warming, weather is getting milder. Summers last longer and, instead, winters are getting shorter.[1]

Since the focus of this thesis is on daylight, it is important to notice that Trondheim is at 63° 26' 48" N, which is rather close to the polar circle (conventionally located at 66° N). High latitude locations are characterized by distinct summer and winter daylight conditions, therefore by an high variability of the daylight hours during the year.

[1]Sayigh, A. (Ed.) (2018) *Seaside Building Design: Principles and Practice: Buildings in Maritime Zones*

Figure 3. Sunpath diagram of Trondheim (source: gaisma.com)



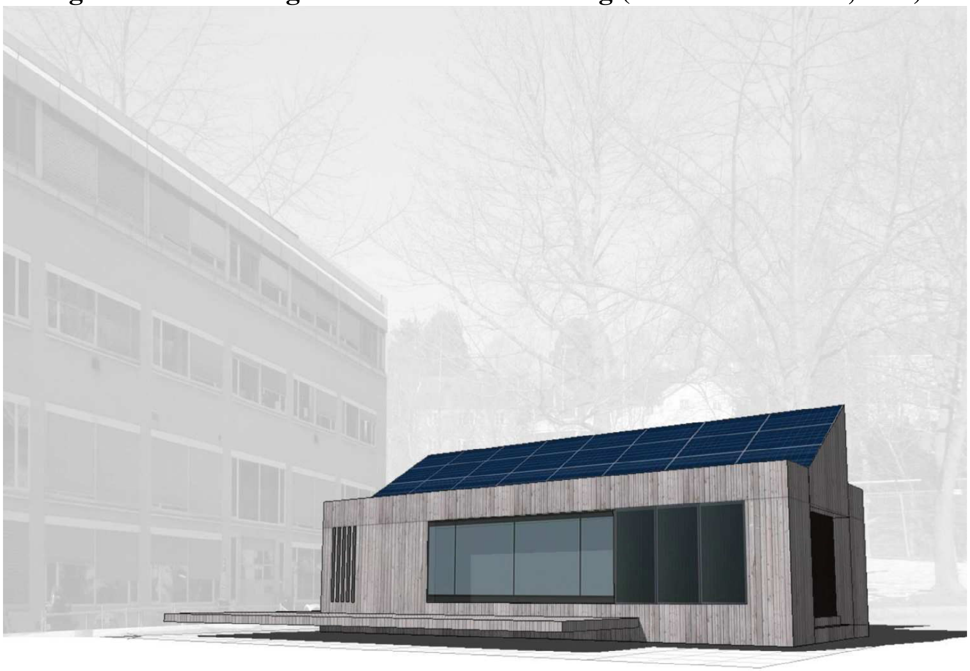
In fact, in winter, there is no actual sun light, since overcast sky conditions are rather recurring. On winter's solstice the sun rises around 10:00 and sets at 14:30. The civil twilight goes from 8:47 in the morning till the sunrise and lasts until 15:45 after the sunset. This means that there is a rather long transition between day and night. The altitude angle in really low and reaches the highest value of 4° at midday.

While the opposite happens on summer's solstice when the sun rises at 3:02 and sets at 23:37, reaching the highest altitude of 50° around 13:26, and there is no actual darkness between the sunset and the dawn.

Figure 4. Sun hours in Trondheim throughout the year.

High variability in the daylight hours during the year combined with a rather long transition between the day and night are conditions to keep in mind when analyzing users' behavior.

Figure 5. The Living Lab and its surrounding (Finocchiaro et al.,2014)



2.2 Daylight Availability: Metrics and Knowledge Gap

Solar radiation is the term used to identify the electromagnetic radiation emitted by the sun. Geographic location, time of the day, season, local landscape and weather are the fundamental factors that influence the amount of solar radiation that impinges on Earth's surface.

The sunlight, passing through atmosphere, is absorbed, scatted and reflected by clouds, air molecules, water vapour, and pollutants. This is called diffuse solar radiation. The solar radiation that reaches the Earth's surface without being diffused is called direct beam solar radiation. The global solar radiation is the sum of the direct and the diffuse solar radiation.

The global radiation that hits the Earth's surface is again partly absorbed and partly sent back to the atmosphere as reflected solar radiation (Solar Radiation Basics, 2013).

Daylighting implies a process by which direct sunlight and diffuse daylight are reflected, scattered, admitted and/or blocked to achieve a desired lighting effect (Reinhart, 2014, p.9). Therefore, there is the need for metrics able to represent and assess the daylight available in a space, taking into consideration its high variability in time (daily and hourly basis), as well as its variation according to climate and location.

At present, the most used metric to assess daylight availability in a space is the Daylight Factor. Daylight Factor is defined as the ratio between the illuminance at a sensor point inside the space to the illuminance at an unshaded, upward facing exterior reference point under CIE overcast sky conditions (Reinhart and Weissman, 2012). It was conceived as a means to assess the daylighting performance of a space regarding its layout and properties of the space, with no consideration of the actually occurring, instantaneous sky conditions (Mardaljevic and Christoffersen, 2017). In fact, according to its definition, the daylight factor is insensitive to climate, location and orientation of the building; these are aspects that weight considerably in daylighting strategies in building design (Nabil and Mardaljevic, 2005).

The need to assess daylight availability in an interior space under the different sky conditions recurring during the year leads to the definition of climate-based metrics that take into account the hourly sun and sky conditions typically occurring during the year for a given location. However, the evaluation of the provision of internal daylight is possible only by means of dynamic daylight simulations that predict the indoor illuminance distribution in a space during the daylight hours of the year. The outputs of the simulations are further elaborated and processed in order to be summarized in climate-based daylight metrics such as Daylight Autonomy and Useful Daylight Illuminance.

Climate-based metrics take into account the prevailing climate of the site and the properties of the space and its surrounding to assess the availability of natural light in an interior space (Mardaljevic and Christoffersen, 2017). Daylight Autonomy is defined as the percentage of occupied time in the year during which a target illuminance level can be reached by daylight alone. Several studies proved that 300 lux of natural light is considered adequate by the majority of building users and also correlates with the notion of a well daylit space. Therefore, the target illuminance is generally fixed at 300 lux, whereas in office buildings 500 lux is the target illuminance used for design purpose. However, the information provided by Daylight Autonomy is incomplete since it ignores daylight illuminances below the threshold that are perceived as acceptable by the occupants. Moreover, it does not consider the time in which the illuminance is exceeding, generating occupants' discomfort, glare and overheating (Mardaljevic, 2013).

In their paper, Nabil and Mardaljevic (2005), formulated a new climate-based metric, the Useful Daylight Illuminance, based on a survey on users' preferences concerning with illuminance value in office space. From this survey emerged that:

- Daylight illuminances less than 100 lux are generally considered insufficient to be either the sole source of illumination or to contribute significantly to artificial lighting;
- Daylight illuminances in the range of 100-500 lux are considered effective either as the sole source of illumination or in conjunction with artificial lighting;
- Daylight illuminances in the range of 500-2000 lux are often perceived either as desirable or at least tolerable;
- Daylight illuminances higher than 2000 lux are likely to produce visual or thermal discomfort or both.

Therefore, they formulated a new climate-based daylight metric, the UDI, defined as the percentage of the working hours of the year during which the illuminance across the work plane ranges between 100 lux and 2000 lux. The UDI scheme was formulated in order to allow a comparison of multiple design options based on daylighting performance in early design stages. (Nabil and Mardaljevic, 2005)

Based on these findings, they also reported a strong anti-correlation between electric lighting usage and achieved UDI for cellular office spaces with user controlled shades. However, in office-type buildings, occupants generally do not have the possibility to adjust their workstation or their position and have rather stringent visual comfort requirements (Reinhart, C. F., Weissman, D. A., 2011). Therefore, it is easier to indentify a threshold or, as in this case, a range of illuminances which is desirable by user in order to perform visual task.

In contrast to office buildings, task in the domestic setting are not largely desk and display-screen oriented. Therefore in its study concerning with daylight metrics in residential context, Mardaljevic (2011) re-defines the upper limit for preferred daylight illuminance in residential buildings to 3000 lux. Taking into account an ideal user's behaviour, he assessed a decrease in the electric energy use for lighting increasing the daylight provision through the use of skylight.

Both in the case of office buildings and in the case of houses, mentioned above, the reduction of electric lighting use associated with the increasing of daylight provision is based on models of occupants' behaviour that are completely deterministic and do not take into account the stochastic component present in human behaviour. In fact, all these studies are based on the assumption that when a range of illuminances is reached, users switch off the lights and use only the daylight available to perform their visual tasks.

In this study, the aim is to explore to what extent this assumption is correct and users behave as they are expected to, in particular regarding with domestic setting.

A previous study, carried out last year, aims to analyse the correlation between daylight availability and the use of artificial light in a residential building in Nordic climate (Lobaccaro et al., 2017). The study took into consideration the electric energy used by the different occupants' groups for lighting in the ZEB Living Lab in Trondheim. The overall electric energy use for lighting was related to the average indoor illuminance on the working plane placed at height of 0.85 cm from the floor level. Therefore, the whole house was taken into consideration to assess the correlation, with no distinction between the different rooms of the house. The findings concur to prove that in residential context it is rather difficult to find a strong correlation between the daylight availability and the use of artificial lighting. In fact, the results showed no strong inverse correlation, meaning that users generally do not switch off the light when the internal illuminance owing to natural light increases.

This is the point of departure of this work, which aims to investigate if this result persists or changes with the increasing of the level of detail of the analyses.

3. Methodology

3.1 Overview

This study investigates users' behaviour towards electric lighting in relation to daylight availability in residential context. In particular, the aim is to analyse if a correlation between the electric energy use for lighting and the indoor illuminance due to sole daylight does exist.

A correlation is a statistical relationship between two continuous variables. The statistic tool used to assess the correlation is the Pearson's coefficient. It is used to explore the strength of the relationship between two variables, in this case:

- Electric use for lighting, evaluated in a single room;
- Average illuminance on the horizontal plane placed at 0.85 m from the floor level, in the considered room.

As it will be explained in the following paragraph (3.2 ZEB Living Lab), the case study is the ZEB Living Lab, a single family house located in Trondheim. This house is equipped with several indoor and outdoor sensors, as explained in paragraph 3.3 Experimental data. The choice of this case study was supported by the residential experiment that took place in winter 2015-2016 (3.3.1 Monitoring experiment at ZEB Living Lab). During the whole occupation period, all the set of interactions between the users and the building were recorded (i.e. electric energy use for lighting) as well as all the outdoor boundary conditions (i.e. global solar radiation) (Lobaccaro et al, 2017). This experiment provides a large set of data concerning with the actual users' behaviour towards electric lighting. Moreover, the outdoor environmental conditions were recorded as well. This is fundamental information since it is the input data in daylight simulations that help in reconstructing the indoor illuminance level from arbitrary sun and sky conditions.

However, the variables needed to assess the correlation are not directly accessible. Experimental and numerical analyses will be carried out in order to determine reliable information about the actual electric lighting energy use and the indoor illuminance in the rooms taken into consideration at the time of the residential experiment.

As for artificial lighting, the only information recorded by the logging system is the overall electric energy use for lighting in the whole house and the condition of each switch associated with each light. Experimental data elaboration allows obtaining reliable information about the electric energy use for lighting down to the single light source (3.3.2 Characterization of Electric Lighting). The outputs of the data elaboration as well as the coefficients relating the dimmer status to the power for each lighting source will be shown in 4.1 Electric Energy Use for Lighting.

However, for the purpose of the study, these data must be completed with consistent information about the daylight availability during the occupation period. Therefore, there was the need to model the geometry of the ZEB Living Lab and its surrounding (3.4.1 Modelling tool: Rhinoceros) in order to perform the dynamic daylight simulations (3.4.2 Simulation Tool: DIVA-for-Rhino) able to recreate the indoor illuminance at the time of the residential experiment (4.2.3 Indoor illuminance distribution at the time of the residential experiment). However, these dynamic simulations use information about the sun and sky conditions as input (3.4.2.3 DaySim). These two variables are not directly accessible, since the logging system keeps only track of the global solar radiation on the horizontal plane. For this reason, an empirical model was built to distribute the global solar radiation in its two components: direct sunlight and diffuse skylight (3.3.3 Solar Radiation).

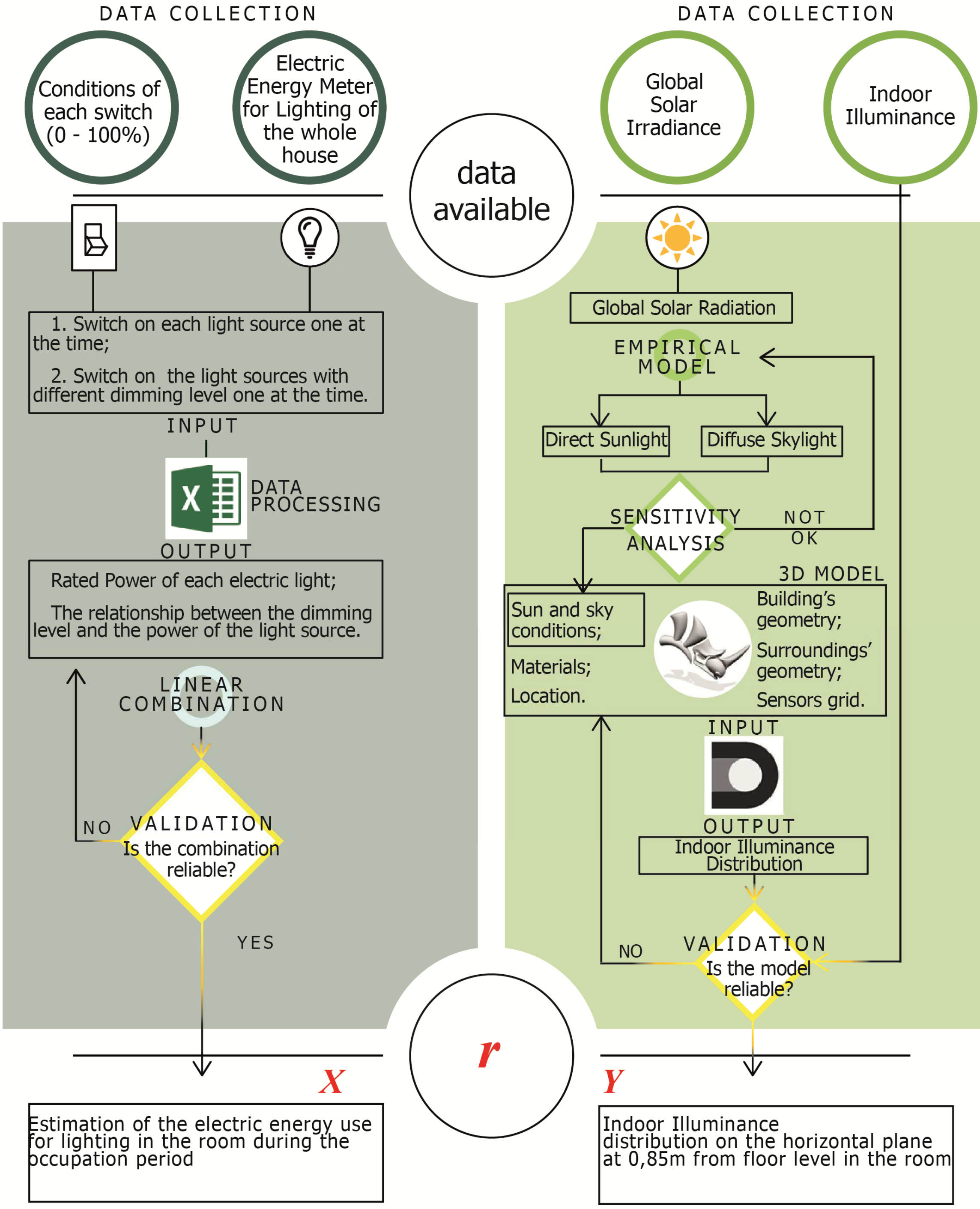
Therefore, a Sensitivity Analysis (3.5 Sensitivity Analysis) was carried out in order to understand how the uncertainty associated with the inputs (global solar radiation distribution) influences the outputs of the dynamic simulations.

After that, a tailor weather file, containing the actual diffuse and direct normal solar radiations was created in order to be used as input for the daylight simulations (3.4.2.4 Energy Plus Weather file (*.epw)).

A validation phase was carried out in order to assess the reliability of the numerical model for electric lighting (3.6.1 Model Validation for Electric Lighting), and the coherence of the outputs of the daylight simulations (3.6.2 Model Validation for Daylight Availability).

At this point it was possible to predict the indoor illuminance distribution occurring at the time of the experiment as well as the energy used by the light sources active during the daylight hours. These are the two variables used to assess the Pearson's coefficient, ***r***.

Figure 6. Methodology overview: flow chart showing the methods and the phases followed to derived the variables needed to assess the Pearson's coefficient from the data available.



3.2 ZEB Living Lab

Figure 7 View of the NTNU Gløshaugen Campus in which the ZEB Living Lab is located (Map data © 2018 Google).

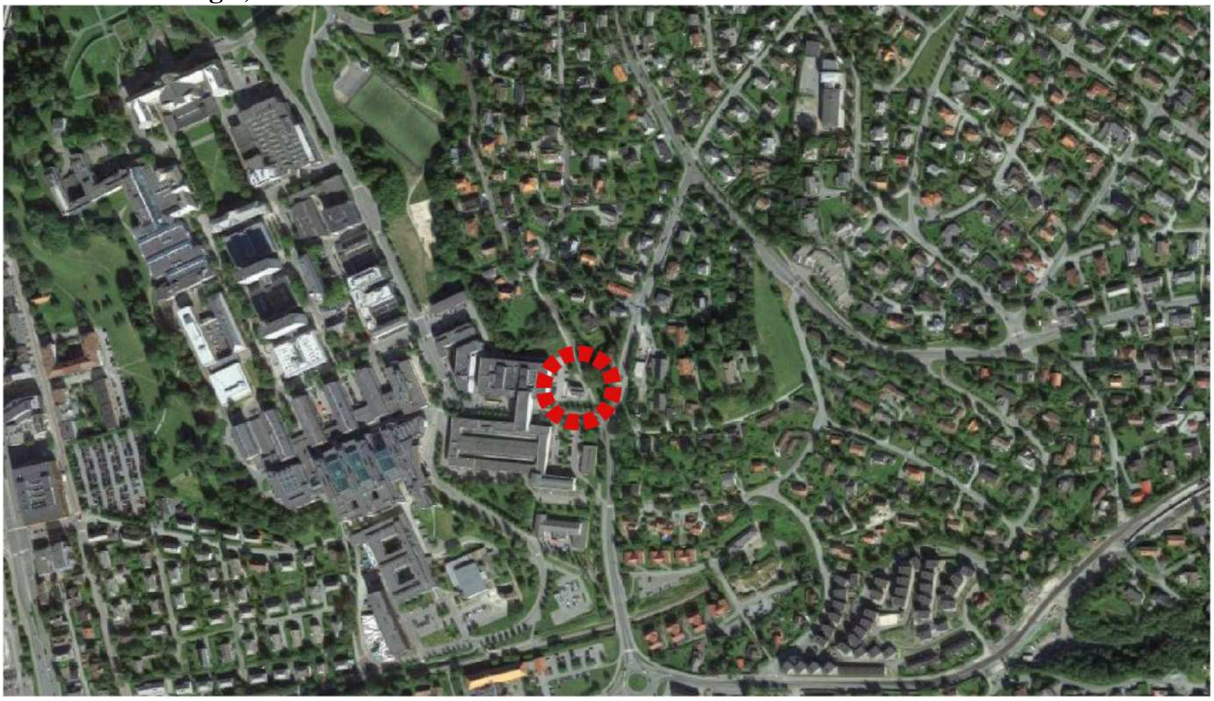


Figure 8. The Zeb Living Lab (source: Finocchiaro et al., 2014)

The ZEB Living Lab is a detached, single-family house, built in 2015 in Trondheim at the Norwegian University of Science and Technology Campus by the NTNU Faculty of Architecture and Fine Arts in cooperation with the ZEB Research Centre. It aims to be a multi-purpose experimental facility, where to study on different levels new technologies and strategies concerning with energy performance as well as the interaction between the users and the house and its impact on the energy demand during building's operation (Finocchiaro et al., 2014).

It is a one-storey single family house with a floor area of approximately 100 m^2, a gross volume of 500 m^3 and it was designed to be representative of the typical Norwegian dwellings.

Figure 9. Plan of the Living Lab

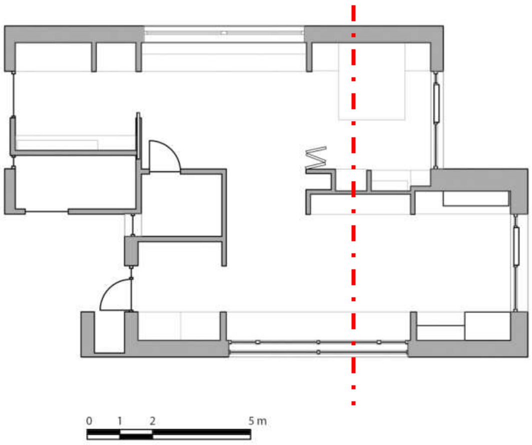
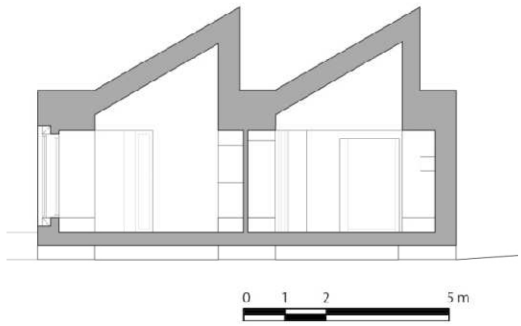


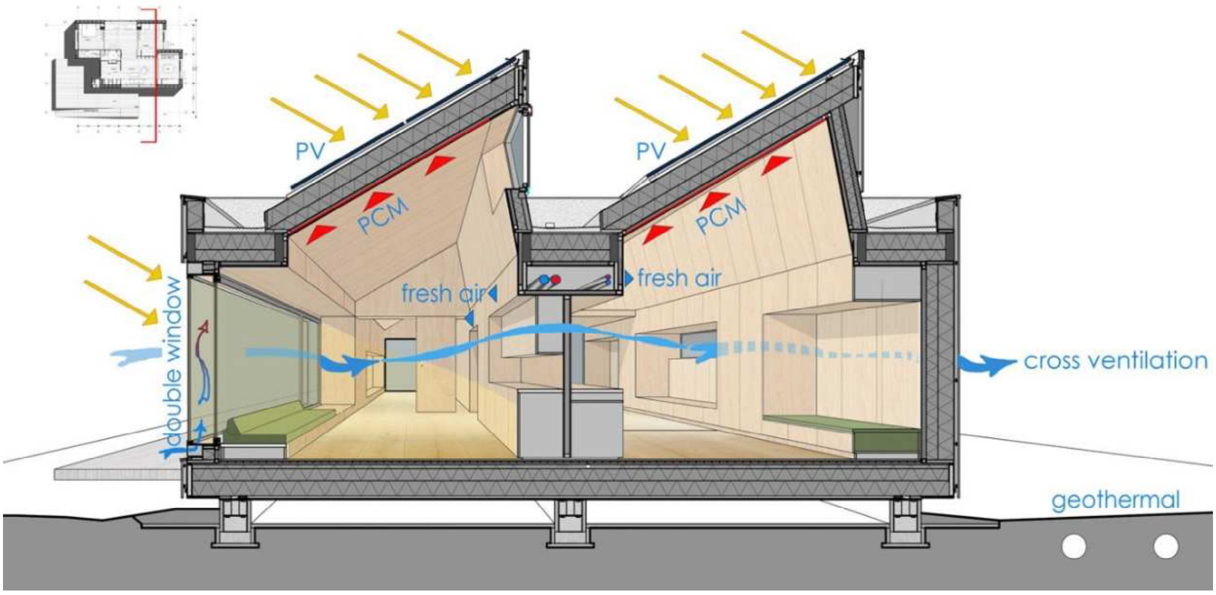
Figure 10. Section of the Living Lab



As showed in the pictures, the house is organized in two main areas:

- The living area facing south, in which the kitchen and the living room are connected and organized in an wide open space;
- The sleeping area facing north, where two bedrooms are placed at the opposite side (east and west respectively) of a working area directly connecting with the south living area.

Figure 11. Section of the Living Lab (Finocchiaro et al., 2014)



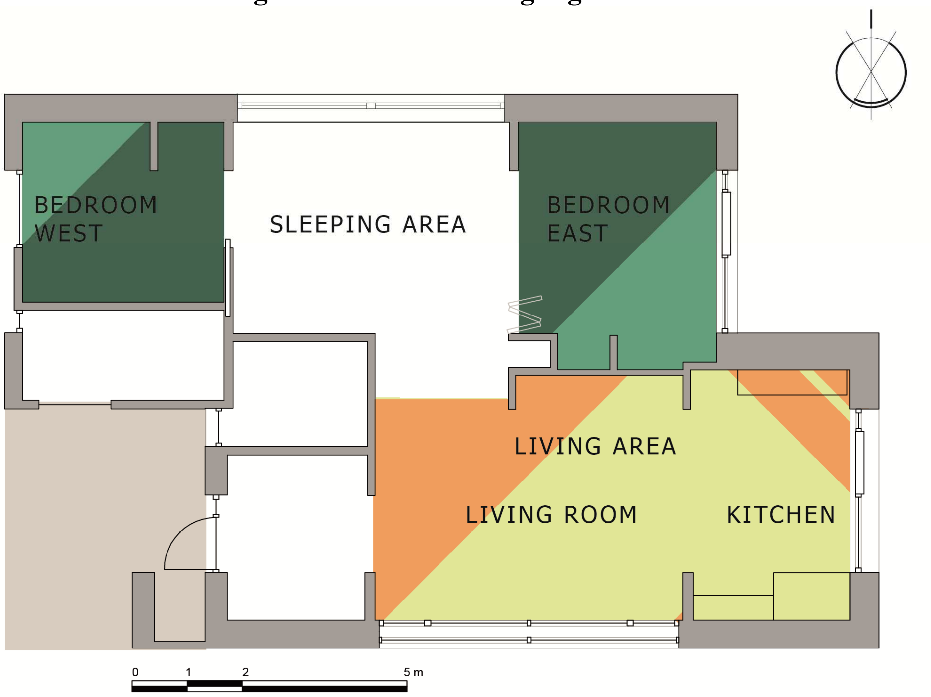
The entrance is placed in the south-west corner, facing the NTNU buildings. The technical room is placed in same area and it is accessible only from the outside. Moreover, it is located in the central spine of the building, aligned to the bathroom and the kitchen, in order to optimize the distribution of the technical equipment.

Table 1. Thermo-physical properties of building envelope components (Finocchiaro et al. 2014)

U-value wall	W/m^2K	0.11
U-value floor	W/m^2K	0.10
U-value roof	W/m^2K	0.10
U-value windows (south façade)	W/m^2K	0.65 / 0.69 (when ventilated)
U-value windows (north façade)	W/m^2K	0.97
U-value windows (east-west façade)	W/m^2K	0.80
U-value skylight	W/m^2K	1.0
g-value	-	0.5
Air tightness	ach	0.5
Thermal bridges (normalized)	W/m^2K	0.03

To increase the level of detail of the analyses implies that the focus is on the single rooms of the house. For the purpose of this study, the two bedrooms (in green) and the living area, including the living room and the kitchen are taken into account because of their different orientation, shape and intended use.

Figure 12. Plan of the ZEB Living Lab in which are highlighted the areas of interest of this study



3.3 Experimental data

The experimental data used in this study are provided by the logging system of the Living Lab. In fact, the house is equipped with several types of sensors that measure both the indoor environmental quantities as well as the outdoor climate conditions. The monitoring system allows to keep records of all these parameters and quantities.

This study focuses on the electrical lighting use and the indoor illuminance level due to daylight alone. Therefore, only the information from the following sensors is taken into consideration:

As for the outdoor environment:

- Pyranometers Huskseflux (model LP02) measure global solar irradiance on the horizontal and tilted roof plane. Accuracy of these sensors are ± 3% (Finocchiaro et. al., 2014).

This information will be further processed in order to obtain the necessary input to run the daylight simulations. In fact, the validated simulation software used for reconstructing the indoor illuminance during the analysed period needs the information about the diffuse and the direct solar radiation.

As for the indoor illuminance level:

- S+S Regeltechnik AHKF-U placed on the ceiling of all the living areas with an accuracy of ±10% (Finocchiaro at al.,2014).

As for the characterization of the lighting system:

- Electric energy meter for lighting;
- Dimmer status of each light source.

Moreover, the status of each physical switch for lighting is recorded by the data acquisition system. This information was used to investigate user interaction with artificial lighting, enabling to calculate the electric energy use for lighting down to each light source and consequently group them for every room analysed.

In addition, indoor illuminance on the horizontal plane at a height of 0.90 cm from the floor level was measured by means of the portable lux-meter in some significant points in every room of the house. This data collection allows to validate the model used to recreate the indoor illuminance distribution, comparing the measured values against the simulated ones.

Moreover, the portable lux-meter was also used to evaluate how reliable were the indoor sensors at the time of the characterization by measuring the diffuse illuminance as close as possible to the ceiling height.

The specifications of lux-meter are described in the table below.

Table 2. Lux-meter Konica Minolta T-10A: specifications

Illuminance Meter T-10A (Standard receptor head)		
Illuminance meter class		Conforms to requirements for Class AA of JIS C 1609-1: 2006 “Illuminance meters Part 1: General measuring instruments” Conforms to DIN 5032 Part 7 Class B
Receptor		Silicon photocell
Relative spectral response		Within 6% (f1´) of the CIE spectral luminous efficiency V (ƛ)
Cosine response (f2)		Within 3%
Measuring range		Auto range (5 manual ranges at the time of analog output)
Measuring function		Illuminance (lx). Illuminance difference (lx). Illuminance ratio (%). Integrated illuminance (lx·h). integration time (h). average illuminance (lx).
Measuring range	Illuminance	0.01 to 299,900 lx; 0.001 to 29,990 fcd
	Integrated illuminance	0.01 to 999,900 x 103 lx·h 0.001 to 99,990 x 10*3 fcd·h / 0.001 to 9999 h
Linearity		±2% ±1 digit of displayed value
Temperature/ humidity drift		Within ±3%

Two different measurements campaign where carried out in order to characterize the indoor illumination system, in its features and electric energy use, and the indoor daylight availability in relation to the architectural features and the weather condition.

As for the actual users’ behaviour towards artificial lighting, the monitoring experience carried out in the ZEB Living Lab in the winter of 2016 provides the relevant information.

3.3.1 Monitoring experiment at ZEB Living Lab

The ZEB Living Lab was chosen as case study because it hosted a residential experiment in which all the set of interaction between the users and the building were observed and recorded by the monitoring system. (Lobaccaro at al., 2017)

The residential experiment took place in the Living Lab between October 2015 and April 2016. During this period, several different groups of people moved in the Living Lab and used it as their own home for twenty-five days each. The groups were chosen in order to be representative of the three main demographic categories, such as: young students, families with children, and elderly couples (Woods at al., 2016). All the new inhabitants were invited to continue with their routines in the Living Lab.

Figure 13. Picture of the Interiors of the Living Lab (photo: Anne J. Bruland)

The purpose of the experiment was to shed light on the interaction between users and the domestic environment of a highly automated house on different levels and from a broader perspective (Woods at al., 2016). In order to not interfere with the study's purpose, it was important that all the new occupants carried on with their habits in the Living Lab. Therefore, no information were provided about how to operate with the building, thus to observe the changes in their everyday's life and how they adapted to the house.

This experiment provides us with useful information about actual energy use, but, also, gives us a large set of data concerning with user's behaviour towards artificial lighting.

However, this work does not take into account the all occupation period. Only one of the three weeks of occupation per group will be analysed. This week will be generally the last before the group moved out from the ZEB Living Lab, in order to give time to the group to adapt to the Living Lab and understand how to operate with the system. In this case, it is possible to have significant information of user's behaviour towards artificial lighting, minimizing the impact of uncertainty due to building's operation.

3.3.2 Characterization of Electric Lighting

A detailed characterization of the artificial lighting system was necessary in order to calculate the electric energy consumed by each light source, and therefore to be able to estimate the energy usage for the single rooms of the house taken into consideration.

Although the Living Lab has more than 20 power lines and their energy use is monitored, there is only one power line for lighting. Therefore, the energy meter measures the overall electric energy used by the lighting system. This means that if several light sources are switched on at the same time, it is not possible to discern the amount of energy used by each of them, because there is no information about the specifics of every single electric light.

In this paragraph, it will be explained the procedure followed to calculate the nominal power of each lights and in different dimming conditions in order to identify the electric lighting energy use in the single rooms.

The lighting fixtures of the Living Lab are LED strips that operate with a potential difference of 12V. A power transformer, always active for the conversion from 240V to 12 V, is in charged for a permanent base-load of 33W. This base-load must be subtracted to the overall electric energy use measured every hour.

The characterization of the lighting system was carried out during January and February 2018. In particular, the following features were analyzed:

- Energy usage of each lighting at the highest of its power, which means with no dimming (this condition will be indicated as Dimmer status 100%);
- The relationship between the dimming level and the energy use of the single lighting source, analyzed only for the most influent lighting sources.

Experimental data were collected and elaborated in order to classify the components of the lighting system.

The first step aims at verifying the information acquired from the technical drawings. This phase was carried out during the week 3 because of the outdoor lighting conditions. In fact, in that time of the year the hours of light are limited.

It was necessary to switch on the light sources for a sufficient amount of time and one at the time in order to be sure that the logging system recorded the electric energy used by the active light. Then, the electric energy use in that time interval was divided by the time interval in order to find the power of the involved electric light, and then the base-load was subtracted.

Below, the example of the calculation is shown for the external light. This operation was repeated for all the lights.

$$BaseLoad = 33\ W$$

$$E(External\ light) = 86\ Wh\ ; t = 0.51\ h;\ P(External\ light) = \frac{86\ Wh}{0.52\ h} = 170\ W$$

$$Nominal\ Power(\ External\ light) = 170W - 33\ W = 137\ W$$

The aim of the second phase is to assess whether there is a relationship between the light dimming and the power of the light source and also to see the influence of the dimming level on the illuminance value. This part was carried out only for the main light sources in the house, such as the ones placed on the ceiling of each room.

These two phases were necessary to build a numerical model that allows estimating the contribution of each lighting fixture to the overall electric energy meter from the available data of the condition of each switch. Therefore, it is possible to discern the electric usage in every single room by superposition, knowing the condition of each physical switch recorded by the monitoring system during the occupation period.

3.3.3 Solar Radiation

In order to have a relevant correlation, it is important to recreate the indoor illuminance distribution at the time of the experiment.

This information is not directly accessible. In fact, it is not possible to use only the information of the indoor sensors on the ceiling, since they give information about the overall diffuse illuminance level and therefore it is not possible to discern the quota owing to natural light penetrating the space from the one due to possible electric light active at the same time.

Moreover, it was chosen to reconstruct the daylight availability on the horizontal plane at 0,85 m from the floor level because it gives a better understanding of the indoor daylight condition since it characterizes the overall daylight provision of the space (Mardaljevic, 2011) and also it represents physical surfaces for specific tasks such as kitchen worktops and table.

To recreate the indoor illuminance experienced by the users, the data of the global solar radiation recorded at the time of the residential experiment were used as input in climate-based simulations. These dynamic simulations are called "climate-based" because they use the hourly sun and sky conditions derived from annual climate datasets that included information about direct normal radiation and global horizontal radiation typically occurring during the year for a given location These simulations can predict the hourly internal daylight illuminances for a full year using realistic representation of sun and sky (Nabil, A., Mardaljevic, J., 2004).

Climate-based simulations require data of the direct normal and diffuse horizontal radiations because they use this information to recreate the luminous distribution of the sky vault according to Perez sky model. However, the pyranometer of the Living Lab senses only the global solar irradiance on the horizontal plane; therefore no information about the direct and diffuse radiations is directly available. It was necessary to build an empirical model able to distribute the measured values of global solar radiation in its direct and diffuse components.

$$Global\ Radiation = Diffuse\ Radiation + Direct\ Radiation\ \left[\frac{Wh}{m^2}\right]$$

The global solar radiation, measured by the pyranometer, was distributed in its two components according to the following criteria:

- If the Global Solar Radiation measured was < 100 Wh/m^2, it was considered all as Diffuse Radiation;
- If the Global Solar Radiation measured was > 100 Wh/m^2:
    - The quota up to 100 Wh/m^2 was considered Diffuse Radiantion;
    - The remaining quota (= $GSR_{mesasured}$ – 100 Wh/m^2) was equally split in the Diffuse and Normal Radiation (therefore the diffuse radiation was summed to the 100 Wh/m^2)

The pyranometer records the values of global irradiance every 30 seconds. Therefore, 2880 global radiation values in Wh/m^2 are collected throughout the day. These are gathered in the hourly values (averaged over time) obtaining 24 values of Global Solar Radiation in Wh/m^2.

3.4 Modelling and Simulation Tools

At first, a brief introduction on simulation software adopted will be provided, followed by the reasons behind their choice and the type of simulations used. Then, the three-dimensional model of the ZEB Living Lab, used as geometrical support for the simulations, will be described in its features and material properties.

Table 3. Modelling and simulation tools adopted

Rhinoceros 5.0	**DIVA-for-Rhino 4.0**	**Microsoft Excel**
Geometry of the building and its surrounding; Sensors grid. **Microsoft Excel**	Input: Materials; Location; Sun and Sky Conditions; Electric lighting fixtures.	Input: Indoor Illuminance distribution; Electric energy use by each lighting fixture in the room.
Data analyses to define lighting system in its energy use and illuminance features.	Output: sDA (Indoor Illuminance distribution throughout the year).	Output: Correlation between the two variables.

3.4.1 Modelling tool: Rhinoceros

In order to carry out reliable daylight simulations, it was chosen to elaborate a 3D model of the ZEB Living Lab using the graphic software Rhinoceros 5.0 which is commercial computer-aided design program developed by Robert McNeel & Associates.

The fundamental element of Rhinoceros's modelling environment is NURBS-based geometry. NURBS is the acronym of "Non Uniform Rational B-Spine" and it is a mathematical model adopted for generating and representing a wide range of curves and surfaces. Because of their flexibility, it is possible to use them in a varying of processes and applications since they are efficient and accurate, granting high-level 3D modelling capability of the software. However, this is not the only reason why we chose to develop the model with Rhinoceros. This decision was also supported by the potentiality to use Rhinoceros in combination with the plug-in Diva-for-Rhino.

3.4.1.1 Three- dimensional geometry model

"The nature of the simulation errors lay in basic model properties, such as scene geometry and material properties, which are of equal importance for static and dynamic daylighting metric" (Ibarra and Reinhart, 2009).

Figure 14. 3D model from south-east point of view

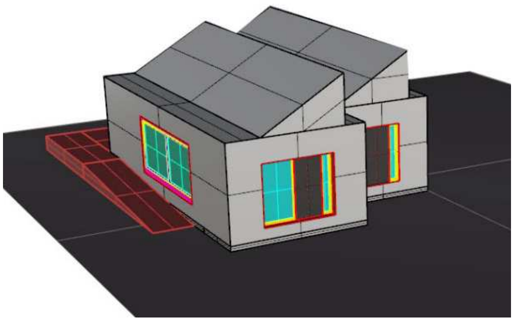
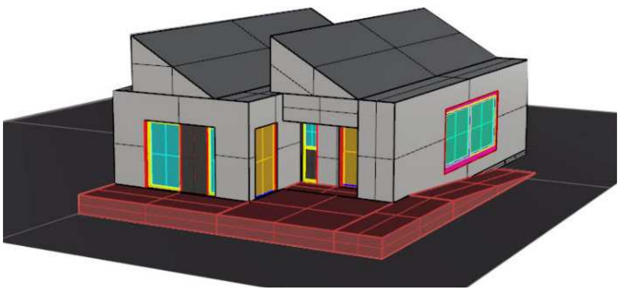


Figure 15. 3D model from south-west point of view



The ZEB Living Lab was modelled its three dimensional features, considering wall-thickness, fenestrations, furniture and the building's surroundings in order to avoid gross mistakes on the simulation outputs. Moreover, the Living Lab is surrounded by the university buildings. The ones closer to the house were modelled as volumes in order to simulate their obstruction on the house.

Figure 16. View from south-east of the model of Living Lab in the campus NTNU

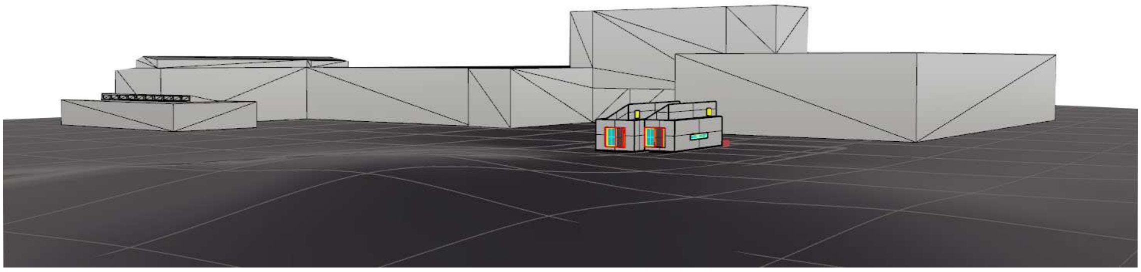


Figure 17. North view of the model of Living Lab surrounded by NTNU buildings

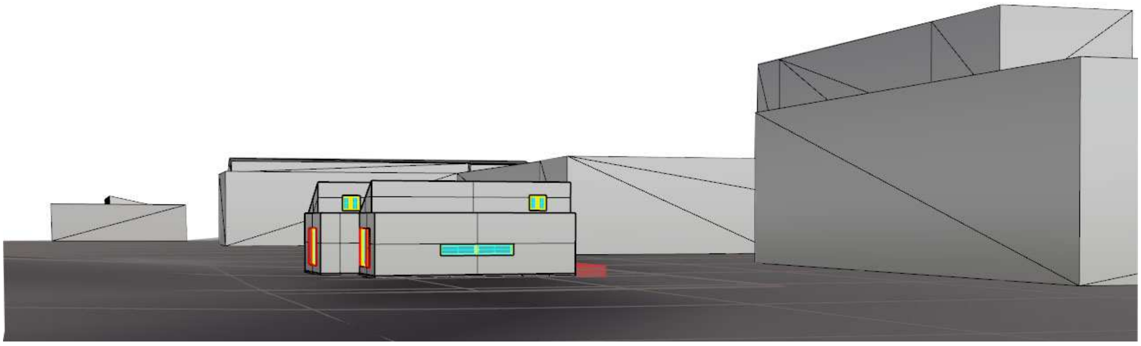
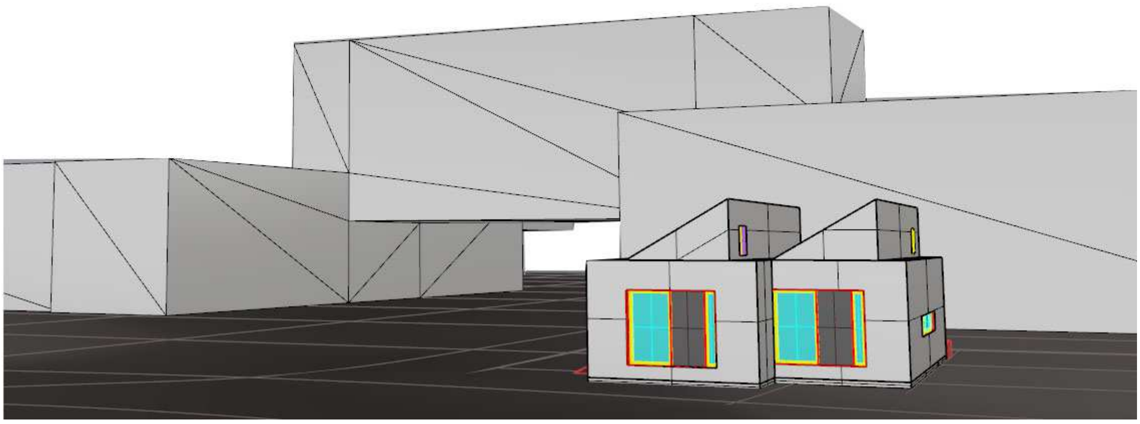
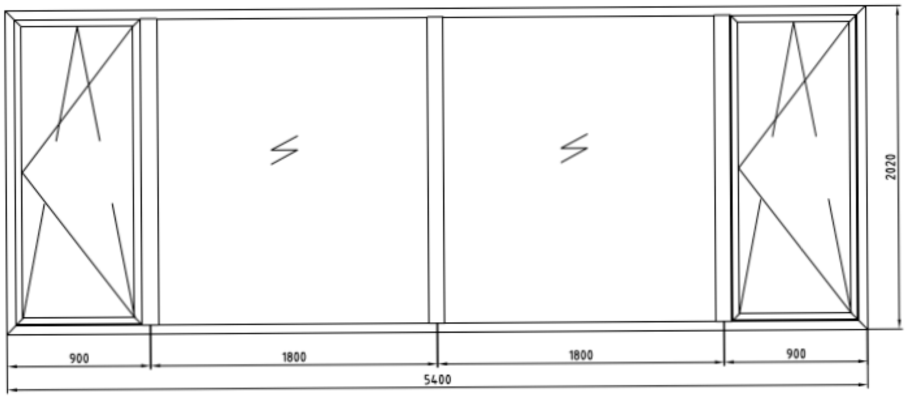


Figure 18. East view of the model of Living Lab and its surrounding



The indoor environment is lit through eight windows briefly described below.

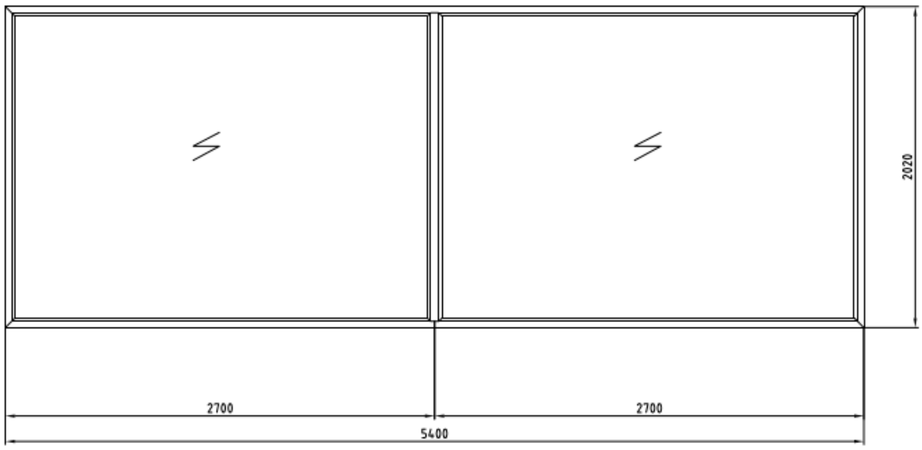
Figure 19. Inner Window of the Living Room South



South window			
Openable inner windows			
Dimension	745mm x 1860mm		
Total Thickness	50mm		6Float/18Argon/4Float/18Argon/4Float
Specifics	Ug=0.5W/m²K	Tl=0.74	g=0.53

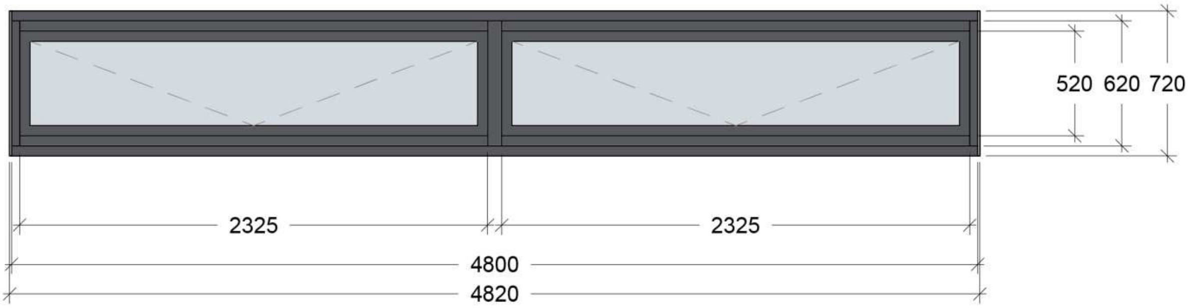
Fixed inner windows			
Dimension	1736mm x 1946mm		
Total Thickness	50mm		6Float/18Argon/4Float/18Argon/4Float
Specifics	Ug=0.5W/m²K	Tl=0.74	g=0.53

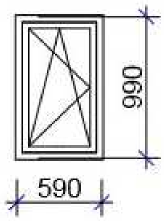
Figure 20. Outer window of the Living Room North

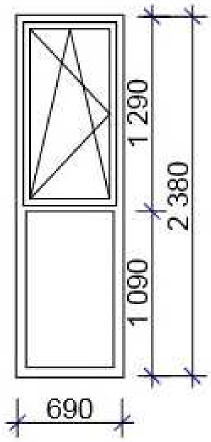


Fixed outer windows	
Dimension	1736mm x 1946mm
Total Thickness	8mm
Glass Specifics	single glass pane tempered, heat soak tested

Figure 21. Window in the Living Room North







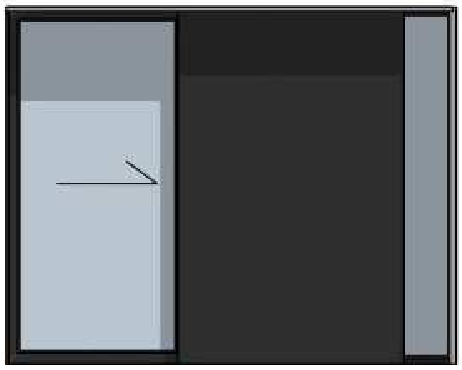


Figure 22. North window mezzanine

Figure 23: West window of the bathroom

Figure 24: Window in the bedrooms

3.4.2 Simulation Tool: DIVA-for-Rhino

The choice of Rhinoceros as modelling tool was also supported by the potentiality to use Rhinoceros in combination with the plug-in Diva-for-Rhino.

DIVA, which is the acronym of "Design- Iterate- Validate- Adapt" is a highly optimized lighting and energy modelling plug-in that was initially developed at the Graduate School of Design at Harvard University and then distributed by Solemma LLC. DIVA-for-Rhino allows the evaluation of several environmental performance metrics for indoor spaces and individual buildings as well as for urban landscapes.

Therefore, the combined use of Rhinoceros and DIVA-for-Rhino permit to accurately create and define the building's geometry and obtain visualizations, daylighting metrics and dynamic daylight analysis with the same accuracy of Radiance-based software. Moreover, the use of the same three-dimensional model grants to minimize the chances of information loss owing to import processes or geometric conversions from CAD to Radiance software.

To run daylight simulations with DIVA-for-Rhino, it is necessary to introduce some fundamental inputs that complete the information of the scene modelled within Rhinoceros.

The main inputs are:

- Location: to set the location of the project by associating a weather file that contains the basics information about the latitude, longitude, time zone as well as other variables such as temperature, relative humidity, global and diffuse radiations values that are needed to carry out daylight simulations. The weather file used by DIVA-for-Rhino is EnergyPlus weather file to generate the sky luminance distribution using the Perez sky model to yield dynamic daylight simulations.
- A grid of the points used to calculate the illuminance;
- Materials define how the light interacts with the elements/object of the model.

After that, it is possible to control the simulation type to run and its parameters such as quality, sky condition, date and time or schedule, lighting units, the radiance parameters and

Two types of grid-based simulations were performed in order to fulfil the thesis's goal:

1. Climate-based simulations to assess the Daylight Autonomy;
2. Point-in-Time Illuminace.

Daylight Autonomy simulations were run not for its final result, the Daylight Autonomy itself, but for the intermediate output which is the *.ill file containing the Annual Illuminance Profile of a defined set of nodes.

A tailored weather file containing the actual sun and sky condition recorded during the time of the residential experiment will be used as input in the simulations. Therefore, the importance of the Annual Illuminance Profile lies in the fact that it will contain the indoor illuminance corresponding to such outdoor conditions.

Whereas, Point-in-Time Illuminance simulations measure illuminance levels at a specific date and time.

The reliability of the daylight simulations performed with DIVA-for-Rhino lies in the fact that it uses two validated lighting simulation engines: Radiance and Daysim. Their features and specifics will be explained below.

3.4.2.1 Radiance and custom materials

Radiance is the name of a rendering system developed by Greg Ward at the Lawrence Berkeley Laboratories in California and the École Polytechnique Fédérale de Lausanne in Switzerland. It aims to produce accurate lighting simulation and visualization based on ray-tracing technique (Ward, 1994).

The peculiarity of Radiance ray tracing algorithm is that it works backward/in reverse, meaning that the rays are traced in the opposite direction to the one that they naturally follow. Instead of going from the source of light to the object, Radiance draws the light rays from viewpoint back to the source of light, taking into account all physical interactions with the surfaces of the objects composing the scene (Compagnon, 1997). Radiance blends deterministic and stochastic ray tracing techniques to produce physically based simulations of indoor illuminance and luminance distributions for diffuse, specular and partly specular material surfaces (Reinhart and Walkernhost, 2001).

In Radiance software, a scene is described by primitives. Primitives are the basic elements of Radiance and are entities used for the description of the scene in its geometry specifying the size, position, shape, and material type. All primitives have the same general format and it will be here described since this is the description format for the custom materials used in our model.

In fact, DIVA-for-Rhino automatically converts the geometries modelled in Rhinoceros into scene descriptions and objects that Radiance is able to analyse. However, it does not import any material information defined in Rhinoceros. Materials must be defined according to Radiance parameter and this can be done modifying the *.rad files in Diva directory.

Materials, as the other primitives, are defined by a *modifier*, a *type*, and an *identifier*. The *modifier* can be materials, mixtures, textures or patterns. The *type* determines the number and the type of strings and real arguments that defines the primitive. The *identifier* is a unique name that identifies the primitive.

Material primitives determines how light will interact with the geometric surface. They are defined by a diffuse and specular component, a colour and a roughness factor. The materials' types tailored for this model are: plastic, metal and translucent materials. Plastic and metal are both defined by a red green and blue reflectance value, a specularity value and by a roughness value. The difference lies in the range of values assumed by the specularity factor, which is generally higher for metal, and that highlights are influenced by the colour material for metal, while plastic has uncoloured highlights. An example of material definition in Radiance text file is provided below:

Modifier Type Identifier

```
void plastic GenericCeiling_70
0
0
5 0.7 0.7 0.7   0 0  (R G B S R)
```

Modifier Type Identifier

```
void metal SheetMetal
0
0
5 .9 .9 .9 .8 0 (R G B S R)
```

Another type of material used in the model is trans material. It is a translucent plastic characterized by two more parameters that are transmission factor and a transmitted specularity value. The transmission factor is the fraction of penetrating light that travels through the material. The fraction of transmitted light that is not diffusely scattered is the specular transmitted value. This material modifies the colour of the scattered light.[2]

```
#LED strips cover tau_vis_0.75
void trans LightcoverPlaticMaterial
0
0
7 1 1 1 0 0 0.75 1
```

Glass instead is treated as a dielectric material, which is a transparent material that refracts and reflects light. The glass type material has the peculiarity of producing one reflected and one transmitted ray.

[2] http://radsite.lbl.gov/radiance/refer/usman2.pdf

```
# Glazing_SinglePane: Tau_vis = 0.88; SHGC= 0.82 ; U-Value=
5.82W/m2K
# visual transmittance: 88%
# visual transmissivity: 96%
void glass Glazing_SinglePane_88
0
0
3 0.96 0.96 0.96
```

DIVA-for-Rhino uses a radiance file containing a set of standard materials. However, there was the need to create custom materials that better describe the indoor environment in the ZEB Living Lab.

Figure 25. Living Lab Interiors (photo: Nicola Lolli)

The definition of reflectance, specularity and roughness of the opaque components was supported by information provided by the Radiance User Manual and by **qualitative** comparison of the visualization outputs with the real internal illumination. Visual simulations were used for display purpose only, to verify that the type of illumination of the model resembles the real illumination inside and that they both create the same effect.

Figure 26. Living Lab Interiors (photo: Nicola Lolli)

For instance, Radiance User Manual suggests to use for light-coloured wood RGB reflectance of 0.5 -0.3 0.2 and specularity and roughness values of 0. Indoor wall and ceiling are made of the same material, which is characterized by a very light colour. They were treated like Lambertian surfaces. Whereas, the windows' materials properties were chosen among Diva-for-Rhino's default materials since their features are similar and good approximate the characteristics of the real windows.

All the materials assigned to the model geometrical elements are described in the table below.

Table 4. Materials' properties used in the Radiance-based simulations

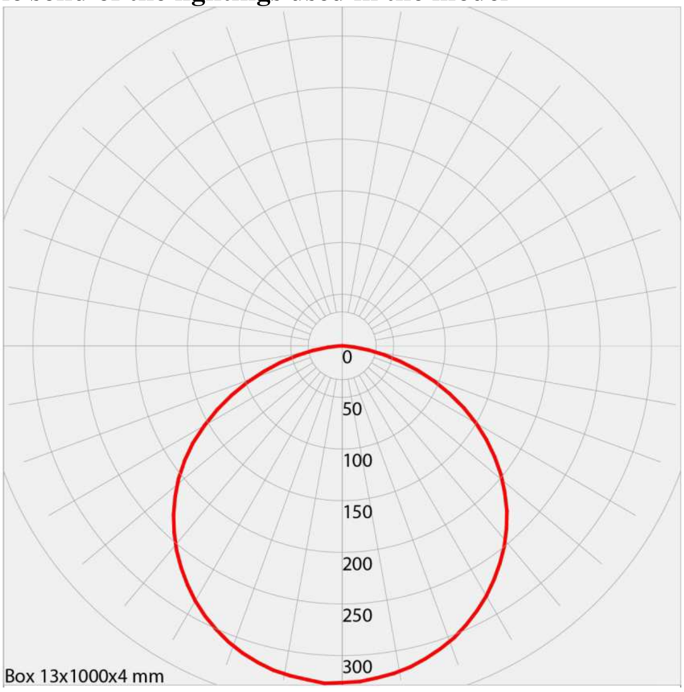
Description	Material/colors	Radiance material	RGB	Specularity	Roughness
Ceiling	Opaque	WoodenCeiling	0.6/0.4/0.3	0	0
Wall	Opaque	WoodenInteriorWall	0.6/0.4/0.3	0	0
Floor	Opaque	WoodenFloor	0.5/0.3/0.2	0	0.02
Furniture	Opaque	WoodenFurniture	0.5/0.3/0.2	0	0
Single Glazing	Translucent	Glazing_SinglePane_88	0.96/0.96/0.96		
Triple Glazing	Translucent	Glazing_TriplePane_Krypton_47	0.5135/0.5135/0.5135		
Mullions	Opaque/ dark grey	MullionsSheetMetal matted	0.1/0.1/0.1	0.8	0
Outside Wood	Opaque	OutsideWood	0.5/0.3/0.2	0	0

From the characterization of the illumination system, the information about the nominal power and the length of the LED strips were used to improve the 3D model in order to have a further support for the analysis.

The technical drawings were used as a reference for the development of the model. However, from the data gathered in the first phase emerged a slight difference between the rated power expected and the actual rated power measured with the experimentation. The latter was the one taken into consideration when developing the model. The ZEB Living Lab is equipped with LED strips with rated power of 14.4 W/m, 9.6 W/m and 4.8 W/m. IES file of such strips were imported through Diva-for-Rhino and put in place according to the actual indoor layout.

The IES Photometric file is text file that contains data about the light distribution produced by the analyzed electric source that can be used for architectural light simulation programs. This file typology is generally freely available from lighting manufacturer website. In the pictures below is described the photometric distribution of the luminaries used in the model, chosen because of their symmetric luminous distribution.

Figure 27. Photometric solid of the lightings used in the model



DIVA-for-Rhino imports and interprets measured luminance data through its command “ies2rad”. Then, it is able to display the correct lighting patterns on the scene and calculate the illuminance distribution derived from the interaction between the luminaries and the indoor environment.

In order to assess if the illuminance level on the horizontal plane due to the lighting fixtures imported in DIVA-for-Rhino is coherent with the actual one measured with the portable lux-meter, a series of simulations of Point-In-Time Illuminance were run. The simulations return the illuminance distribution on the horizontal plane at 0.90m from the floor for a grid of points evenly distributed in the room. Simulation outputs were compared with the measured values of illuminance collected with the lux-meter to verify that the illuminance due to the LED strips placed on the ceiling of each room is coherent to the measured one. The illuminance maps below show the results of the simulations carried out for the lighting of the ceiling of the bedroom east and west.

Figure 28. Illuminance map of the bedroom east when the LED strip on the ceiling is switched n with a dimmer status of 100%

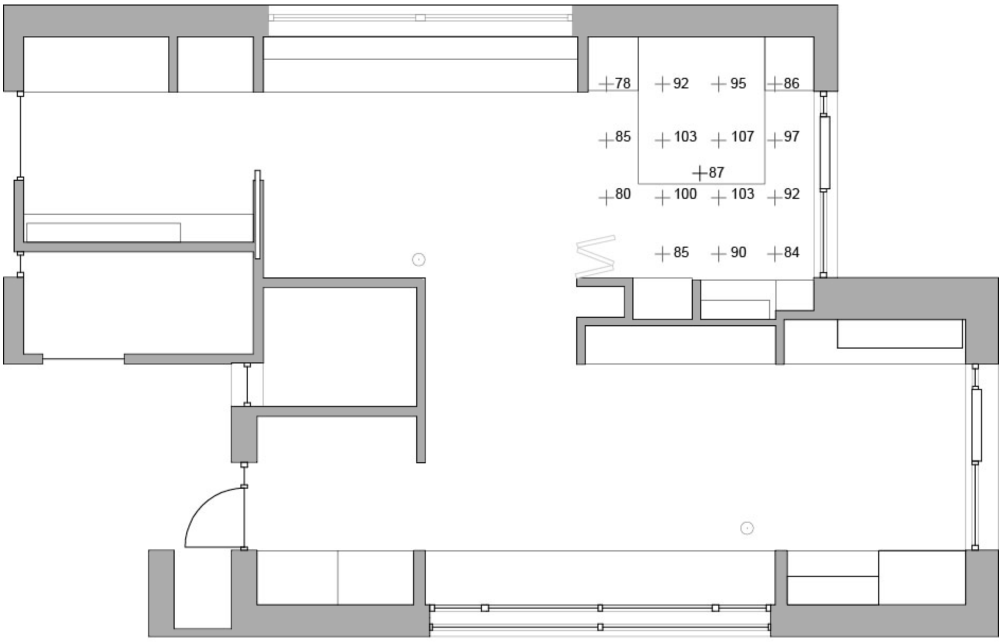
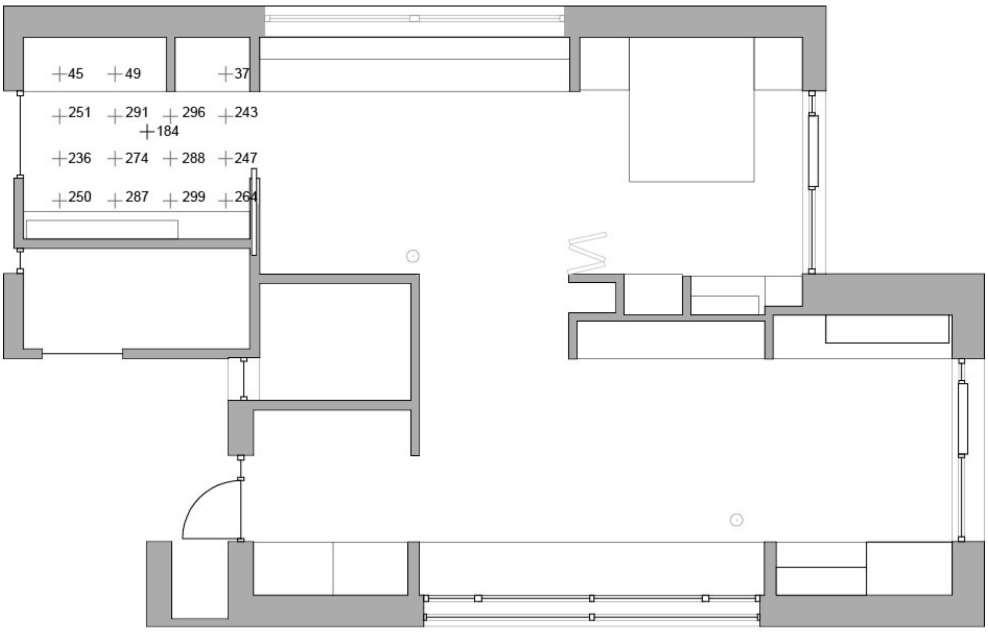


Figure 29. Illuminance map of the bedroom west when the LED strip on the ceiling is switched n with a dimmer status of 100%



This first series of results show that there was around 30%, or even more, discrepancy between the simulation outputs and the measured illuminance value. For this reason, a surface were modelled and placed over the luminaries in order to emulate the plastic element that covers and protect the LED strips. It was modelled as a translucent material which is basically a translucent plastic.

Figure 30. Cover in plastic of the LED strips

The parameters assigned were derived directly from Radiance User Manual, as shown in the table below.

Table 5. Material's properties of the plastic cover

Colour			Specularity	Roughness	Transmission	Transmitted Specularity
R	G	B	S	R	Trans	Tspec
0.7	0.3	0.2	0	0	0.75	1

The output of the second series of Point-In-Time Illuminance simulations show an higher gap between the real illuminance distribution and the one simulated. In fact, the outputs show a reduction of the 60% of the illuminance. This result is in contrast with the expect reduction of the 25%.

Figure 31. Illuminance map of the bedroom east when the LED strip on the ceiling is switched n with a dimmer status of 100% with the plastic cover

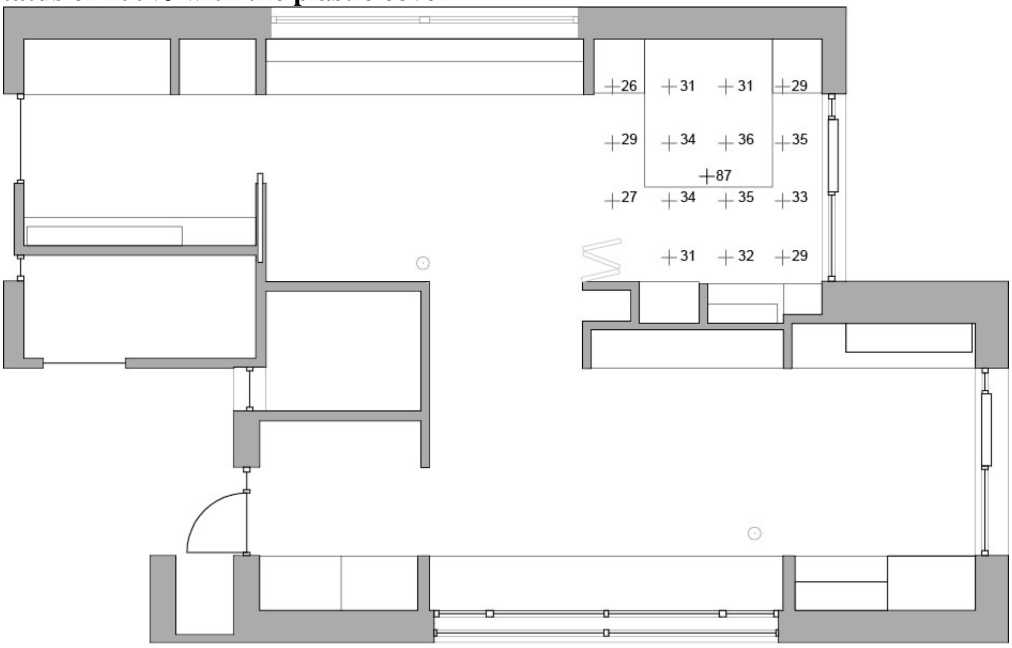
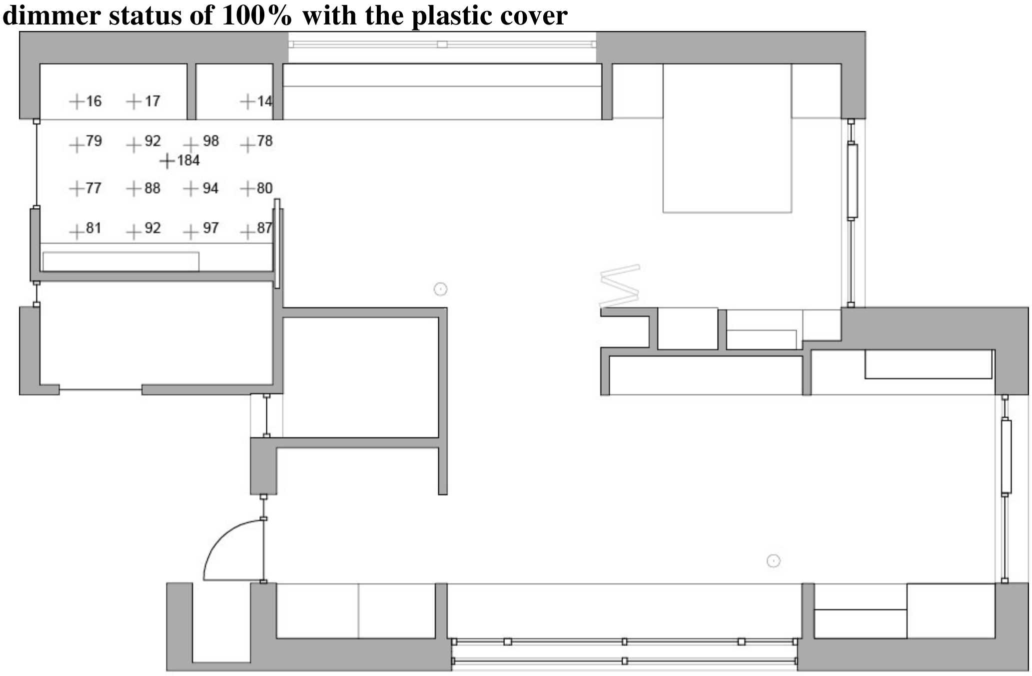


Figure 32. Illuminance map of the bedroom west when the LED strip on the ceiling is switched n with a dimmer status of 100% with the plastic cover



Consequently, the translucent material was modified, this time giving it a white colour in order to avoid further reductions of the transmitted light caused by R-G-B parameters.

Table 6. Material's properties of the translucent material used as a cover for the luminaries

Colour			**Specularity**	**Roughness**	**Transmission**	**Transmitted Specularity**
R	G	B	S	R	Trans	Tspec
1	1	1	0	0	0.75	1

This time, the simulation outputs show a god adhesion to the measured values.

Figure 33. Illuminance map of the bedroom east when the LED strip on the ceiling is switched n with a dimmer status of 100% with the plastic cover

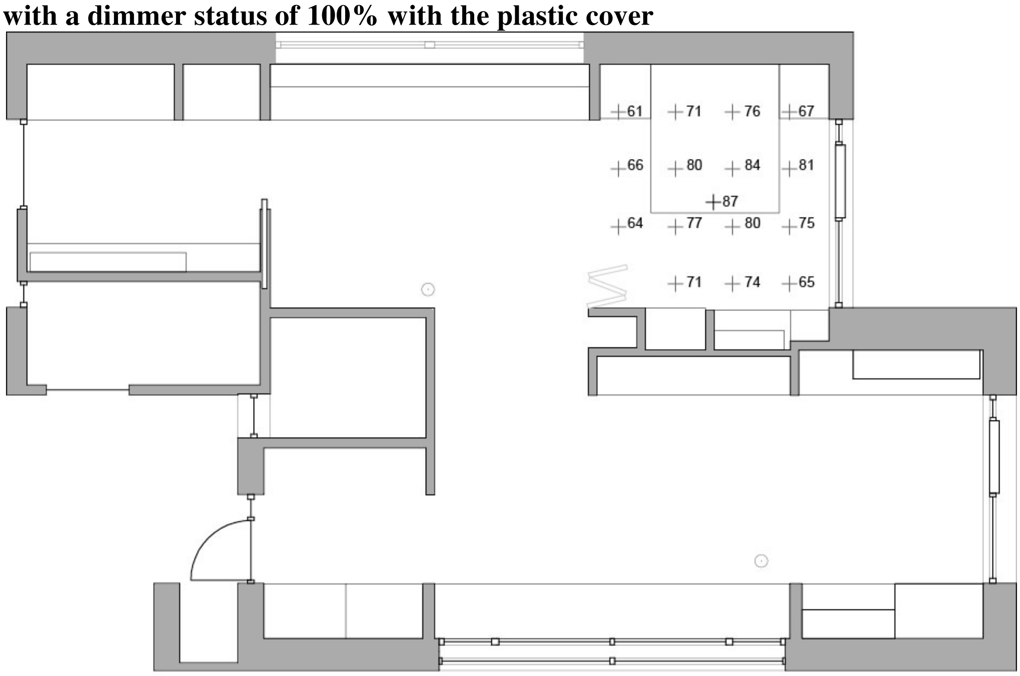
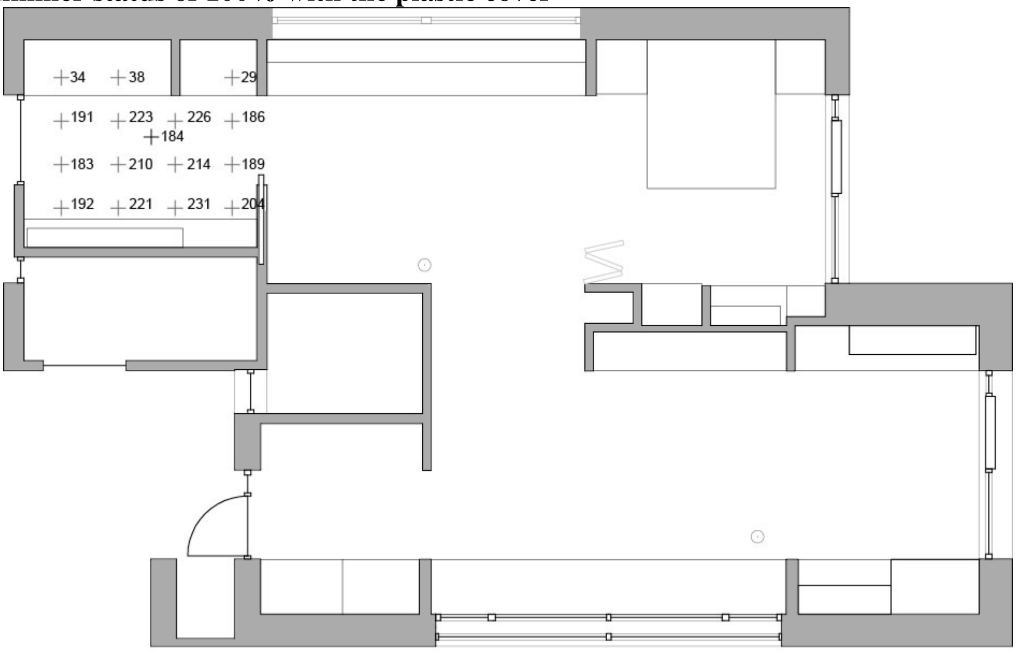


Figure 34. Illuminance map of the bedroom west when the LED strip on the ceiling is switched n with a dimmer status of 100% with the plastic cover



According to these results, a plane surface with the translucent properties described above was modelled over all of the indoor lighting appliances.

The outputs of the visualizations were compared with the photographs, showing a good adhesion of the model to reality.

Figure 35 Visualization outputs of the Living Area South (left) and the Living Room North (right)

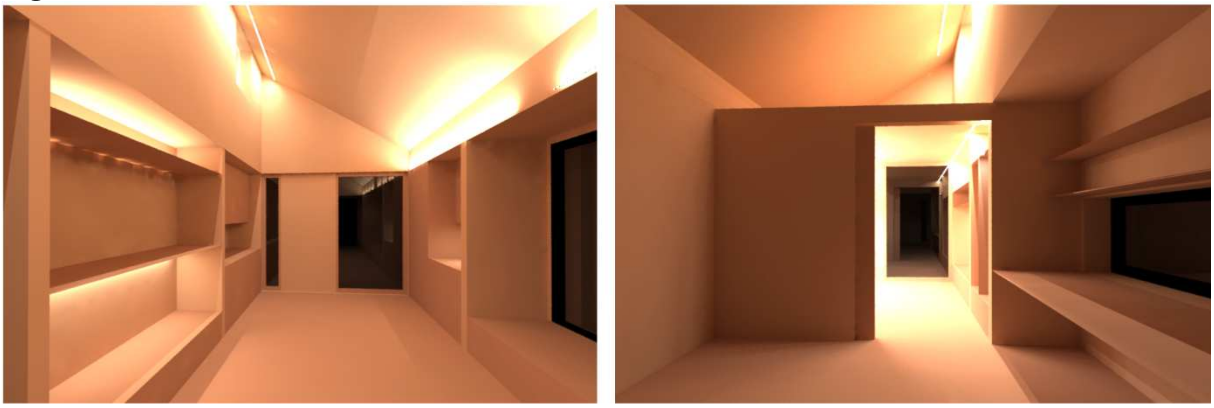
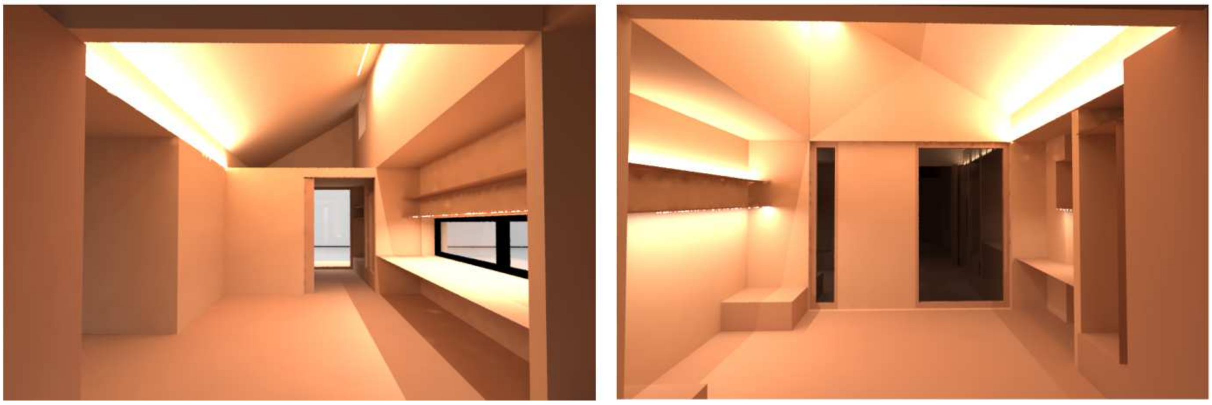


Figure 36 Visualization outputs of the Living Room North (left) and the Bedroom East (right)



3.4.2.2 Radiance simulation parameters

DIVA-for-Rhino simulations use Radiance parameters to define:

- ab (ambient bounces): number of diffuse reflections from sensor to source. It is defined on the number of reflections typically required by the light to reach the task plus one or two extra for inter reflection within the space.
- as (ambient super-sampling): additional rays to regions of high variance e.g. windows; The ad and as options are generally good for reducing noise in a calculation or rendering.
- ar (ambient resolution): defines the calculation grid or size of splotches;
- aa (ambient accuracy): error permitted in indirect interpolation. (Ward and Shakespeare, 1998)

In order to optimize simulation's time and output's accuracy, the following values for the Radiance's simulation parameters were adopted.

Table 7 Radiance's simulation parameters

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

3.4.2.3 DaySim

Daysim is a daylight simulation engine that uses Radiance ray tracing technique in order to assess the performance metrics to evaluate the daylight availability in and around the building.

DAYSIM is the DIVA-for-Rhino component that allows carrying out dynamic daylight analysis throughout the whole year. Inputs of the simulations are: Radiance geometry and materials; area of interest, consisting of a viewpoint or a sensors grid defined by the user; occupancy schedule and space usage; sky model and site information; hourly or sub-hourly direct and diffuse solar radiations contained in the EnergyPlus weather file (*.epw). The elaboration of these data produces intermediate results, which are generally hourly or sub-hourly illuminance or luminance values. These outputs are further processed in order to be summarized in daylight metrics used to assess the daylighting performance of a space (Jakubiec and Reinhart, 2012). Therefore, simulation outputs are climate-based daylighting metrics such as Daylight Autonomy, Useful Daylight Illuminance, Annul Glare Probability and Electric Lighting Use. Further specifictions about the electric lighting systems and its control (manual switches, occupancy sensors or photocell controll dimming), the occupancy, shading device, allow Daysim to model the effects of occupant's behaviour on the daylight availability and lighting energy use and generates lighting and shading schedule files that can be imported and used as inputs in thermal simulation software and thermal analysis on the building.

Daysim uses the daylight coefficient approach that generates the daylight coefficient for all the points of the set grid. Then, the information of the weather file (*.epw) about the diffuse and normal radiations, as well as about the building site, are used to calculate the luminance distribution of the celestial hemisphere according to the Perez sky model. The resulting sky luminous distribution is combined with the daylight coefficient by superposition.

Daylight Coefficient Simulation Method:

For a point and orientation x, a daylight coefficient $DC_\alpha(x)$, related to the sky segment S_α is defined as the illuminance $E_\alpha(x)$ at x caused by the sky segment S_α divided by the luminance L_α and the angular size ΔS_α of the sky segment (Reinhart and Walkenhorst, 2011).

$$DC_\alpha = \frac{E_\alpha(x)}{L_\alpha \cdot \Delta S_\alpha}$$

A completed set of daylight coefficients can be coupled with an arbitrary sky luminance distribution L_α by a simple linear superposition to calculate the total illuminance E(x) at x:

$$E(x) = \sum_{\alpha=1}^{N} DC_\alpha(x) \cdot L_\alpha \cdot \Delta S_\alpha$$

Daylight Coefficient method distinguishes the contribution of the diffuse skylight, ground reflections and direct sunlight. The celestial hemisphere is divided into 145 diffuse sky segments and the luminance of each segment ${L_\alpha}^{diffuse}$ is calculated with the Perez all weather sky model using the information in the *EnergyPlus Weather* file. The contribution of the ground reflection is calculated through the Radiance function *gendaylit* that models the luminances of the three ground segments. The contribution of the direct sunlight is instead modelled using 61 or 65 representative sun positions in the sky vault that are a subset of all the possible positions the sun can assume throughout the year, depending on the latitude of the building site (Reinhart and Walkenhorst, 2011).

$$\begin{aligned} E(x) = &\sum_{\alpha=1}^{145} DC_\alpha(x)^{diffuse} \cdot {L_\alpha}^{diffuse} \cdot {\Delta S_\alpha}^{diffuse} \\ &+ \sum_{\alpha=1}^{3} DC_\alpha(x)^{ground} \cdot {L_\alpha}^{ground} \cdot {\Delta S_\alpha}^{ground} \\ &+ \sum_{\alpha=1}^{65} DC_\alpha(x)^{direct} \cdot {L_\alpha}^{direct} \cdot {\Delta S_\alpha}^{direct} \end{aligned}$$

DAYSIM couples Radiance simulation algorithms with the Daylight Coefficient approach to simulate indoor illuminances under arbitrary sky conditions (Radiance predicts indoor illuminances under a single sky condition) and then calculate Annual Illuminance profiles. The Annual Illuminance Profile is a time series of the indoor illuminance at points of interest in a building. The file contains the illuminances for all the sensors specified in the sensor file for all time steps of the year specified in the DAYSIM climate file (Reinhart, 2018)

3.4.2.4 Energy Plus Weather file (*.epw)

Climate-based dynamic simulations yield daylight illuminances throughout the year, using information of annual climate dataset. The simulation engine Daysim uses the *Energy Plus*

Weather file. This type of file includes hourly information of direct and diffuse solar radiations, as well as temperature and other environmental variables. The peculiarity of this type of weather file is that the information included are based on data recorded over long periods of time in order to more closely match the long-term average climatic conditions for the geographic project location.[3]

In this study, the aim is to reproduce the daylight conditions of a specific time period. Therefore, the weather file of Trondheim was modified *ad-hoc*. The values of the global horizontal solar radiation of the days taken into consideration were distributed in the direct normal and diffuse components (according to the model mentioned in paragraph 2.2.3). Then, the *.*epw* file was updated with information about:

- Global Horizontal Radiation [Wh/m^2] which is the total amount of direct and diffuse solar radiation received on a horizontal surface;
- Direct Normal Radiation [Wh/m^2] which is the amount of solar radiation received directly from the solar disk on a surface perpendicular to the sun's rays;
- Diffuse Horizontal Radiation [Wh/m^2] which is the amount of solar radiation received on a horizontal surface as skylight, without taking the sunlight into account.

The tailored weather file (*.epw) was used as input data for the simulations carried out with DIVA-for-Rhino.

3.5 Sensitivity Analysis

A Sensitivity Analysis (SA) was carried out in order to assess the validity of the model used to elaborate the diffuse and direct normal radiation components from the global solar radiation.

The Sensitivity Analysis aims to assess the effects on the results and on the simulation outputs caused by changes in the values of the input variables. Essentially, this instrument is useful to evaluate the impact of the inputs on the outputs. This analysis assesses to what extent the

[3] https://energyplus.net/weather

uncertainty in the output of a model is influenced by different sources of uncertainty in its inputs associated with each of the independent variables influences the value taken from the base of assessment (Saltelli, 2002).

The sensitivity analysis of the model is the process through which it is possible to study the variation of the response of the model output with the variation of one or more input factors and discriminate between influential factors and not influential.

A fixed range of variation (+ 20%, -20%) is imposed to the values of the model input factors in order to identify the sensitivity for each factor in the model. The Sensitivity Analysis allows determining, within reasonable limits, whether such parameters or input variables produce on the output of the model an effect that can be considered negligible, significant, linear or non-linear.

The sensitivity analysis is performed on the components of solar radiation. Thus the components were recalculated imposing a variation of the 20% to the direct normal component. Consequently, the diffuse component was calculated by subtracting the direct normal component to the global solar radiation.

In this particular case, the sensitivity analysis aims to answer questions: how does the simulation output change if the values of the direct radiation change of 20%?

Three different simulations were performed using: the weather file with solar radiation values calculated with the empirical rule, then, by increasing or decreasing the direct component of 20%.

3.6 Model Validation Process

The level of reliability achieved in terms of adhesion between real and simulated building is checked through an appropriate validation process.

3.6.1 Model Validation for Electric Lighting

In order to estimate the power used by each electric light, a numerical model was built. This numerical model allows estimating the power and, therefore, the energy use of each lighting source in the Living Lab by superposition from the hourly dimmer status associated with the corresponding light source. Experimental data were collected and compared against the estimated ones to assess the reliability of the linear combination used.

This model is rather important. In fact, it allows us to estimate the energy use by each element of the lighting system, from its dimming status, and, therefore, have reliable information about the electric energy use for lighting in every room during the occupation period, and estimate the electric energy use for lighting in the analyzed room when the residential experiment took place.

To verify the reliability of this model, three or more electric lights were switched on at the same time with different dimming randomly sets. They were left on for a sufficient amount of time in order to calculate the electric energy used from the electric energy meter of the Living Lab, as it was done in the first place for calculating the rated power.

Then, the actual power absorbed by all the considered lights was compared with the power estimated with the numerical model. If the relative error were below 10%, for all the considered combination of lights/dimmer status, the model would be considered reliable and accurate in estimating the energy usage for lighting.

Moreover, the illuminance on the horizontal plane by means of the portable lux-meter was measured for such combination. A series of simulations of Point-In-Time Illuminance were carried out to assess the reliability of the three-dimensional model.

The model was corrected and adapted on the basis of the illuminance distributions owing to the LED strips on the ceiling of the main living areas. Therefore, this processed cannot be considered a validation, since the model was modified in order to match the collected data.

Diva-for-Rhino allows controlling the dimming of the lighting, but only by setting an illuminance threshold for some selected points of a set grid. Since this validation was done assessing the illuminance level, this type of lighting dimming control was not useful for the purpose. So another small set of measurements were collected and used to assess the adhesion of the model to reality. In this occasion, several lighting source were switched on with a dimmer status set on 100% (no dimming) in two different combinations.

3.6.2 Model Validation for Daylight Availability

As far as daylight evaluation is concerned, Daylight Autonomy simulations were run for the main rooms of the house in order to validate the model.

For this occasion the *EnergyPlus Weather* file was specifically modified in order to contain the actual data of global solar radiation sensed by the pyranometers of the Weather Station in the ZEB Living Lab.

The data collection was carried out in three days of May, characterized by clear, overcast and intermediate sky conditions.

The validation process requires a comparison between the collected data and simulation outputs to assess the reliability of the model. The data of diffuse indoor illuminance sensed by the indoor fixed lux-meters facing downwards placed at the ceiling height of the considered rooms were compared against the simulated indoor illuminance values calculated at ceiling height.

The output of this type of simulation is the Daylight Autonomy which is defined as the percentage of occupied times in the year during which a target illuminance level can be reach by daylight alone. To support the definition of this metric, DIVA-for-Rhino, (and Daysim) calculates the annual illuminance profile values for all the points in the sensors grid. Since the weather file contains the information about the actual sun and sky conditions occurring when the data collection was carried out, the Annual Illuminance Profile contains the illuminance values calculated in the points of the grid for all the hours of the days considered for the validation.

Table 8. Radiance parameters for Daylight Autonomy simulation

ab	ad	as	ar	aa
5	1024	16	256	0.1

Figure 37. Floor Plan of the Living Lab in which the position of the ceiling sensors is highlighted in red

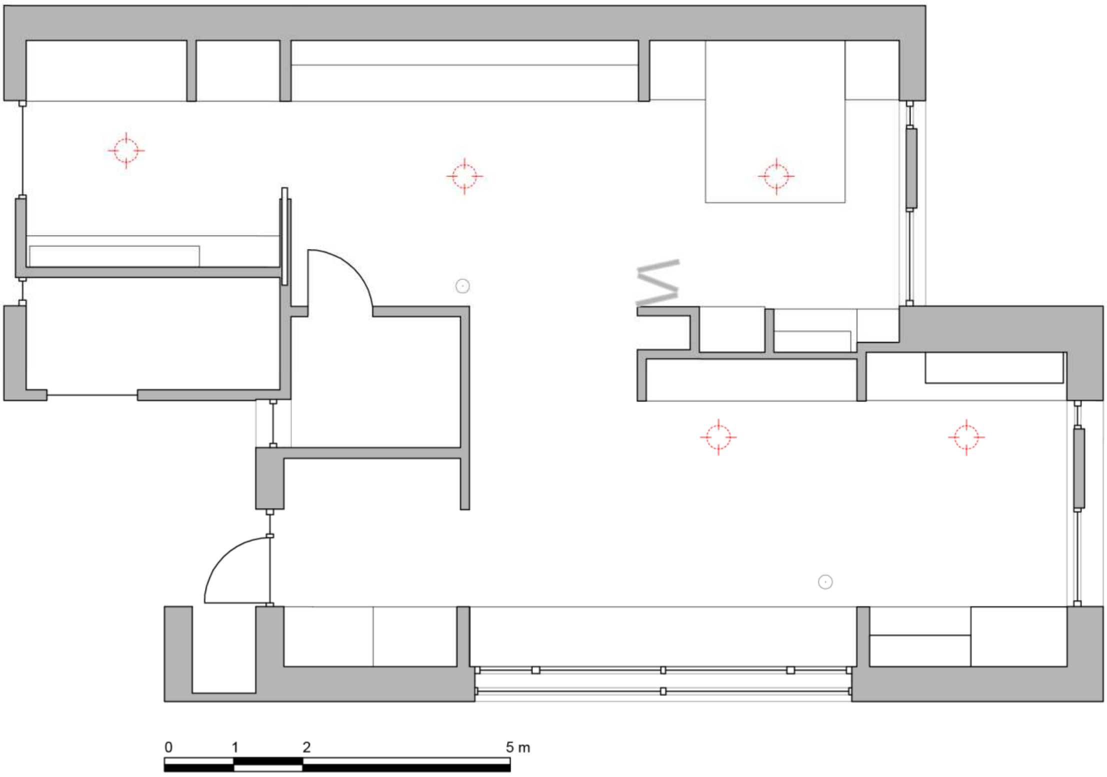


Figure 38. Section of the Living Lab showing the height of the ceiling sensors

4. Results

In this section, the outcomes of the different steps carried out in order to obtain the two variables to correlate are presented.

In the first paragraph, it will be explained the results of the characterization of the lighting system along with the numerical model built to calculate the electric energy use for lighting in the analysed rooms each hours of the days taken into consideration, as well as for the improvements in the 3D model.

After that, the outputs of the Sensitivity Analysis on the model adopted to distribute the global solar radiation in its two components are presented, followed by the outcomes of DIVA-for-Rhino's simulations to assess the validity of the 3D model.

Both electric energy use for lighting and average illuminance were calculated and estimated in the three room of the house during the weeks taken into consideration during the occupation period, flowing the methods explained in the methodology.

Then, it was possible to correlate the two variables obtained through the Pearson coefficient.

4.1 Electric Energy Use for Lighting

As explained in the pertaining paragraph 3.3.2 Characterization of Electric Lighting, characterization activities led to evaluate the nominal power of every lighting source in Living Lab, and the relationship between the dimming level, the power absorbed and the illuminance level. These information were summarized in a numerical model that allows to discern and calculate by linear superposition the electric energy use for lighting in every single room of the house.

The table below shows the results of the first part concerning with the rated power.

Table 9 Summary of LED strips in the ZEB Living Lab

	Rated Power [W]	BaseLoad [W]	Time [h]	Energy use [Wh]	Dimmer Status [%]
LED external lighting	137	33	0.5083	86	100
LED entrance (ceiling)	35	33	0.5175	35	100
LED entrance (furniture)	3	33	0.5097	18	100
LED living room south (ceiling)	70	33	0.5178	53	100
LED living room south (furniture)	22	33	0.5094	28	100
LED living room south (floor lamp)	19	33	0.5025	26	100
LED living room south (furniture sofa)	0	33	0.5514	18	100
LED kitchen (ceiling)	72	33	0.5264	55	100
LED kitchen (pendant lamp)	58	33	0.5178	47	100
LED kitchen (furniture south)	4	33	0.5183	19	100
LED kitchen (furniture north)	0	33	0.6433	21	100
LED living room north (ceiling)	97	33	0.5086	66	100
LED living room north (desk)	32	33	0.5417	35	100
LED living room north (lamp)	3	33	0.5086	18	100
LED mezzanine	44	33	0.5336	41	100
LED bedroom east (ceiling)	76	33	0.5917	64	100
LED bedroom east (desk)	2	33	0.5767	20	100
LED bedroom east (cabinet)	2	33	0.5511	19	100
LED bedroom east (bedlight)	22	33	0.5083	28	100
LED bathroom	38	33	0.5083	36	100
LED bedroom west (ceiling)	82	33	0.5256	60	100
LED bedroom west (desk)	43	33	0.5000	38	100
LED bedroom west (cabinet)	1	33	0.5083	17	100
LED bedroom west (bedlight)	16	33	0.5175	25	100

Regarding the second phase, the results of the data elaboration show a linear relationship between the light dimming and the rated power, although such correlation is not strong to the same degree for all the light sources taken into consideration, in fact, the higher the rated power, the stronger the correlation. To better explain this result, the outputs of the analysis of three lighting fixtures are compared below. The tables and the charts show the correlation found for the LED strips on the ceiling of the living room north and bedroom west, which are characterize by a high rated power (100W and 82W respectively), in contrast with the results obtained for the LED strips placed above the desk of the living room north and for the floor lamp in the living room south, whose rated powers are lower (30W and 19W respectively).

These examples are representative of the main influent categories of LED strips installed in the house: high power LED strips of the ceiling, and the medium power LED strips placed in the furniture. Another category is represented by LED strips with a rated power below 10 W that were not analyzed in this phase since they do not remarkably influence the final result.

The power absorbed by the lighting on the ceiling of the Living Room North increases proportionally with the dimmer status.

Instead, for lighting characterized by a lower rated power, the trend and the line that plots the two points of dimmer level-power are slightly different.

Table 10. LED ceiling Living Room North

Dimmer Status [%]	Time span [h]	Electric energy meter - Lighting [Wh]	Power [W]
0	0	0	0
70	0,4678	48	70
100	0,3539	47	100

Figure 39. Plot of the dimmer status-Rated power relationship for the LED ceiling Living Room North

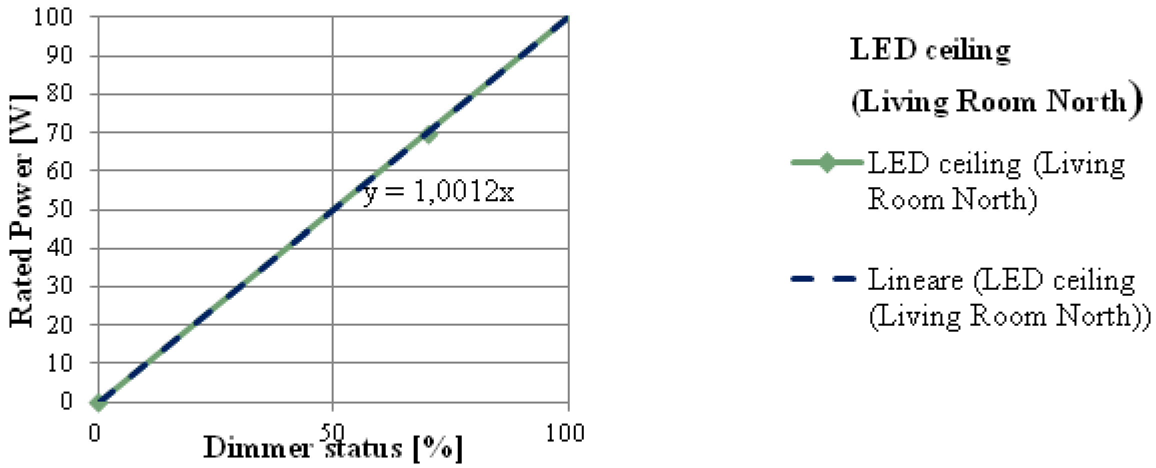


Table 11. LED ceiling Bedroom west

Dimmer Status [%]	Time span [h]	Electric energy meter - Lighting [Wh]	Power [W]
0	0	0	0
50	0,3508	26	41
100	0,3600	41	81

Figure 40. Plot of the dimmer status-Rated power relationship for the LED ceiling Bedroom West

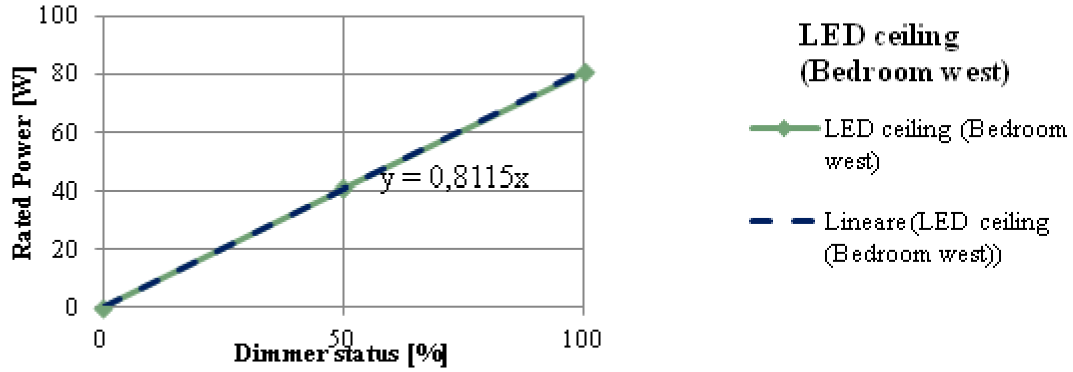


Table 12 LED desk Living Room North

Dimmer Status [%]	Time span [h]	Electric energy meter - Lighting [Wh]	Power [W]
0	0,0000	0	0
70	0,2506	14	23
100	0,2089	13	30

Figure 41. Plot of the dimmer status-Rated power relationship for the LED desk Living Room North

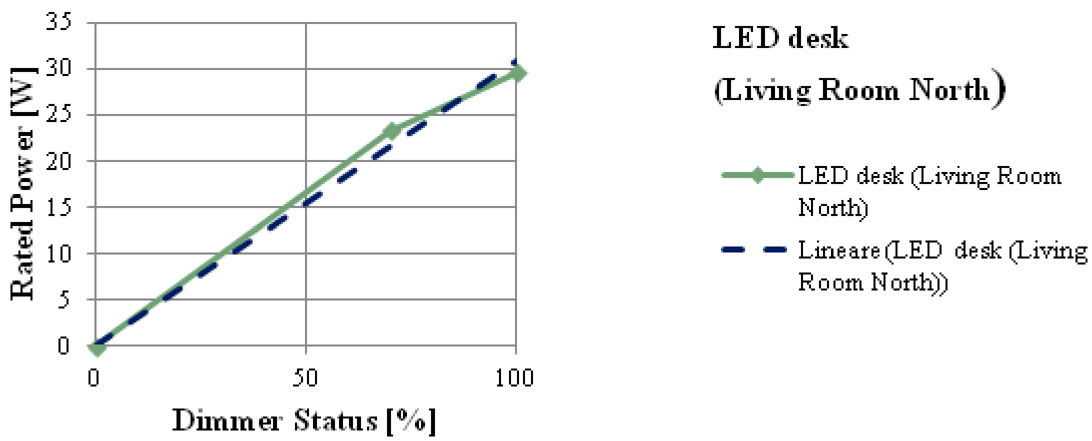
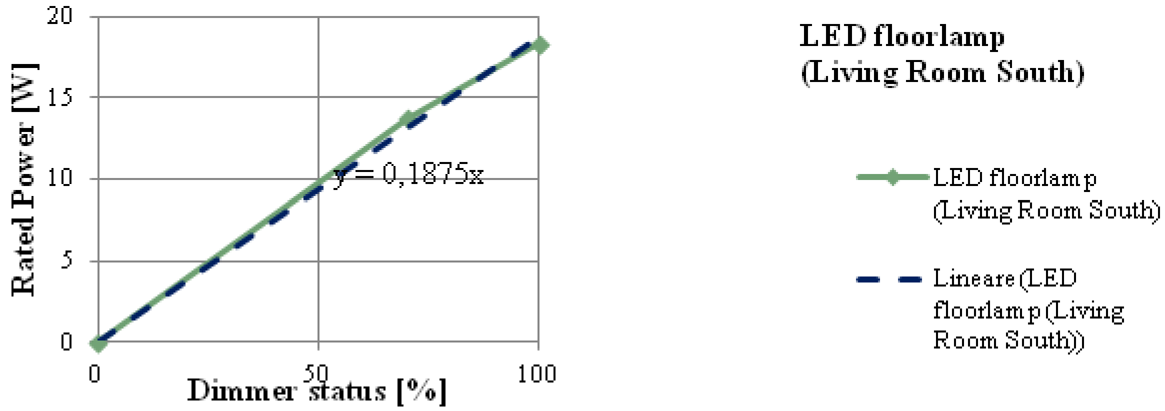


Table 13 LED floorlamp Living Room South

Dimmer Status [%]	Time span [h]	Electric energy meter - Lighting [Wh]	Power [W]
0	0,0000	0	0
70	0,4100	19	14
100	0,3925	20	18

Figure 42 Plot of the dimmer status-Rated power relationship for the LED floorlamp – Living Room South



The same analysis was carried out for the illuminance level evaluated both at ceiling height and on two points of the horizontal plane at 0.90 m above the floor level.

Figure 43 Floor plan in which the point used for manually measuring illuminance are highlighted in blue.

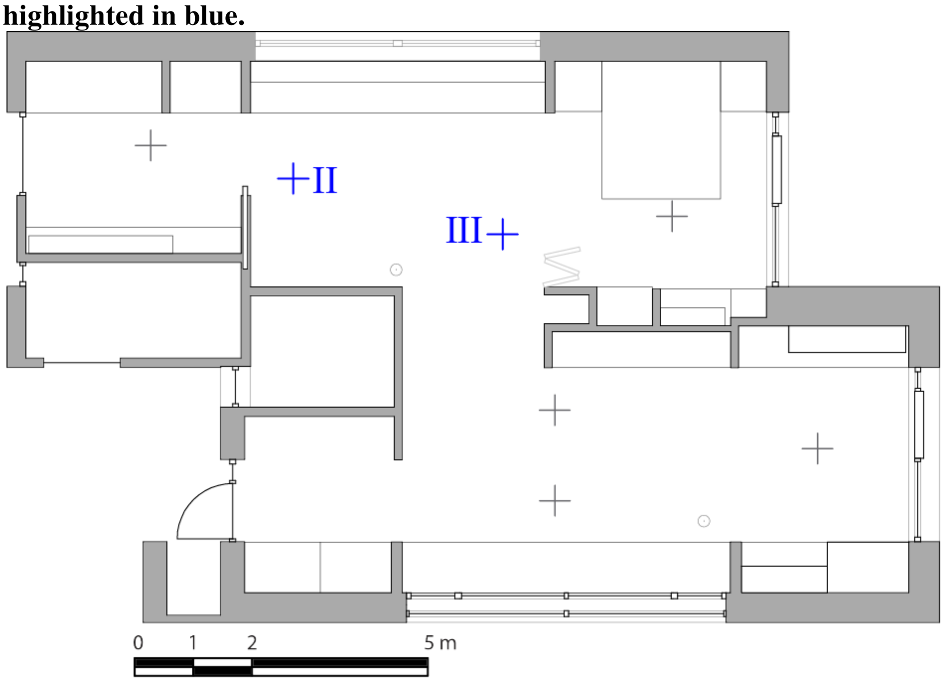


Figure 44 Illuminance-Dimmer Status relationship for LED ceiling Living Room North on the horizontal plane

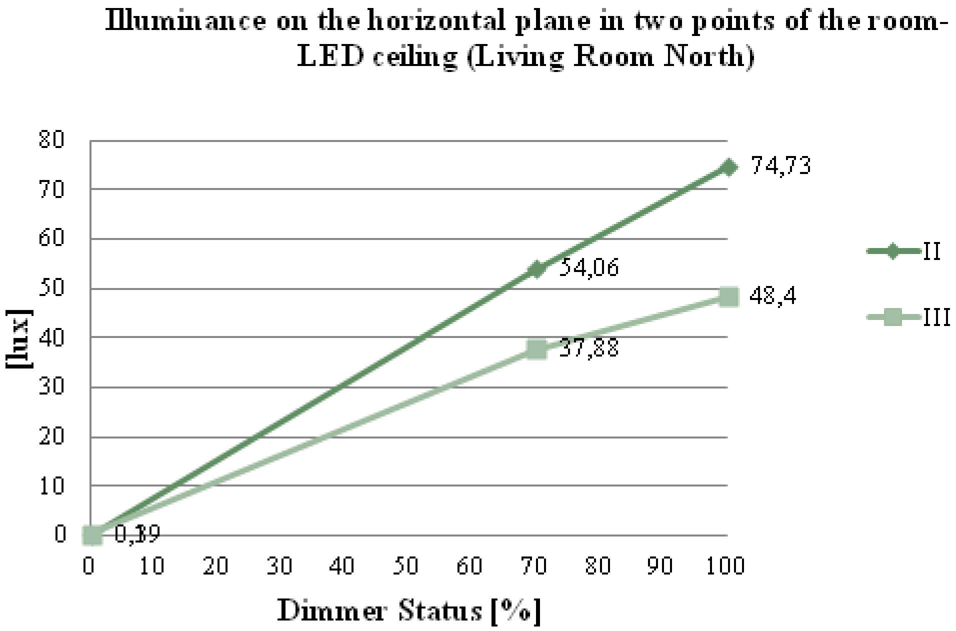


Figure 45 Illuminance-Dimmer Status relationship for LED desk Living Room North on the horizontal plane

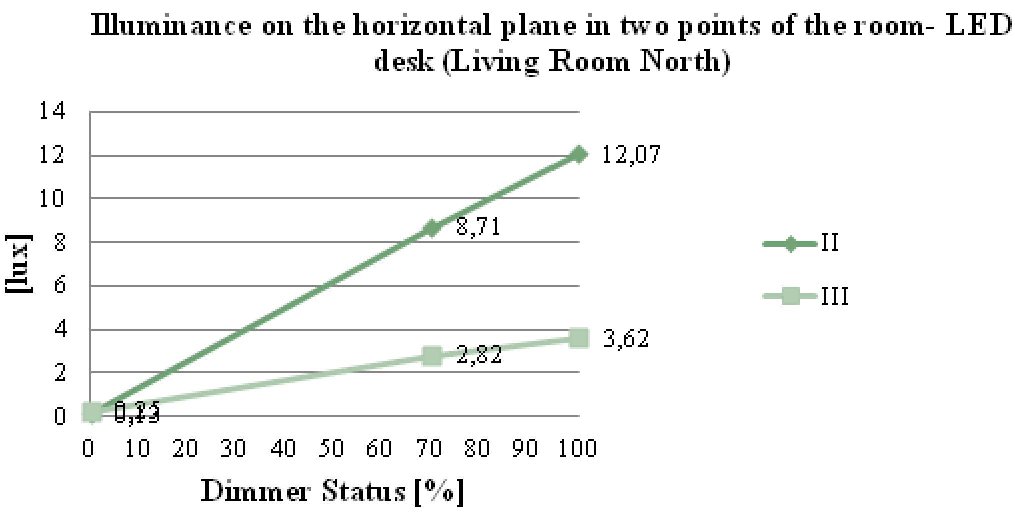


Figure 46 Illuminance-Dimmer Status relationship for LED ceiling Living Room North at ceiling height

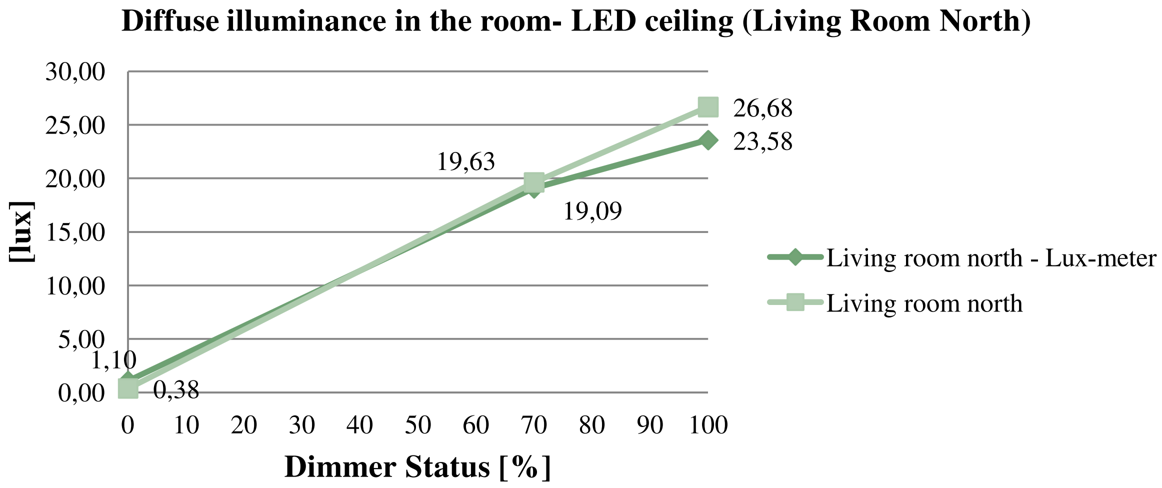
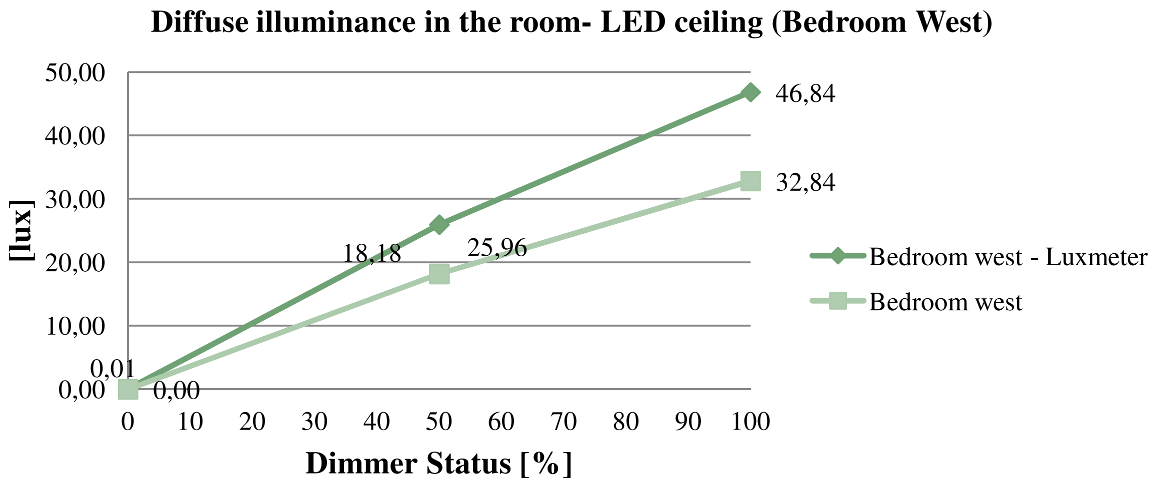


Figure 47 Illuminance-Dimmer Status relationship for LED ceiling Bedroom West at ceiling height



Nevertheless, when considering the power directly proportional to the dimmer status, the difference between the estimated value and the actual measure is always less than the 10% of the rated power for the analyzed lighting. The relative error is always below the 10% which a reasonable margin. Therefore, it was assumed that there is a linear relationship between the power used and the dimming level for all the lighting that constituted the illumination system.

The estimated power was calculated using the results of the second phase, when available, or assuming a direct proportion between the dimming and the power.

Table 14. Numerical model for the estimation of electric energy use for lighting by each lighting source

Nominal power/Dimming Ratio	Calculated	Estimated	Dimmer Satus	Estimated Power [W]
LED external lighting	-	1,37	100	137
LED entrance (ceiling)	-	0,35	100	35
LED entrance (furniture)	-	0,04	100	4
LED living room south (ceiling)	0,715	-	100	72
LED living room south (furniture)	-	0,22	100	22
LED living room south (floor lamp)	0,187	-	100	19
LED kitchen (ceiling)	0,717	-	100	72
LED kitchen (pendant lamp)	0,595	-	100	60
LED kitchen (furniture south)	-	0,05	100	5
LED kitchen (furniture north)	-	0,1	100	10
LED bedroom east (ceiling)	0,833	-	100	83
LED bedroom east (desk)	-	0,43	100	43
LED bedroom east (cabinet)	-	0,01	100	1
LED bedroom east (bed light)	-	0,24	100	24
LED mezzanine	-	0,44	100	44
LED living room north (ceiling)	1	-	100	100
LED living room north (desk)	0,332	-	100	33
LED living room north (lamp)	-	0,03	100	3
LED bathroom	0,367	-	100	37
LED bedroom west (ceiling)	0,754	-	100	75
LED bedroom west (desk)	-	0,02	100	2
LED bedroom west (cabinet)	-	0,02	100	2
LED bedroom west (bedlight)	-	0,22	100	22

The validation of the model was then carried out, as explained in 3.6.1 Model Validation for Electric Lighting.

The table below explains the model and its validation for the Living Room North. In fact, the lighting sources in the first column were switched on at the same time. A random dimming level was associated with each lighting, as reported in the second column. The total estimated power was compared with the actual power used and recorded by the system.

Table 15 Comparison between the measured energy use for lighting and the estimated one for a group of lighting fixtures active in the same time interval.

	Dimmer Status [%]	Rated Power [W]	Light Dimming - Power coefficient	Estimated Power [W]
Light - Living room north ceiling	70	97	1,00	70
Light - Living room north floor lamp	20	3	0,03	1
Light - Living room north desk	50	32	0,302	15
Light - Mezzanine	100	44	0,44	44
			Estimated Used Power	130 W
			Actual Used Power	133 W
				2%

Table 16 Comparison between the measured energy use for lighting and the estimated one for another group of lighting fixtures active in the same time interval.

	Dimmer Status [%]	Rated Power [W]	Light Dimming - Power coefficient	Estimated Power [W]
Light - Living Room South ceiling	40	70	0,703	28
Light – Living Room South (furniture)	100	22	0,22	22
Light - Entrance (furniture)	30	3	0,03	1
Light - Living Room South (floor lamp)	70	19	0,186	13
Light - Kitchen (pendant lamp)	60	58	0,593	35
			Estimated Used Power	99 W
			Actual Used Power	95 W
				4%

This is a rather important result. In fact, knowing the status of the switch of the lighting, it is possible to estimate the energy use by each elements of the lighting system and therefore have reliable information about the electric energy use for lighting in every room.

The dimming status of the switch of each lighting is recorded at the time of the experiment will be multiplied with the corresponding coefficient in order to obtain the estimated energy used by the lighting source in the considered hour.

By superposition, it is possible to obtain the estimated energy used by the lighting sources in the considered room.

Table 17 Example of the estimation of Electric Energy meter for Lighting in the Bedroom East

Bedroom east							
04/12/2015	**Ceiling (Dimmer Status) [%]**	**Desk (Dimmer Status) [%]**	**Cabinet (Dimmer Status) [%]**	**Bedlight (Dimmer Status) [%]**	**Power/ Dimmer ratio (Bedlight)**	**Bedlight [Wh]**	**Electric energy use [Wh]**
12:00 AM	0	0	0	0	0,22	0	0
1:00 AM	0	0	0	0	0,22	0	0
2:00 AM	0	0	0	0	0,22	0	0
3:00 AM	0	0	0	0	0,22	0	0
4:00 AM	0	0	0	0	0,22	0	0
5:00 AM	0	0	0	0	0,22	0	0
6:00 AM	0	0	0	0	0,22	0	0
7:00 AM	0	0	0	0	0,22	0	0
8:00 AM	0	0	0	23	0,22	5	5
9:00 AM	0	0	0	100	0,22	22	22
10:00 AM	0	0	0	100	0,22	22	22
11:00 AM	0	0	0	100	0,22	22	22
12:00 PM	0	0	0	100	0,22	22	22
1:00 PM	0	0	0	100	0,22	22	22
2:00 PM	0	0	0	36	0,22	8	8
3:00 PM	0	0	0	18	0,22	4	4
4:00 PM	0	0	0	0	0,22	0	0
5:00 PM	0	0	0	0	0,22	0	0
6:00 PM	0	0	0	0	0,22	0	0
7:00 PM	0	0	0	0	0,22	0	0
8:00 PM	0	0	0	0	0,22	0	0
9:00 PM	0	0	0	0	0,22	0	0
10:00 PM	0	0	0	0	0,22	0	0
11:00 PM	0	0	0	0	0,22	0	0

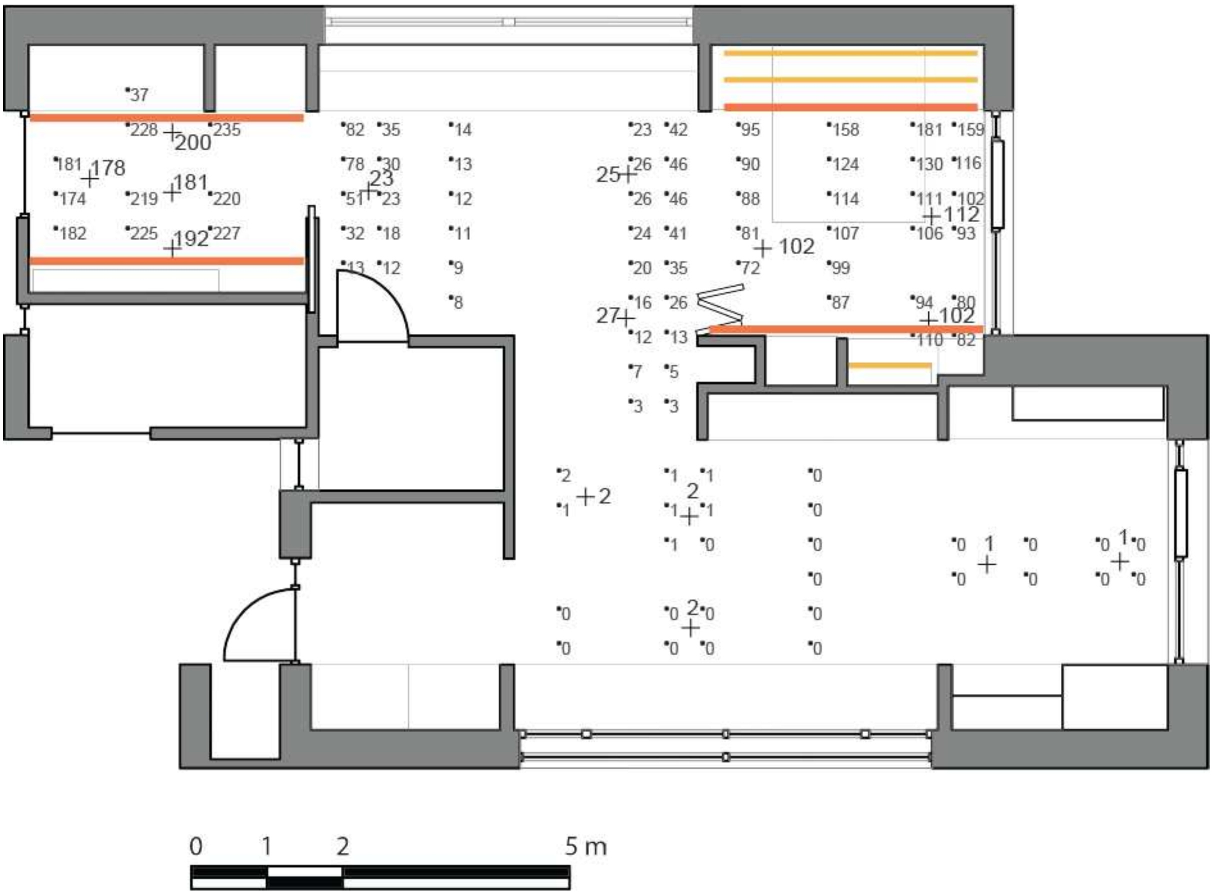
The three-dimensional model was also validated according to a different combination of light sources.

The illuminance map in the next page shows the comparison between the results of the Point-In-Time Illuminance simulation against the value measured with the portable luxmeter, when the lights in the Table 18. Light sources active for model validation were activated.

Table 18. Light sources active for model validation

Light source active	Dimmer Status [%]
LED Bedroom West (ceiling)	100
LED Bedroom East (ceiling)	100
LED Bedroom East (bedlight)	100
LED Bedroom East (desk)	100

Figure 48. Illuminance map of the living lab for the lighting source of table 19.



4.2 Daylight Availability

The model validation phase aims to assess the reliability of the three-dimensional model developed in Rhinoceros and of the simulation outputs.

In this phase, the simulated indoor illuminance values calculated for down facing sensors placed at ceiling height are compared with the measured values sensed by the indoor lux-meter placed at ceiling height and facing downwards in the centre of the rooms taken into consideration.

However, it is necessary to assess the impact of the uncertainty in the simulation input at first. For this purpose a Sensitivity Analysis was carried out in order to understand how the empirical rule used to split the global solar radiation influences the simulation output.

After that, the outputs of the simulations are compared against the collected data, as shown below.

Once the model is proved to be reliable in simulating the variation of the indoor illuminance level throughout the day, it was possible to reconstruct the indoor daylight availability at the time of the experiment.

4.2.1 Sensitivity analysis

The sensitivity analysis was carried out to assess the impact of the model used to distribute the global solar radiation in its two components, direct normal and diffuse, on the output of the dynamic daylight simulations.

The analysis was conducted for the week of April 2016. The results are showed below for one illustrative day. In fact, the results show that the simulation outputs. i.e. illuminance value measured in the room on the horizontal plane, are insensitive to this variation in the simulation inputs, meaning that the variation of the illuminances is under the 10%, which is the simulation accuracy.

Table 19 Global solar radiation, its components and their variation

	+20%		0			-20%	
13/04/2016	**Normal Solar [W/m^2]**	**Diffuse Solar [W/m^2]**	**Global Solar [W/m^2]**	**Diffuse Solar [W/m^2]**	**Normal Solar [W/m^2]**	**Normal Solar [W/m^2]**	**Diffuse Solar [W/m^2]**
12:00 AM	0	0	0	0	0	0	0
1:00 AM	0	0	0	0	0	0	0
2:00 AM	0	0	0	0	0	0	0
3:00 AM	0	0	0	0	0	0	0
4:00 AM	0	0	0	0	0	0	0
5:00 AM	0	0	0	0	0	0	0
6:00 AM	0	6	6	6	0	0	6
7:00 AM	0	33	33	33	0	0	33
8:00 AM	0	76	76	76	0	0	76
9:00 AM	61	192	252	176	76	91	161
10:00 AM	113	270	382	241	141	169	213
11:00 AM	102	253	355	228	128	154	202
12:00 PM	186	379	566	333	233	280	286
1:00 PM	158	338	496	298	198	238	259
2:00 PM	169	353	522	311	211	253	268
3:00 PM	145	316	461	281	181	217	244
4:00 PM	128	291	419	260	160	192	227
5:00 PM	82	223	306	203	103	124	182
6:00 PM	0	67	67	67	0	0	67
7:00 PM	0	37	37	37	0	0	37
8:00 PM	0	13	13	13	0	0	13
9:00 PM	0	0	0	0	0	0	0
10:00 PM	0	0	0	0	0	0	0
11:00 PM	0	0	0	0	0	0	0

Table 20. Outputs of the simulations for the Bedroom west

	+20%		0	-20%	
13/04/2016	**Illuminance diva - BW**		**Illuminance diva - BW**	**Illuminance diva - BW**	
12:00 AM	0		0	0	
1:00 AM	0		0	0	
2:00 AM	0		0	0	
3:00 AM	0		0	0	
4:00 AM	0		0	0	
5:00 AM	0		0	0	
6:00 AM	21	11%	19	18	2%
7:00 AM	106	11%	95	93	2%
8:00 AM	234	11%	211	206	2%
9:00 AM	450	5%	431	458	6%
10:00 AM	589	4%	613	643	5%
11:00 AM	581	2%	595	622	5%
12:00 PM	900	2%	916	993	8%
1:00 PM	987	1%	1002	1066	6%
2:00 PM	1518	2%	1485	1512	2%
3:00 PM	1510	1%	1492	1506	1%
4:00 PM	912	3%	938	1031	10%
5:00 PM	659	4%	690	742	8%
6:00 PM	219	10%	200	196	2%
7:00 PM	105	8%	97	95	2%
8:00 PM	0		0	0	
9:00 PM	0		0	0	
10:00 PM	0		0	0	
11:00 PM	0		0	0	

Figure 49 Diagrams of the outputs of the simulations for the Bedroom west

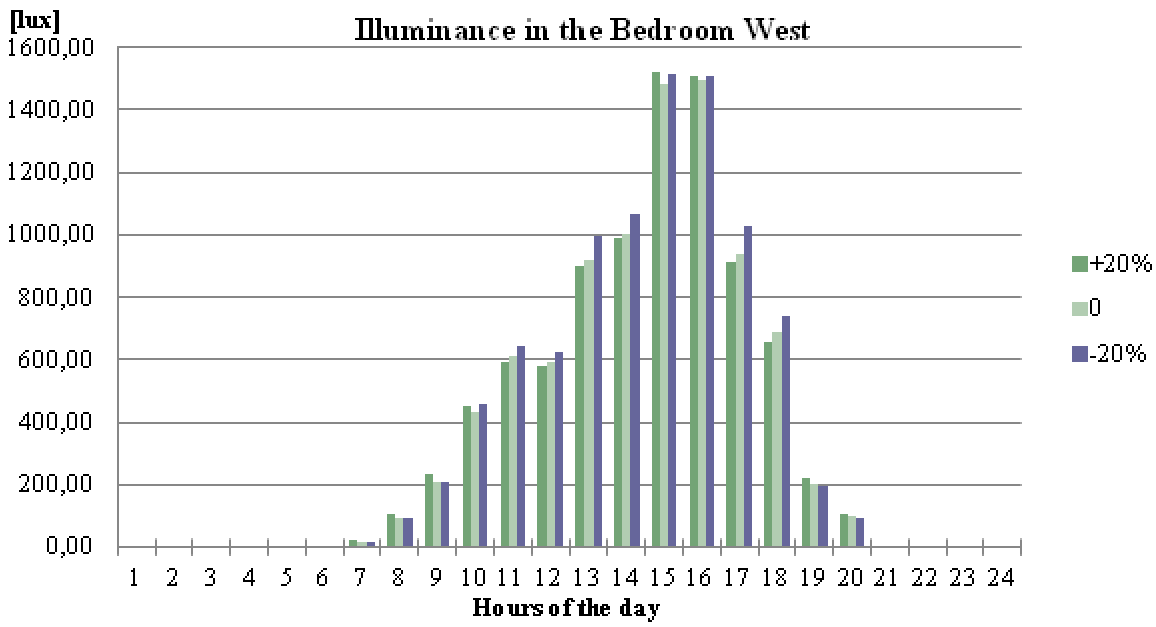


Table 21. Outputs of the simulations for the Bedroom East

	+20%		0	-20%	
13/04/2016	**Illuminance diva - BE**		**Illuminance diva - BE**	**Illuminance diva - BE**	
12:00 AM	0		0	0	
1:00 AM	0		0	0	
2:00 AM	0		0	0	
3:00 AM	0		0	0	
4:00 AM	0		0	0	
5:00 AM	0		0	0	
6:00 AM	12	6%	11	11	3%
7:00 AM	63	6%	59	57	3%
8:00 AM	145	6%	137	133	3%
9:00 AM	419	0%	420	434	3%
10:00 AM	415	4%	433	455	5%
11:00 AM	342	3%	351	370	5%
12:00 PM	421	3%	433	474	9%
1:00 PM	352	4%	367	400	9%
2:00 PM	348	5%	366	392	7%
3:00 PM	316	5%	334	355	6%
4:00 PM	291	8%	317	335	6%
5:00 PM	246	5%	259	272	5%
6:00 PM	101	7%	94	91	3%
7:00 PM	61	4%	58	56	3%
8:00 PM	0		0	0	
9:00 PM	0		0	0	
10:00 PM	0		0	0	
11:00 PM	0		0	0	

Figure 50. Diagrams of the outputs of the simulations for the Bedroom East

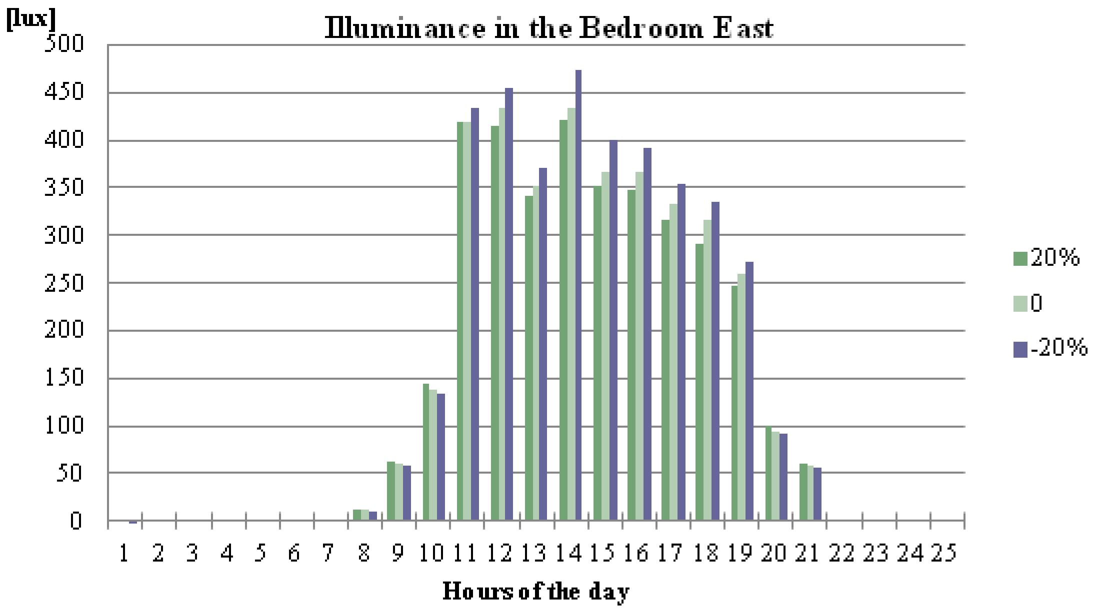
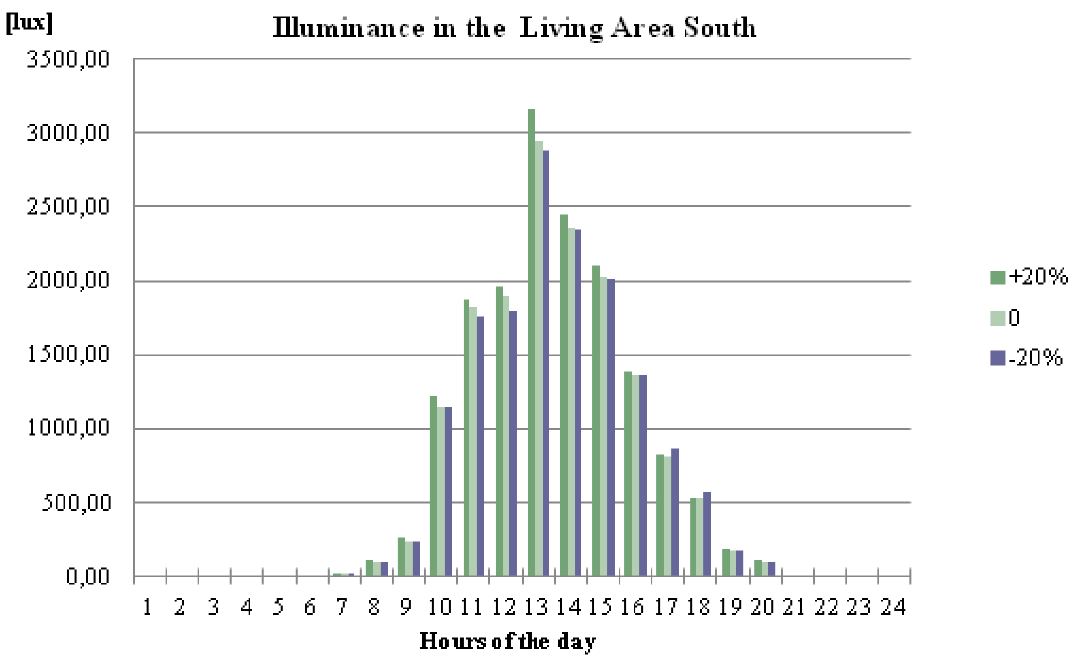


Table 22. Outputs of the simulations for the Living Area South

	+20%		0	-20%	
13/04/2016	Illuminance Living Area South - Diva		Illuminance Living Area South - Diva	Illuminance Living Area South - Diva	
12:00 AM	0		0	0	
1:00 AM	0		0	0	
2:00 AM	0		0	0	
3:00 AM	0		0	0	
4:00 AM	0		0	0	
5:00 AM	0		0	0	
6:00 AM	22	10%	20	20	2%
7:00 AM	115	10%	104	103	1%
8:00 AM	264	10%	240	237	1%
9:00 AM	1225	7%	1143	1152	1%
10:00 AM	1869	3%	1819	1765	3%
11:00 AM	1964	3%	1900	1799	5%
12:00 PM	3160	7%	2945	2888	2%
1:00 PM	2453	4%	2361	2340	1%
2:00 PM	2100	3%	2033	2018	1%
3:00 PM	1386	2%	1358	1363	0%
4:00 PM	824	2%	809	870	7%
5:00 PM	531	0%	533	577	8%
6:00 PM	193	12%	172	170	1%
7:00 PM	107	9%	98	97	1%
8:00 PM	0		0	0	
9:00 PM	0		0	0	
10:00 PM	0		0	0	
11:00 PM	0		0	0	

Figure 51. Diagrams of the outputs of the simulations for the Living Area South



As can be seen in the tables above, by varying the three + 20% and -20% input, it emerges a minimum variation of the outputs and thus concurring to show that the model is not very sensitive to these variations. The sensitivity analysis showed that, at least in the considered period (excluding the summertime), the model is rather insensitive to these differences between direct and diffuse radiation.

4.2.2 Indoor diffuse illuminance

The data collected the 1st of May represents overcast sky condition, in which the global and diffuse solar radiation correspond, instead the direct component of the solar radiation is equal to zero, since no direct solar beam passes through the cloudy sky.

Table 23 Solar radiation – 01/05/2018

01/05/2018	Global Solar [W/m^2]	Diffuse Solar [W/m^2]	Normal Solar [W/m^2]
12:00 AM	0	0	0
1:00 AM	0	0	0
2:00 AM	0	0	0
3:00 AM	0	0	0
4:00 AM	2	2	0
5:00 AM	17	17	0
6:00 AM	47	47	0
7:00 AM	79	79	0
8:00 AM	86	86	0
9:00 AM	108	108	0
10:00 AM	125	125	0
11:00 AM	161	161	0
12:00 PM	181	181	0
1:00 PM	191	191	0
2:00 PM	155	155	0
3:00 PM	218	218	0
4:00 PM	183	183	0
5:00 PM	157	157	0
6:00 PM	182	182	0
7:00 PM	97	97	0
8:00 PM	23	23	0
9:00 PM	3	3	0
10:00 PM	0	0	0
11:00 PM	0	0	0

Figure 52. Diagram of the Global Solar Radiation – 01/05/2018

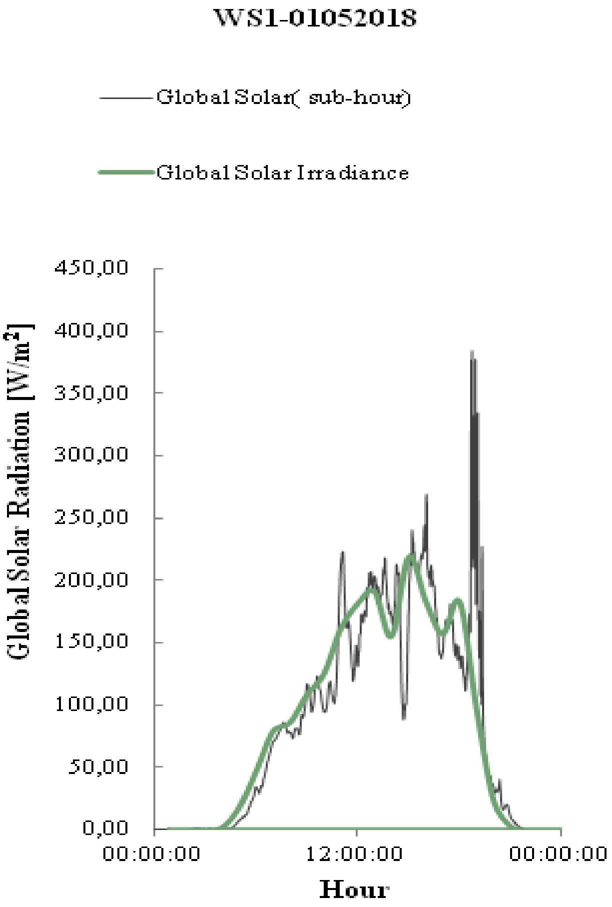


Figure 53.Plot of DIVA-for-Rhino's simulation output and the measured diffuse indoor illuminance in the living room facing south – 01/05/2018

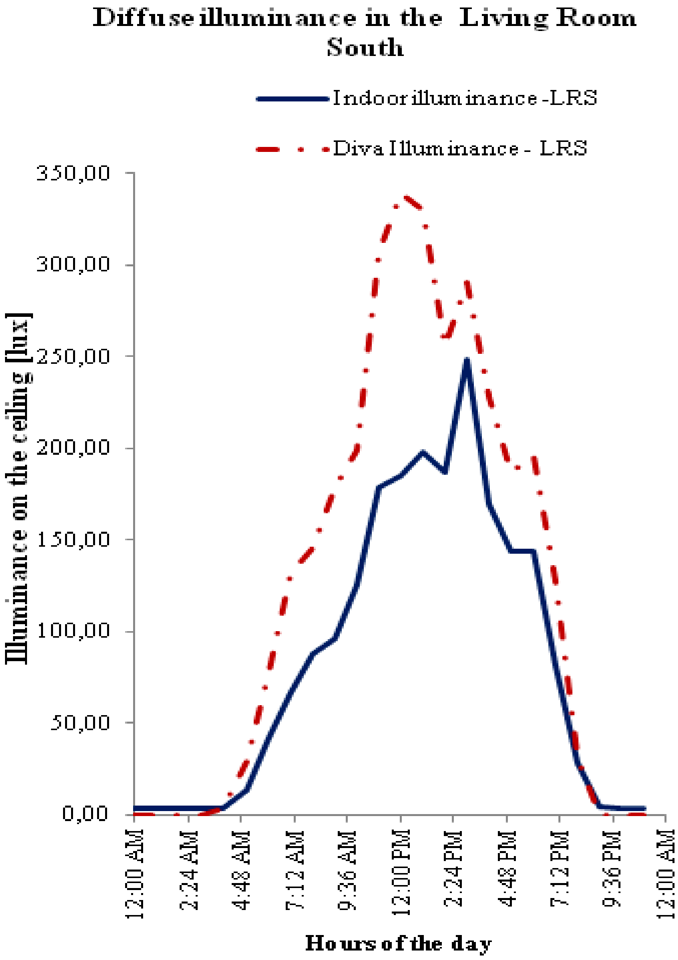


Table 24. DIVA-for-Rhino's simulation output and the measured diffuse indoor illuminance in the living room facing south – 01/05/2018

01/05/2018	Indoor Sensor	Diva Simulation
12:00 AM	3,54	0,00
1:00 AM	3,55	0,00
2:00 AM	3,59	0,00
3:00 AM	3,61	0,00
4:00 AM	3,60	4,00
5:00 AM	13,82	29,00
6:00 AM	42,03	78,00
7:00 AM	67,17	132,00
8:00 AM	87,77	146,00
9:00 AM	95,85	179,00
10:00 AM	125,59	199,00
11:00 AM	178,50	307,00
12:00 PM	185,54	339,00
1:00 PM	198,32	330,00
2:00 PM	187,45	256,00
3:00 PM	248,24	291,00
4:00 PM	169,88	228,00
5:00 PM	143,55	187,00
6:00 PM	143,50	196,00
7:00 PM	81,48	127,00
8:00 PM	28,21	31,00
9:00 PM	4,58	0,00
10:00 PM	3,73	0,00
11:00 PM	3,72	0,00

Figure 54 Plot of DIVA-for-Rhino's simulation output and the measured diffuse indoor illuminance in the kitchen – 01/05/2018

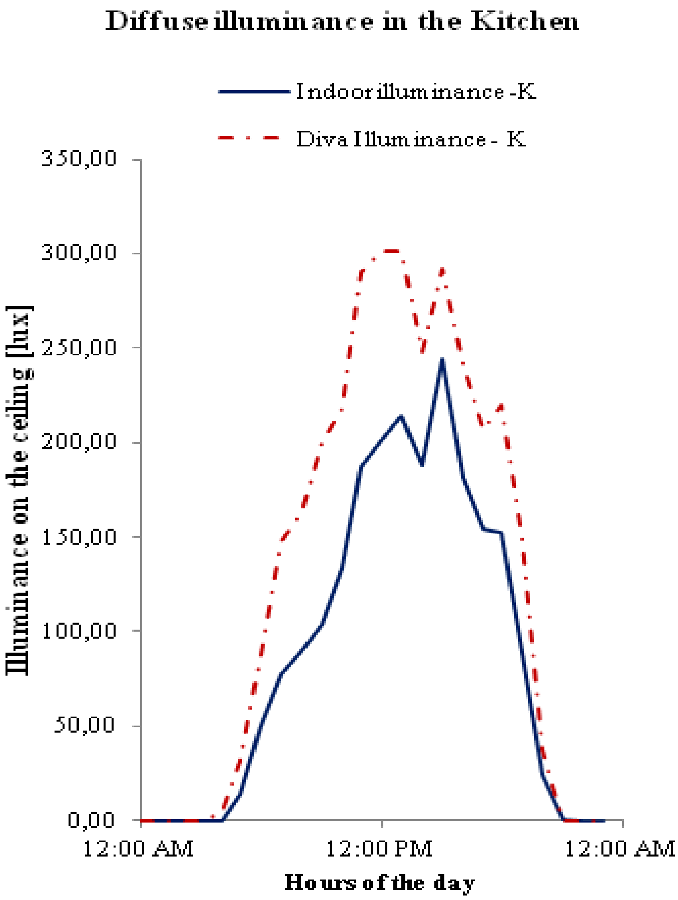


Table 25. DIVA-for-Rhino's simulation output and the measured diffuse indoor illuminance in the kitchen – 01/05/2018

01/05/2018	Indoor Sensor	Diva Simulation
12:00 AM	0,00	0,00
1:00 AM	0,00	0,00
2:00 AM	0,00	0,00
3:00 AM	0,00	0,00
4:00 AM	0,00	4,00
5:00 AM	14,13	32,00
6:00 AM	50,10	88,00
7:00 AM	77,57	148,00
8:00 AM	89,35	163,00
9:00 AM	103,91	200,00
10:00 AM	133,92	218,00
11:00 AM	186,68	290,00
12:00 PM	200,97	301,00
1:00 PM	214,36	301,00
2:00 PM	187,80	248,00
3:00 PM	243,94	292,00
4:00 PM	181,13	241,00
5:00 PM	154,72	207,00
6:00 PM	152,60	220,00
7:00 PM	88,34	149,00
8:00 PM	23,74	37,00
9:00 PM	0,65	0,00
10:00 PM	0,00	0,00
11:00 PM	0,00	0,00

Figure 55. DIVA-for-Rhino's simulation output and the measured diffuse indoor illuminance in the bedroom west – 01/05/2018

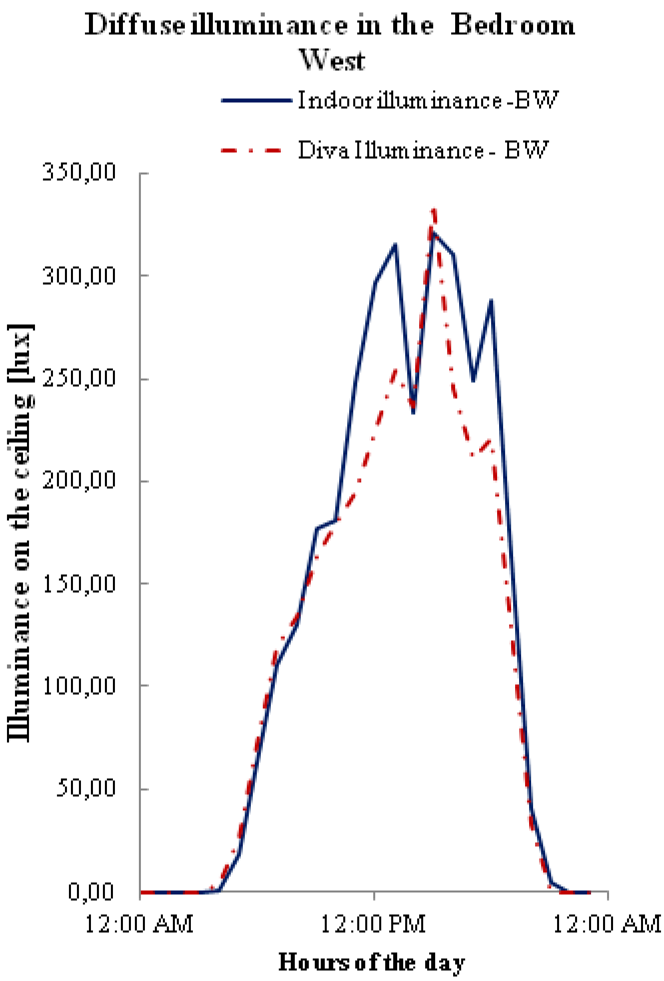


Table 26. DIVA-for-Rhino's simulation output and the measured diffuse indoor illuminance in the bedroom west – 01/05/2018

01/05/2018	Indoor Sensor	Diva Simulation
12:00 AM	0,00	0,00
1:00 AM	0,00	0,00
2:00 AM	0,00	0,00
3:00 AM	0,00	0,00
4:00 AM	0,14	3,17
5:00 AM	18,38	26,33
6:00 AM	62,68	71,33
7:00 AM	110,63	119,17
8:00 AM	130,45	133,67
9:00 AM	177,40	163,17
10:00 AM	180,94	178,83
11:00 AM	247,73	194,17
12:00 PM	296,54	224,50
1:00 PM	315,22	253,83
2:00 PM	233,73	236,67
3:00 PM	320,95	336,00
4:00 PM	310,65	244,67
5:00 PM	249,49	210,83
6:00 PM	287,88	221,00
7:00 PM	163,56	128,33
8:00 PM	40,67	32,33
9:00 PM	4,20	0,00
10:00 PM	0,00	0,00
11:00 PM	0,00	0,00

The data collected the 7th of May represents intermediate sky condition. In this case the empirical rule to distribute the measured values of the global solar radiation in its components, diffuse and direct, was used. The two derived values were introduced in the *EnergyPlus Weather* file and constituted the simulation's inputs.

Table 27. Global Solar Radiation – 07/05/2018- simulation input

07/05/2018	Global Solar [W/m^2]	Diffuse Solar [W/m^2]	Normal Solar [W/m^2]
12:00 AM	0	0	0
1:00 AM	0	0	0
2:00 AM	0	0	0
3:00 AM	0	0	0
4:00 AM	1	1	0
5:00 AM	12	12	0
6:00 AM	31	31	0
7:00 AM	40	40	0
8:00 AM	76	76	0
9:00 AM	47	47	0
10:00 AM	90	90	0
11:00 AM	216	158	58
12:00 PM	313	206	106
1:00 PM	477	289	189
2:00 PM	491	296	196
3:00 PM	413	256	156
4:00 PM	459	279	179
5:00 PM	405	252	152
6:00 PM	276	188	88
7:00 PM	117	109	9
8:00 PM	44	44	0
9:00 PM	9	9	0
10:00 PM	1	1	0
11:00 PM	0	0	0

Figure 56 Global Solar Radiation – 07/05/2018

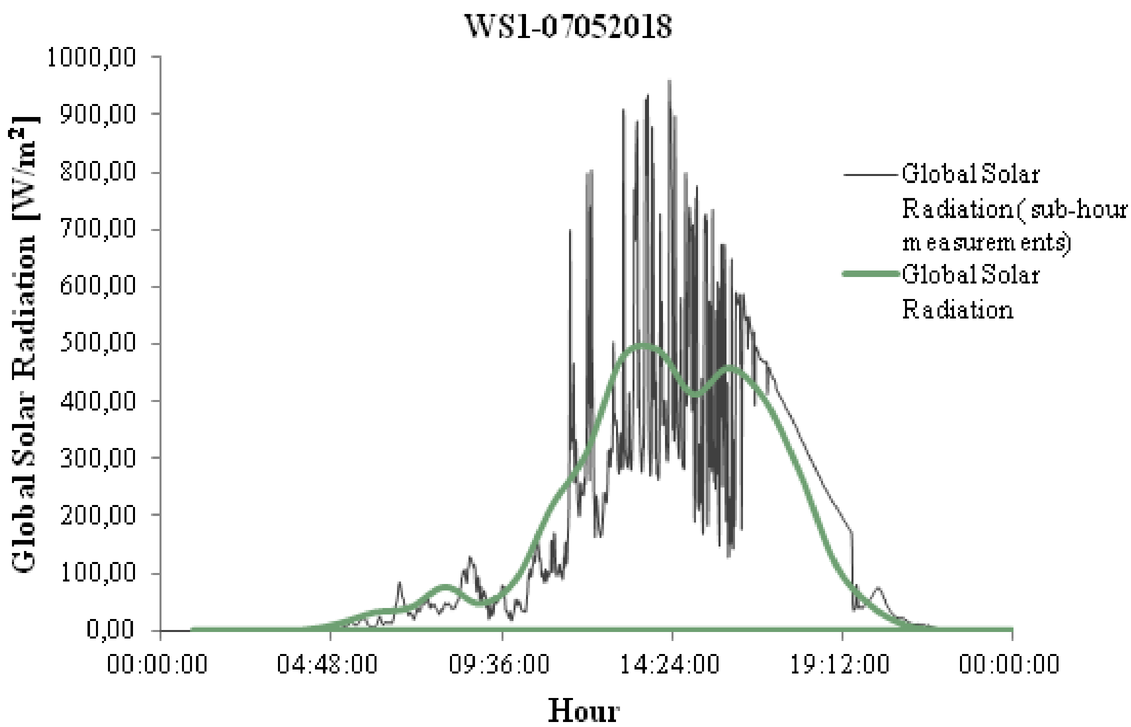


Figure 57. DIVA-for-Rhino's simulation output and the measured diffuse indoor illuminance in the living room facing south

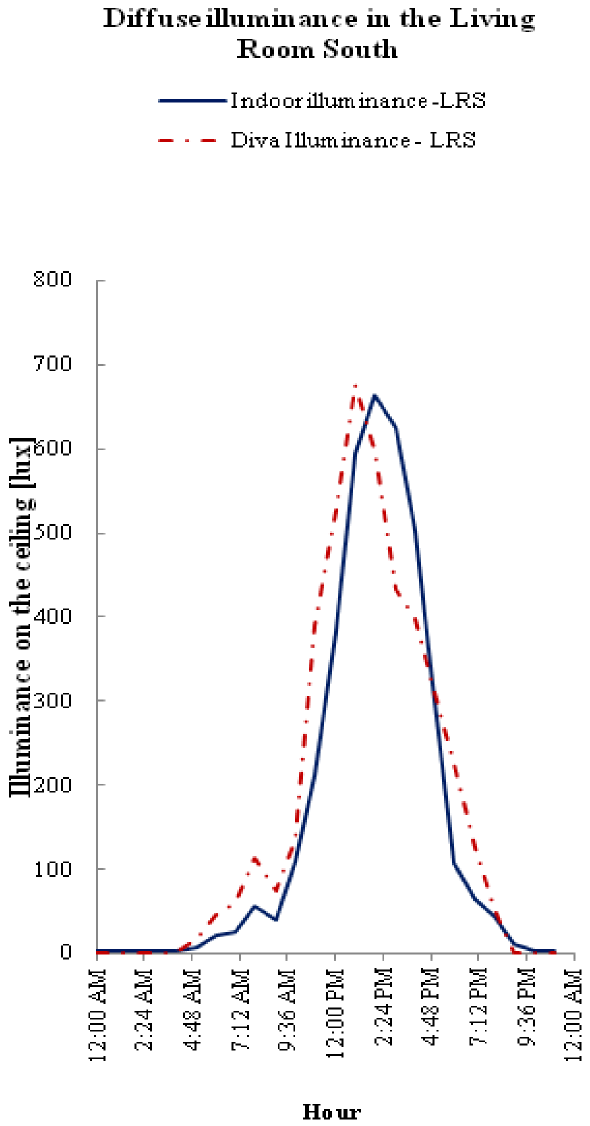


Table 28. DIVA-for-Rhino's simulation output and the measured diffuse indoor illuminance in the living room

07/05/2018	Indoor Sensor	Diva Simulation
12:00 AM	4	0
1:00 AM	4	0
2:00 AM	4	0
3:00 AM	4	0
4:00 AM	4	0
5:00 AM	7	18
6:00 AM	21	47
7:00 AM	25	61
8:00 AM	56	114
9:00 AM	40	74
10:00 AM	110	137
11:00 AM	212	389
12:00 PM	383	526
1:00 PM	594	677
2:00 PM	665	599
3:00 PM	624	433
4:00 PM	502	397
5:00 PM	299	309
6:00 PM	107	225
7:00 PM	64	126
8:00 PM	43	53
9:00 PM	12	0
10:00 PM	4	0
11:00 PM	4	0

Figure 58. Plot of DIVA-for-Rhino's simulation output and the measured diffuse indoor illuminance in the kitchen

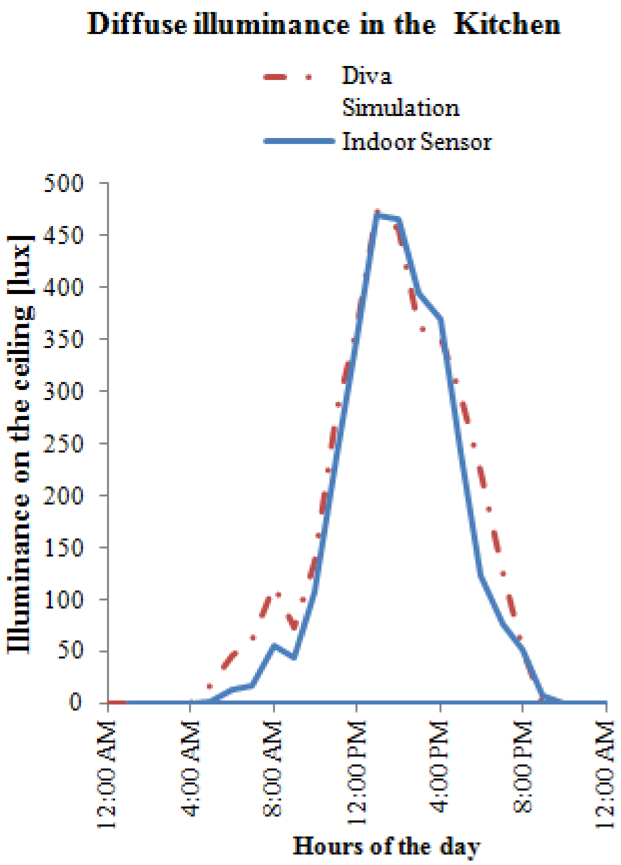


Table 29. DIVA-for-Rhino's simulation output and the measured diffuse indoor illuminance

07/05/2018	Indoor Sensor	Diva Simulation
12:00 AM	0	0
1:00 AM	0	0
2:00 AM	0	0
3:00 AM	0	0
4:00 AM	0	0
5:00 AM	2	18
6:00 AM	14	47
7:00 AM	18	61
8:00 AM	56	113
9:00 AM	45	73
10:00 AM	107	137
11:00 AM	239	281
12:00 PM	351	361
1:00 PM	469	474
2:00 PM	466	456
3:00 PM	394	363
4:00 PM	369	352
5:00 PM	242	297
6:00 PM	122	223
7:00 PM	76	126
8:00 PM	51	53
9:00 PM	9	0
10:00 PM	0	0
11:00 PM	0	0

Figure 59. Plot of DIVA-for-Rhino's simulation output and the measured diffuse indoor illuminance sensed by the lux- meter in the bedroom west.

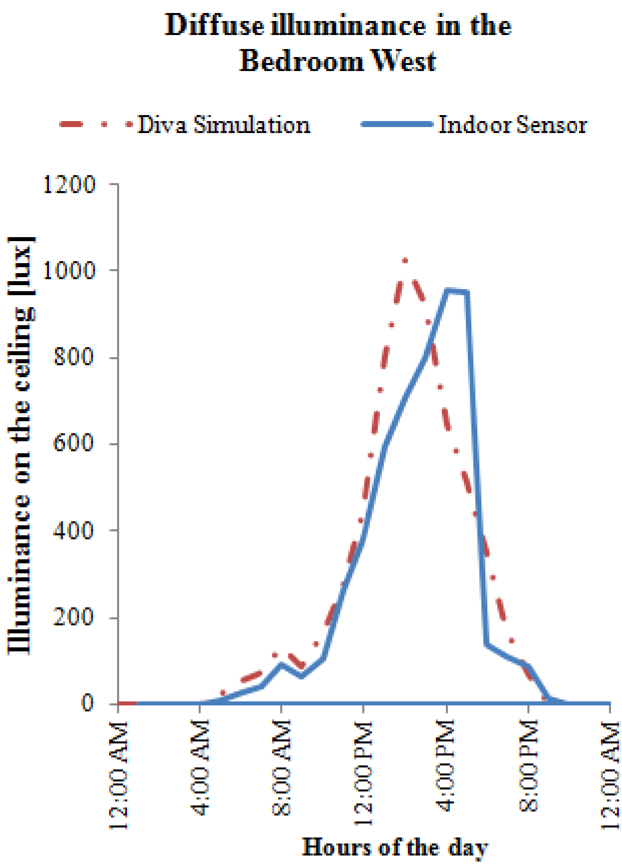


Table 30. DIVA-for-Rhino's simulation output and the measured diffuse indoor illuminance

07/05/2018	Indoor Sensor	Diva Simulation
12:00 AM	0	0
1:00 AM	0	0
2:00 AM	0	0
3:00 AM	0	0
4:00 AM	0	0
5:00 AM	8	22
6:00 AM	28	55
7:00 AM	42	73
8:00 AM	94	135
9:00 AM	64	89
10:00 AM	107	164
11:00 AM	263	275
12:00 PM	381	446
1:00 PM	594	802
2:00 PM	707	1024
3:00 PM	800	921
4:00 PM	956	646
5:00 PM	949	512
6:00 PM	139	352
7:00 PM	111	170
8:00 PM	87	67
9:00 PM	15	0
10:00 PM	0	0
11:00 PM	0	0

The data collected the 9th of May represents clear sky condition. In this case the empirical rule to distribute the measured values of the global solar radiation in its components, diffuse and direct, was used. The two derived values were introduced in the *EnergyPlus Weather* file and constituted the simulation's inputs. The indoor sensors, however, sense only illuminance below 1000 lux, therefore the peak of illuminance calculated with DIVA-for-Rhino connot be compared against the measured values. Moreover, the indoor sensors sensed a descreasing in the illuminance level between 8:00AM and 12:00AM that is not measured by the outdoor sensor, therefore indoor illuminance values simulated with DIVA-for-Rhino do not calculate this anomaly.

Table 31. Global, Diffuse and Direct Solar Radiation on the 9th of May 2018

09/05/2018	Global Solar [W/m²]	Diffuse Solar [W/m²]	Normal Solar [W/m²]
12:00 AM	0	0	0
1:00 AM	0	0	0
2:00 AM	0	0	0
3:00 AM	0	0	0
4:00 AM	3	3	0
5:00 AM	16	16	0
6:00 AM	75	75	0
7:00 AM	225	162	62
8:00 AM	344	222	122
9:00 AM	456	278	178
10:00 AM	552	326	226
11:00 AM	612	356	256
12:00 PM	657	378	278
1:00 PM	670	385	285
2:00 PM	651	375	275
3:00 PM	599	349	249
4:00 PM	517	309	209
5:00 PM	405	252	152
6:00 PM	275	188	88
7:00 PM	121	111	11
8:00 PM	28	28	0
9:00 PM	10	10	0
10:00 PM	0	0	0
11:00 PM	0	0	0

Figure 60. Global Solar Radiation on the 9th of May 2015

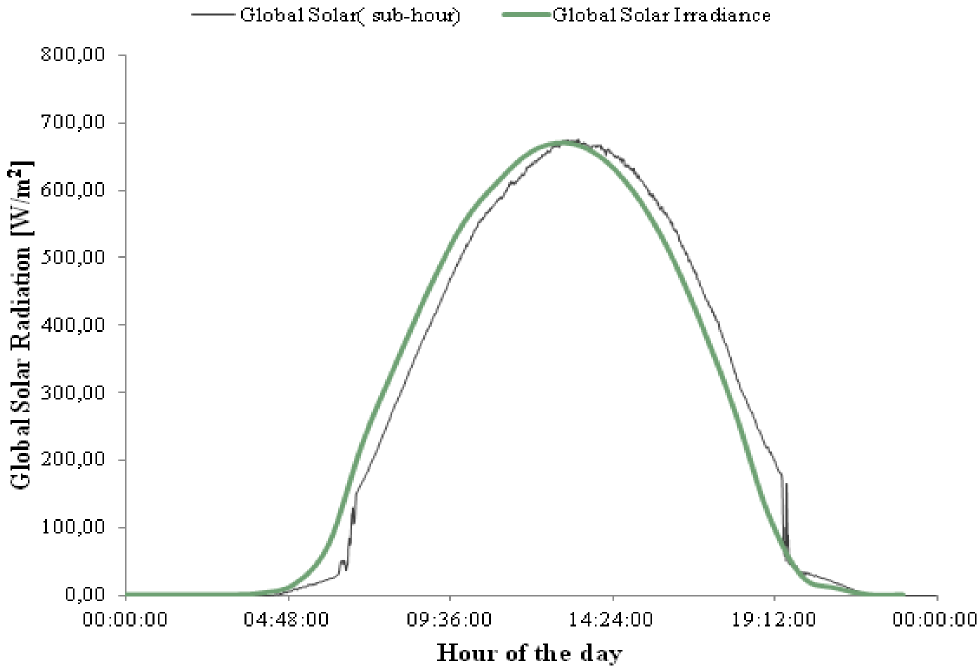


Figure 61. Plot of DIVA-for-Rhino's simulation outputs, the measured diffuse indoor illuminance sensed by the lux- meter and the measured global solar radiation in the living area

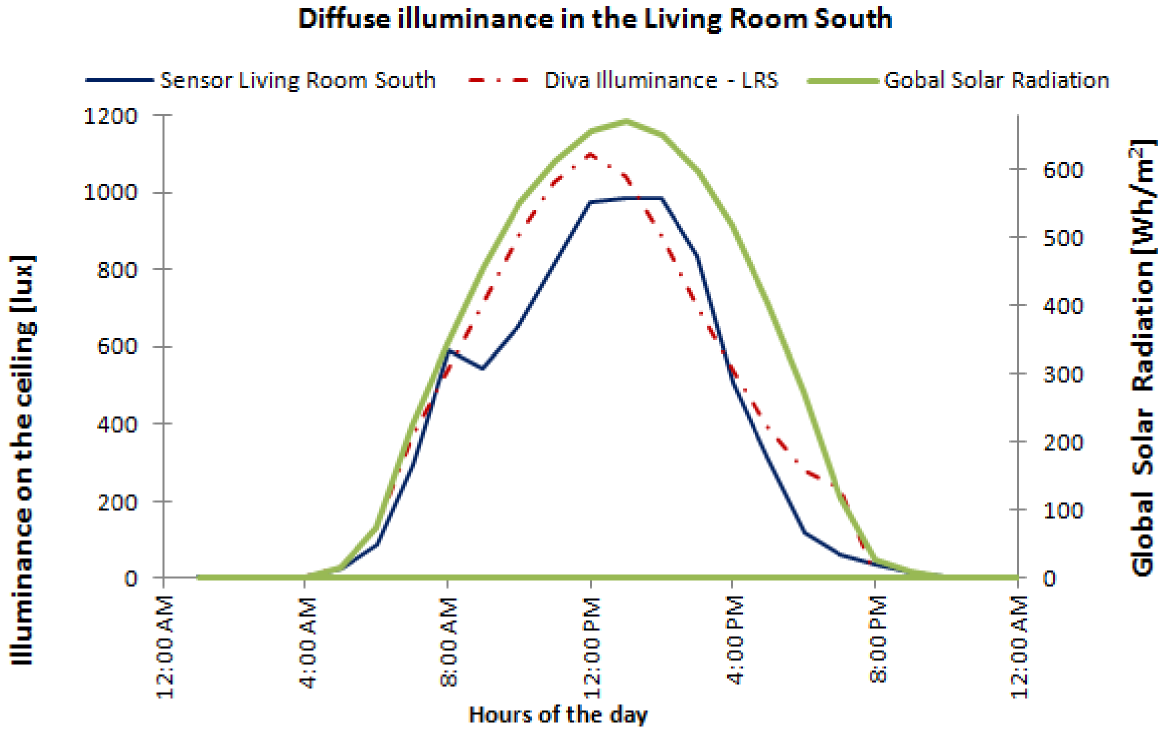


Figure 62. Plot of DIVA-for-Rhino's simulation outputs, the measured diffuse indoor illuminance sensed by the lux- meter and the measured global solar radiation in the bedroom west

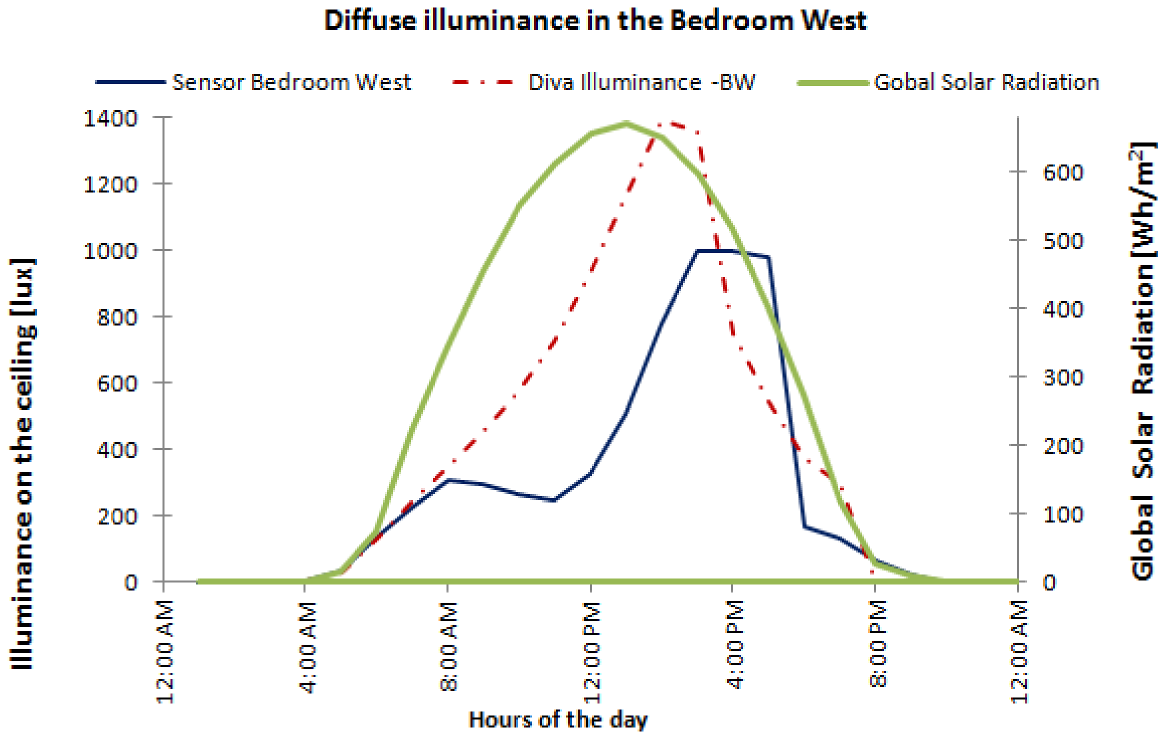


Table 32 Living Room South and Bedroom West- Illuminance value on the ceiling measured by the sensor and simulated with DIVA-for-Rhino

Living Room South			Bedroom West		
09/05/2018	**Indoor Sensor**	**DIVA simulation**	**09/05/2018**	**Indoor Sensor**	**Diva Simulation**
12:00 AM	3,35	0	12:00 AM	0,00	0
1:00 AM	3,33	0	1:00 AM	0,00	0
2:00 AM	3,32	0	2:00 AM	0,00	0
3:00 AM	3,35	0	3:00 AM	0,00	0
4:00 AM	6,12	6,0	4:00 AM	4,34	6
5:00 AM	27,70	30,2	5:00 AM	36,27	31
6:00 AM	87,25	133,3	6:00 AM	137,02	132
7:00 AM	295,32	372,6	7:00 AM	230,55	249
8:00 AM	589,62	545,9	8:00 AM	310,82	352
9:00 AM	545,63	707,4	9:00 AM	297,26	453
10:00 AM	651,76	885,3	10:00 AM	262,89	576
11:00 AM	814,38	1027,7	11:00 AM	245,02	728
12:00 PM	976,35	1100,9	12:00 PM	328,10	928
1:00 PM	984,66	1039,3	1:00 PM	509,35	1161
2:00 PM	984,56	883,9	2:00 PM	777,40	1391
3:00 PM	836,66	707,0	3:00 PM	1000,00	1360
4:00 PM	508,46	541,2	4:00 PM	1000,00	752
5:00 PM	304,63	387,7	5:00 PM	980,38	544
6:00 PM	119,06	281,4	6:00 PM	171,05	376
7:00 PM	60,82	231,7	7:00 PM	131,33	294
8:00 PM	38,61	0,0	8:00 PM	69,26	0
9:00 PM	14,02	0,0	9:00 PM	21,53	0
10:00 PM	3,18	0,0	10:00 PM	0,21	0
11:00 PM	3,21	0,0	11:00 PM	0,00	0

The tables and the charts above show a good resemblance between the simulated values and the experimental measurements. However, in clear sky days, such as the 9th of May 2018, the resemblance gets weaker. Between 10 AM and 12 AM the indoor lux-meters sensed a decrease in the illuminance. But, this was not captured by the outdoor pyranometer. In fact, the global solar radiation diagram is similar to a typical diagram of solar radiation for clear sky condition. Therefore, the simulated values of illuminance follow the same trend. Moreover, the indoor lux-meters do not sense values above 1000 lux, that is the reason why the top-value simulated is not similar to the highest value recorded.

Approximations in the solar position used by Daysim are accountable for the differences between the simulations and the measures data.

Except for that, for the purpose of this study, the model was proved reliable for the simulation of the indoor illuminances, since it simulates with a good approximation the trend of variation of the illuminances in the indoor environment.

4.2.3 Indoor illuminance distribution at the time of the residential experiment

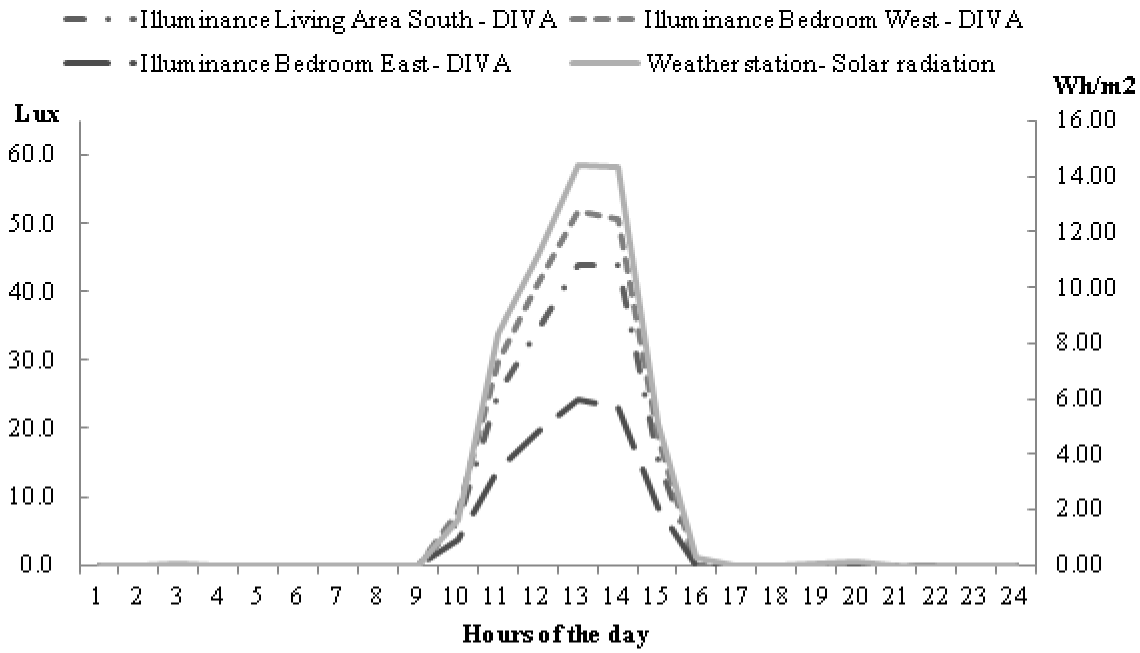
Once the models are proved reliable, it is possible to use them to reproduce the indoor illuminances at the time of the residential experiment.

To provide an example, the results obtained for the 27th of November 2015 are shown below. The global solar radiation recoded is distributed between the two components of diffuse and direct radiations, according to the model explained in the paragraph 3.3.3 Solar Radiation. This information was the input DIVA-for-Rhino's Daylight Autonomy simulations. For every room, a horizontal grid of up facing sensors evenly distributed across the plane at 0.85m height from the floor level was set. The simulations return the annual illuminance profile for each point of the grid. Then, for every hour of the day, the average illuminance across the plane of the considered rooms was calculated.

Table 33 Global Solar radiation, its components and DIVA-For-Rhino Output

	INPUT			OUTPUT		
27/11/2015	**Global Solar radiation [W/m2]**	**Direct Solar radiation [W/m2]**	**Diffuse Solar radiation [W/m2]**	**Bedroom East – DIVA [lux]**	**Bedroom West - DIVA [lux]**	**Living Area South - DIVA [lux]**
12:00 AM	0	0	0	0,00	0,0	0,0
1:00 AM	0	0	0	0,00	0,0	0,0
2:00 AM	0	0	0	0,00	0,0	0,0
3:00 AM	0	0	0	0,00	0,0	0,0
4:00 AM	0	0	0	0,00	0,0	0,0
5:00 AM	0	0	0	0,00	0,0	0,0
6:00 AM	0	0	0	0,00	0,0	0,0
7:00 AM	0	0	0	0,00	0,0	0,0
8:00 AM	0	0	0	0,00	0,0	0,0
9:00 AM	2	0	2	3,76	7,9	6,4
10:00 AM	8	0	8	14,13	29,8	25,0
11:00 AM	11	0	11	19,47	41,3	34,4
12:00 PM	14	0	14	24,19	51,8	43,8
1:00 PM	14	0	14	23,21	50,7	43,9
2:00 PM	5	0	5	8,55	18,6	15,5
3:00 PM	0	0	0	0,00	0,0	0,0
4:00 PM	0	0	0	0,00	0,0	0,0
5:00 PM	0	0	0	0,00	0,0	0,0
6:00 PM	0	0	0	0,00	0,0	0,0
7:00 PM	0	0	0	0,00	0,0	0,0
8:00 PM	0	0	0	0,00	0,0	0,0
9:00 PM	0	0	0	0,00	0,0	0,0
10:00 PM	0	0	0	0,00	0,0	0,0
11:00 PM	0	0	0	0,00	0,0	0,0

Figure 63. Plot of the global solar radiation and DIVA-for-Rhino's simulation outputs on the 27/11/2015



4.3 Correlations

The information derived from the daylight simulations and the numerical models for electric lighting were related in order to assess the Pearson's coefficient.

The Pearson coefficient $\boldsymbol{r}$ gives an understanding of the strength and direction of the linear relationship between two variables. In fact, it can take only values between -1 and +1. The sign, + or -, indicates direct or inverse correlation respectively, whereas the magnitude of the coefficient indicates the strength of the correlation. In general, it is possible to have a strong, a medium and a weak correlation. The range of values that defines if the correlation is strong or weak is not universally defined. Several authors have identified different ranges and they are all quite differing. In this study, in order to have continuity with the previous study about daylight availability in relation to electric energy demand carried out by Esposito (2017) and Lobaccaro et al. (2017) and be able to compare the results, the following criteria will be used to assess the strength of the correlation:

- Strong correlation $|\boldsymbol{r}|$ = 0.50 to 1.0
- Medium correlation $|\boldsymbol{r}|$ = 0.30 to 0.49
- Weak correlation $|\boldsymbol{r}|$ = 0.10 to 0.29

The correlation coefficient is calculated using the Pearson Excel's function, in which:

$$\boldsymbol{r} = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}}$$

Where $\bar{x}$ and $\bar{y}$ are the values corresponding respectively to Average (matrix1) and Average (matrix2) of the average sample. For the purpose of the study, the relationship is assess only during the daylight hours of the day, meaning that only the hours in which the illuminance is above zero are considered.

The hourly values of the daylight availability are calculated on the horizontal plane at 0.85 cm from the floor level for a grid of up facing sensors evenly distributed across the plane in every room taken into consideration.

Figure 64. Output of the Daylight Autonomy simulation for the Living Area South showing the distribution of the nodes

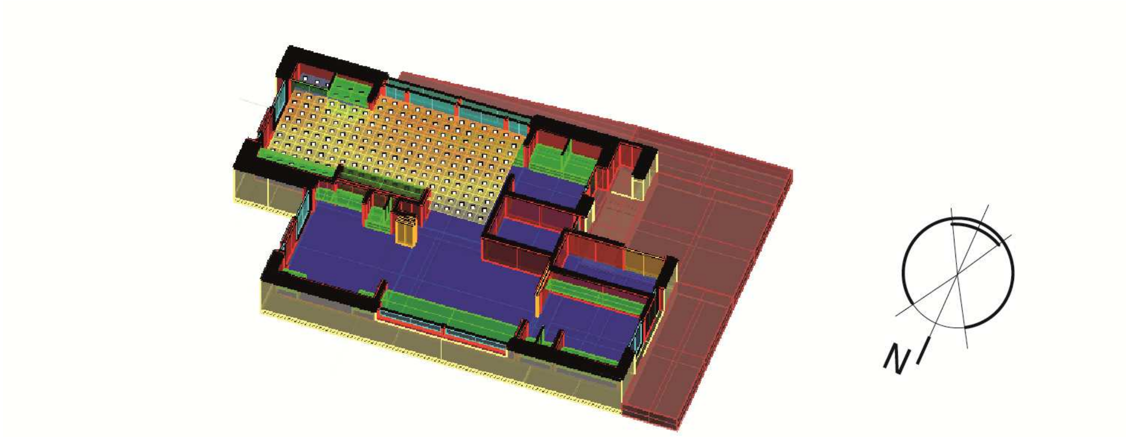
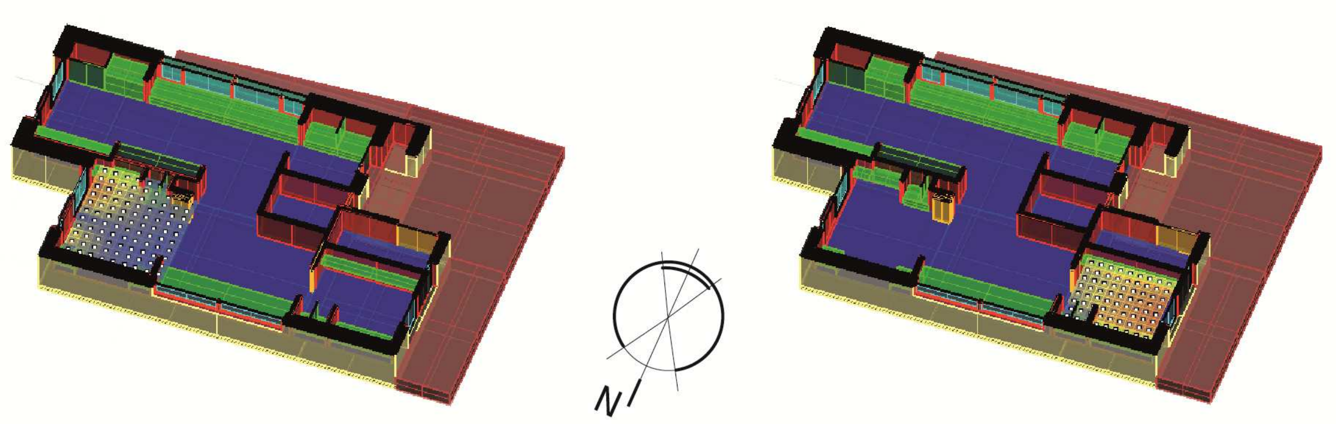


Figure 65. Outputs of the Daylight Autonomy simulations carried out for the bedrooms separately showing the nodes distribution



The pictures above show the outputs of the Daylight Autonomy simulations carried out with DIVA-for-Rhino for the rooms taken into consideration. DIVA-for-Rhino calculates the illuminance values in each point of the grid for every hour of the year, which is the Annual Illuminance Profile.

For every hour of the days taken into consideration, the spatial distribution of the illuminance values is summarized into one value of average illuminance. When this value is above zero, therefore only when the indoor illuminance due to natural light only is available, the average illuminance is related to the electric energy use for lighting calculated in the room in the same hour.

Table 34. The electric energy use for lighting (X) and the average illuminance level (Y) calculated every hour of Day 1 of the week of March 2016

Day 1 – Week of March 2016

Hours [h]	X [Wh]	Y[lux]
12:00 AM	0	0,00
1:00 AM	0	0,00
2:00 AM	0	0,00
3:00 AM	0	0,00
4:00 AM	0	0,00
5:00 AM	0	0,00
6:00 AM	0	0,00
7:00 AM	0	49,95
8:00 AM	0	315,90
9:00 AM	0	920,95
10:00 AM	0	1381,85
11:00 AM	0	1820,66
12:00 PM	0	2131,62
1:00 PM	0	1850,56
2:00 PM	0	1346,84
3:00 PM	0	740,67
4:00 PM	0	100,06
5:00 PM	69	49,85
6:00 PM	202	0,00
7:00 PM	63	0,00
8:00 PM	23	0,00
9:00 PM	23	0,00
10:00 PM	16	0,00
11:00 PM	0	0,00
	r = - 0,392	

Figure 66. Plot of the illuminance values simulated with DIVA-for-Rhino against the electric energy use on day 1, for the family group

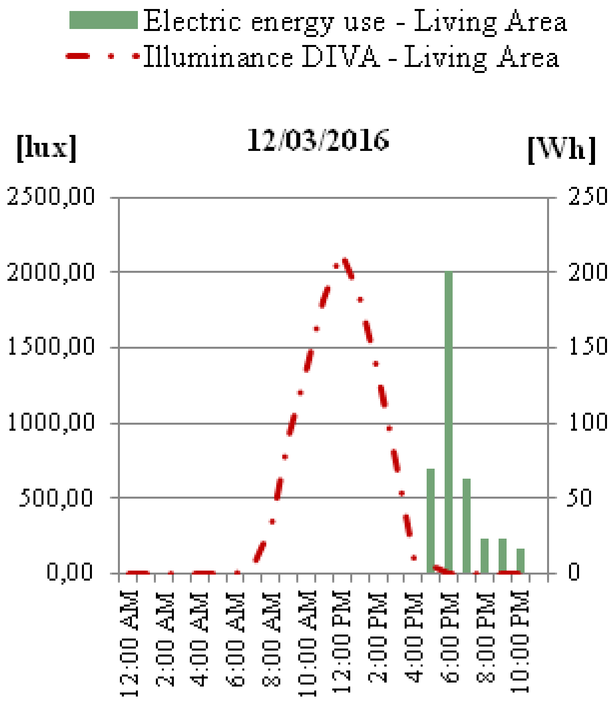
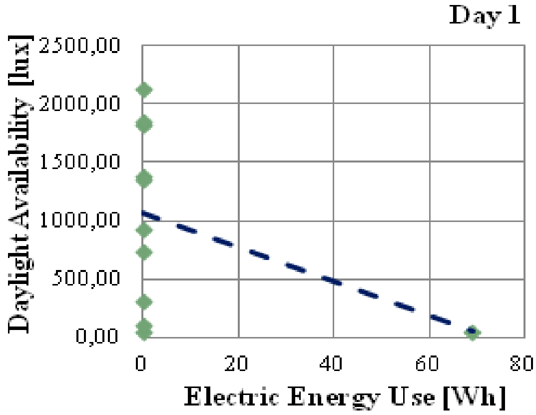


Figure 67. Scatter Plot - Correlation between Electric Energy Meter and Hour Illuminance



X = Electric energy use for Lighting in the Living Area
Y = Average Indoor Illuminance simulated with DIVA-for-Rhino in the Living Area

The Pearson Excel's function uses only the highlighted values, shown in the Table 34. The electric energy use for lighting (X) and the average illuminance level (Y) calculated every hour of Day 1 of the week of March 2016, to assess the Pearson's coefficient and returns **r** value ranging from 0 to ±1.

Table 35 Table of results: Pearson's coefficient calculated for the two bedrooms and the open space of the living area facing south. Highlighted: in bold the strong correlation values, in red the positive ones. N/A values mean that there is no electric lighting energy use in the daylight hours of the day.

Period of year	**Users**	**Day**	**Pearson Correlation Coefficient *r***		
			Living Area South	Bedroom West	Bedroom East
from November, the 27th to December, the 4th 2015	Couple of students	Day 1	N/A	N/A	N/A
		Day 2	0,324	**0,565**	-0,040
		Day 3	0,300	0,385	**0,673**
		Day 4	-0,392	-0,431	-0,420
		Day 5	-0,271	-0,302	-0,279
		Day 6	0,021	-0,066	-0,147
		Day 7	-0,473	N/A*	**-0,770**
		Day 8	**0,579**	0,126	**0,545**
From the 18th to the 24th of January 2016	Family with two children	Day 1	N/A	N/A	N/A
		Day 2	N/A	N/A	N/A
		Day 3	N/A	N/A	N/A
		Day 4	N/A	N/A	N/A
		Day 5	N/A	N/A	N/A
		Day 6	**0,599**	N/A	N/A
		Day 7	-0,485	N/A	N/A
from the 9th to the 15th of February 2016	Retired couple	Day 1	**-0,574**	N/A	N/A
		Day 2	**-0,589**	N/A	**-0,573**
		Day 3	**-0,575**	N/A	N/A
		Day 4	**-0,761**	N/A	N/A
		Day 5	**-0,771**	N/A	**-0,588**
		Day 6	**-0,732**	N/A	N/A
		Day 7	-0,380	N/A	-0,274
from 12 to 18 March 2016	Family with two children	Day 1	-0,392	-0,460	N/A
		Day 2	0,192	N/A	N/A
		Day 3	-0,435	-0,473	-0,348
		Day 4	-0,356	**-0,503**	N/A
		Day 5	-0,473	-0,477	-0,429
		Day 6	-0,367	-0,415	-0,248
		Day 7	0,128	-0,192	0,033
from 11 to 17 April 2016	Retired couple	Day 1	0,172	N/A	N/A
		Day 2	N/A	N/A	0,455
		Day 3	-0,329	N/A	N/A
		Day 4	**-0,629**	N/A	N/A
		Day 5	-0,467	N/A	N/A
		Day 6	-0,052	N/A	N/A
		Day 7	-0,282	0,556	N/A

The table in the previous page summarizes the results obtained. The Pearson's coefficient was calculated for the thirty-six days taken into consideration and for all the three different area of the house considered. For the one representative week considered for each group, the Pearson's coefficient relates the use of electric lighting to the availability of natural light.

The negative values mean that the electric lighting energy use decreases as the indoor illuminance level due to daylight alone increases. This means that users tend to switch off the lights in the room when the daylight provision of the space increases. If the value is close to -1, then the relationship between the daylight availability and the electric energy use for lighting is quiet strong, meaning the electric lighting energy use depends on daylight availability. Strong negative values are highlighted in bold.

Instead the positive values taken by the Pearson's coefficient are highlighted in red. The positive values indicate that the electric lighting energy use increases as the indoor daylight illuminance increases.

Not applicable cases (N/A) represent the cases in which there is no electric energy use for lighting in the room during the daylight hours of the day, therefore it is not possible to assess the correlation. This is most common result, meaning that there is no electric lighting energy use in the room during the daylight hours. This constitutes the main results in the bedroom (64% of the cases in the Bedroom West and 58% in the Bedroom East, instead only 7% of the cases in the Living Area), proving the user's carefulness in switching off the lights when leaving the room.

The results of the correlations show the differences between the different groups.

Basically, all of them behave differently, but the analysis shows some similarity between the groups belonging to the same category.

All the results must be contextualized by the daylight condition. From November to February, daylight hours are limited and consequently the illuminance levels are very low. It is not rare to have average indoor illuminance value below 100 lux, sometimes even below 50 lux. This may be one of the reasons behind the recurring positive correlation. In fact, as days get longer, the number of positive correlation decreases. This decreasing in the positive correlations does not go with an increasing in strong-negative correlations.

However, the cases of strong correlation are really rare. Pearson’s coefficient highest magnitude is 0.770. Analysing the 36 days for the living room south, only 7 days characterized by a strong correlation were found and 6 out of 7 recurs in the same week. For the bedrooms the number of strong correlations drops. Meaning that in the bedrooms the use of artificial lighting is independent of the daylight available.

In the next paragraph, the most significant results will be discussed.

5. Discussion

In this section the most relevant results of the correlation will be discussed, analysing the behaviour of the different users in the analysed week. Then, the results will be compared with the other groups as well as with the outcome of the previous study (Esposito, 2017)

5.1 Electric energy in relation to daylight availability

From the results of the correlations, a differences in the behaviour of the groups emerged.

Generally, the groups belonging to the same category tends to behave in the same way towards artificial lighting. A peculiar case is the group of students.

This is the only group that actively used the sleeping area during the day. Unlikely the other groups, the electric lights of the bedrooms were widely used throughout the analysed week.

Day 7 constitutes a particular case. In contrast with the other cases of non – acceptable results found in the study, in which there use no electric energy use in the room, in this case the electric consumption instead stays constant, despite the increasing or decreasing of the daylight availability.

This means that the use of artificial lighting is totally independent of the daylight availability. Accountable for that might be the use of curtains, which is not recorded, or the need for a higher level of illuminance on a specific area of the room.

Day 7- Students -December

Figure 68 Plot of the illuminance values simulated with DIVA-for-Rhino on day 7, for the student group and of the electric energy use

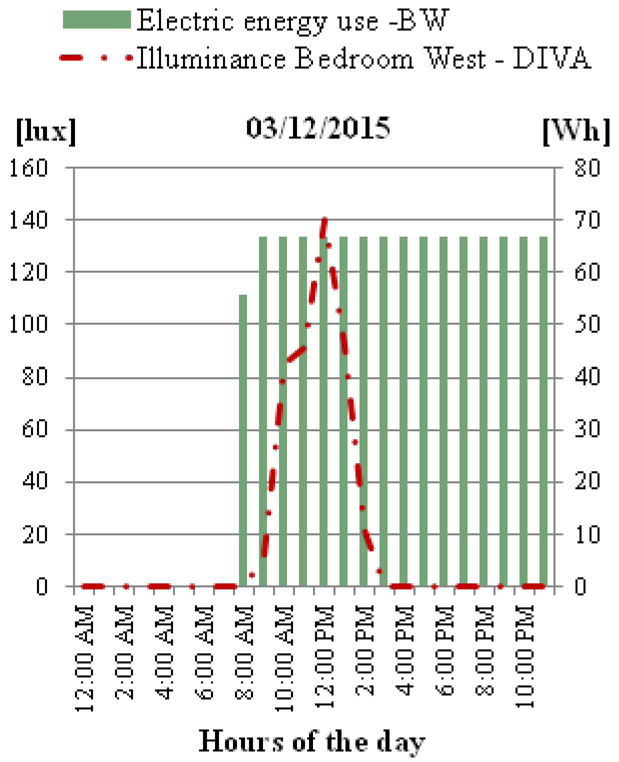
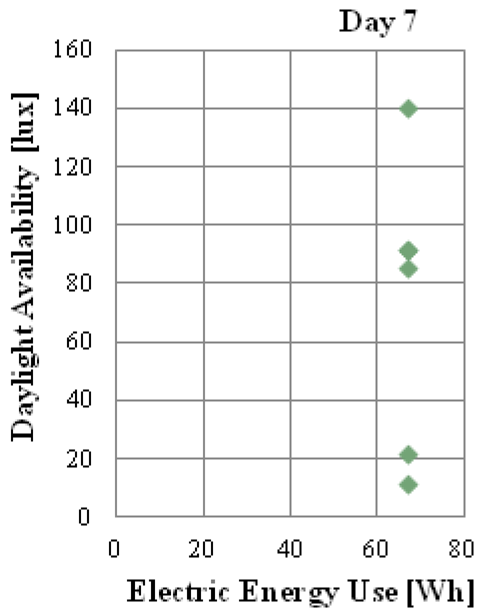


Figure 69 Scatter Plot - Correlation between Electric Energy Meter and Illuminance of the Bedroom West on day 7 N/A



This day also concurs to show how it is difficult to define preferences and assess a universally accepted level of indoor illuminance in a residential context. In this case, the different pattern and preferences are shown by the two inhabitants of the house. In fact, even though in one room an acceptable level of illuminance is reached during the day (>100 lux), this is not related to a decreasing of the electric energy usage for lighting in the bedroom west (analysed above). On the other hand, a strong negative correlation was found for the bedroom facing east, despite the low level of illuminance.

Day 7- Students - December

Figure 70 Plot of the illuminance values simulated with DIVA-for-Rhino on day 7 for the Bedroom East

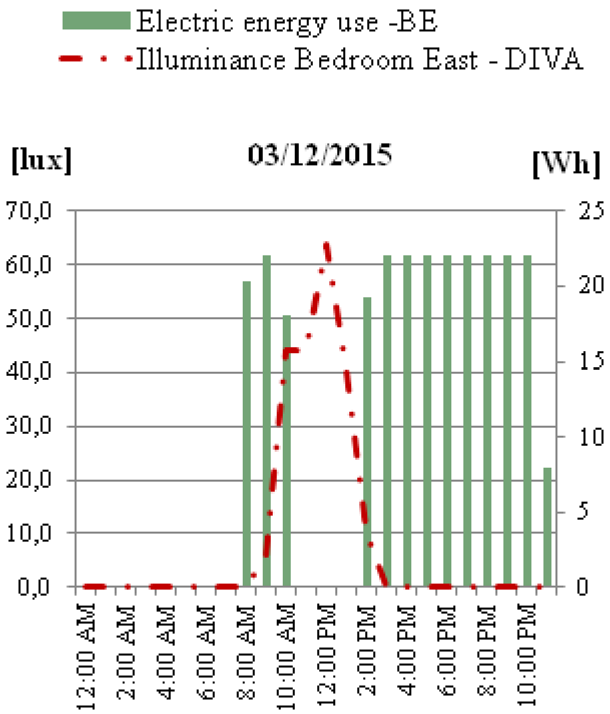
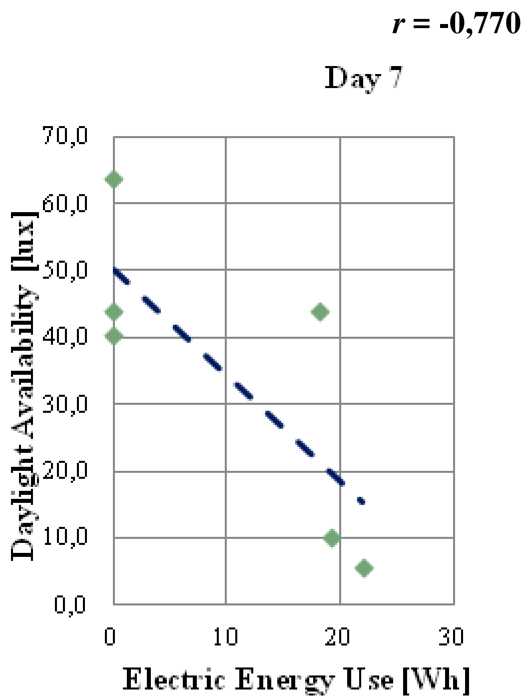


Figure 71 Scatter Plot - Correlation between Electric Energy Meter and Illuminance of the Bedroom East on day 7



Instead in the living area the correlations are rather weak throughout the whole week.

The day 5 and 6 show a typical situation of this observed week. The use of artificial lighting could be considered totally independent of the daylight availability, except for the day 7. On that day the level on indoor illuminance reaches a peak of 170 lux and a decrease in the use of electric light in the living area is observed. However, the correlation is still weak.

Day 5- Students - December

Figure 72 Illuminance and Electric energy –Day 5

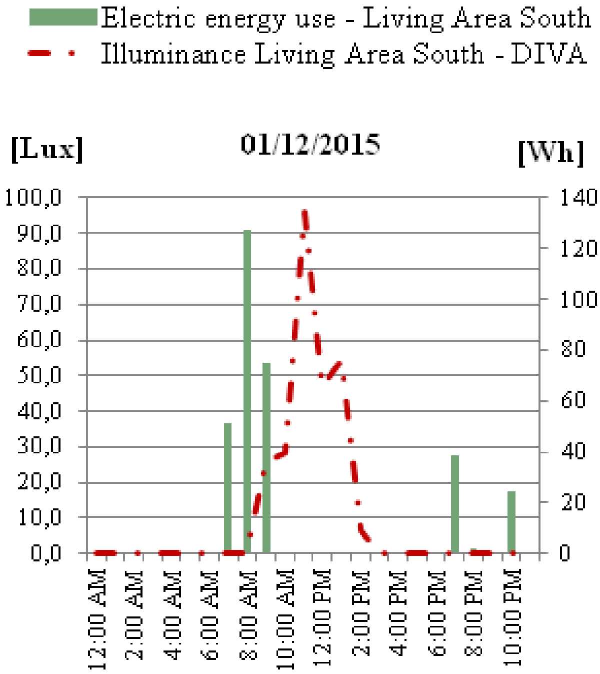
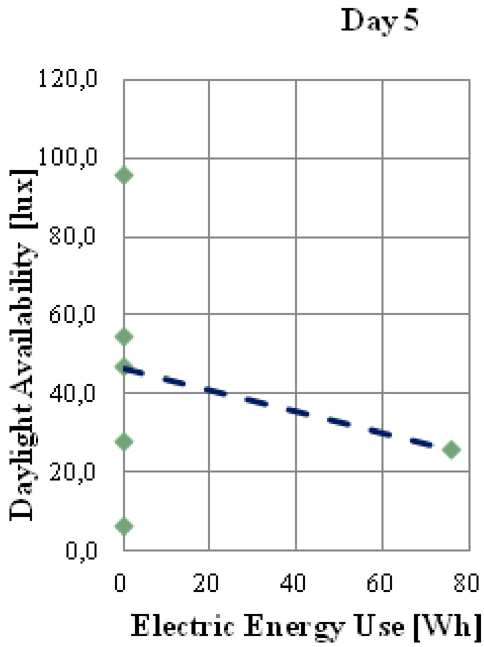


Figure 73 Scatter plot Living Area –Day 5
***r* = - 0,271**



Day 6 - Students

Figure 74 Plot of the illuminance values simulated with DIVA-for-Rhino on day 6

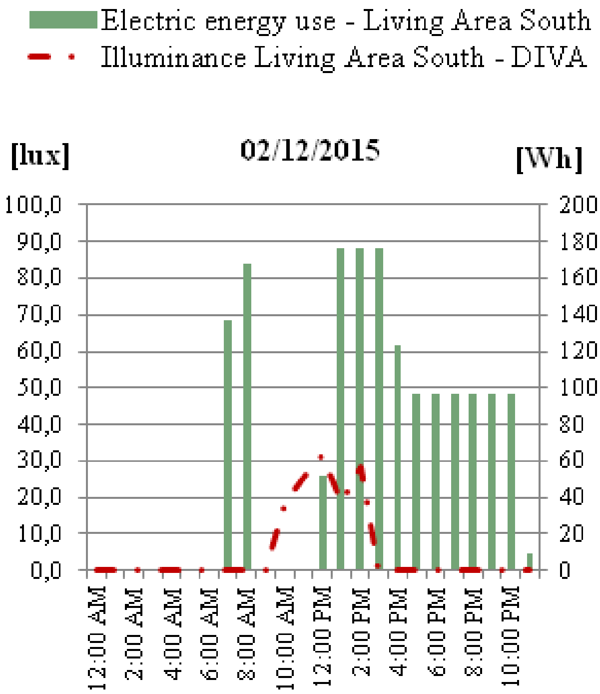
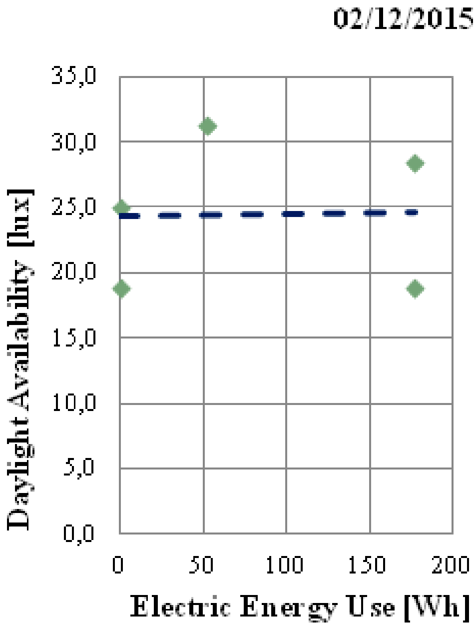


Figure 75 Scatter Plot - Electric Energy Meter and Illuminance of the Living Area South on day 6
***r* = + 0,021**



Day 7- Students - December

Figure 76 Plot of the illuminance values simulated with DIVA-for-Rhino on day 7

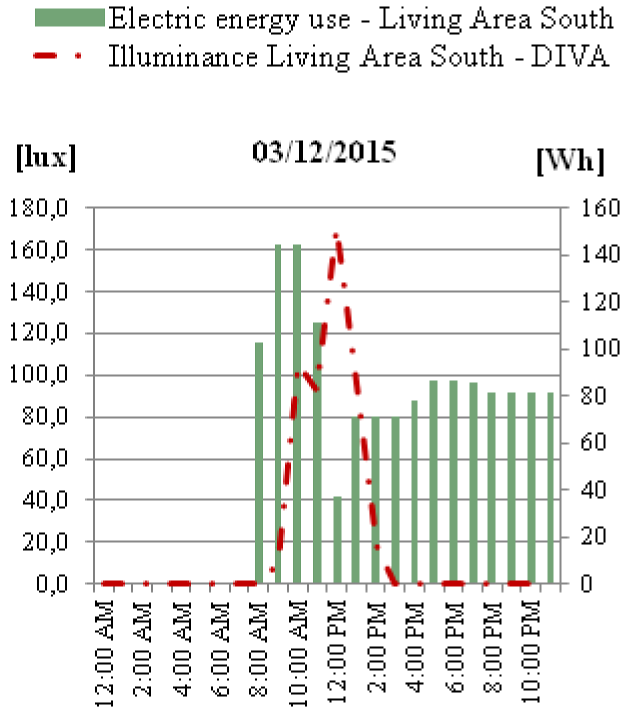
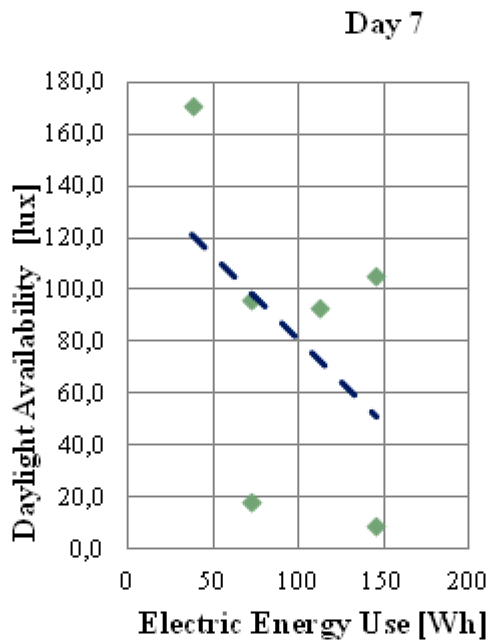


Figure 77 Scatter Plot - Electric Energy Meter and Illuminance of the Living Area South
r = -0,473



Except for only one case of strong negative correlation between the daylight availability and the use of electric lighting, in most days of the analysed week correlations are weak and sometimes even positive, meaning that the use of artificial lighting does not depend on the daylight available. Accountable for that is the fact that the internal illuminance was very low, therefore we might assume that artificial lightings were used to help reaching an adequate illuminance level to perform visual task.

The two groups that lived in the Living Lab in December and January show two completely different pattern of behaviour. Accountable for that is the fact that they belong to different categories, students and families.

One of the two families with children experienced the limited daylight hours in January. The analysis reveals that there was no the energy use for indoor lighting during the working days, demonstrating habits and behaviour completely different from the group of students.

In the observed week, an important result regarding the occupancy schedule emerged. In fact, the house was generally occupied from the afternoon till the morning and during the weekends, showing an occupancy schedule in opposition with the one generally used in office building.

Moreover, on day 6 a strong direct correlation is found for the living area south. Even in this case the daylight illuminance was really low; therefore it is reasonable to assume that the indoor illuminance level was not enough for visual task.

But, even thought the illuminance level on the next day was even lower, a medium correlation was found.

These results concur to show that the occupancy schedule and user’s habits influences the electric lighting energy use in residential context.

Day 6 – Family with children - January

Figure 78 Plot of the illuminance values simulated with DIVA-for-Rhino on day 6 for the Living area south in January.

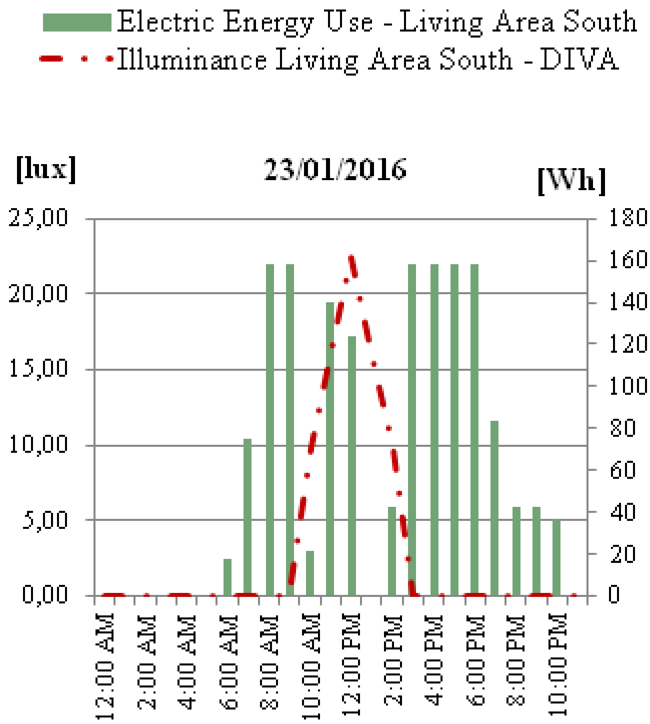
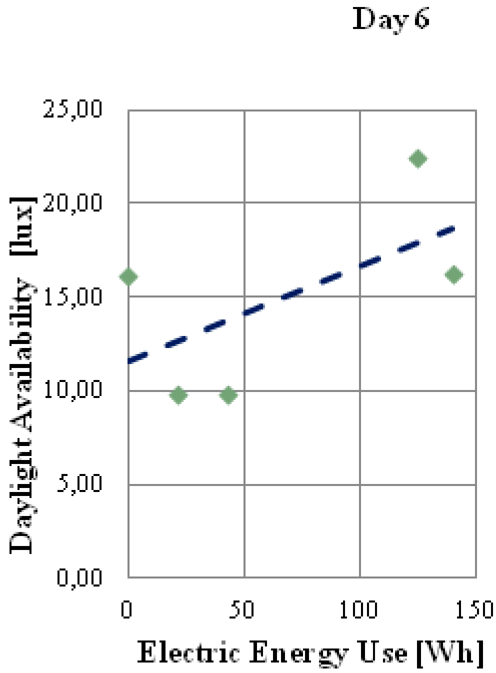


Figure 79. Scatter plot – Electric energy meter for lighting and daylight availability on January, day 6.

r = + 0,599



Day 7 - Family with children - January

Figure 80. Plot of the illuminance values simulated with DIVA-for-Rhino on day 7 in January.

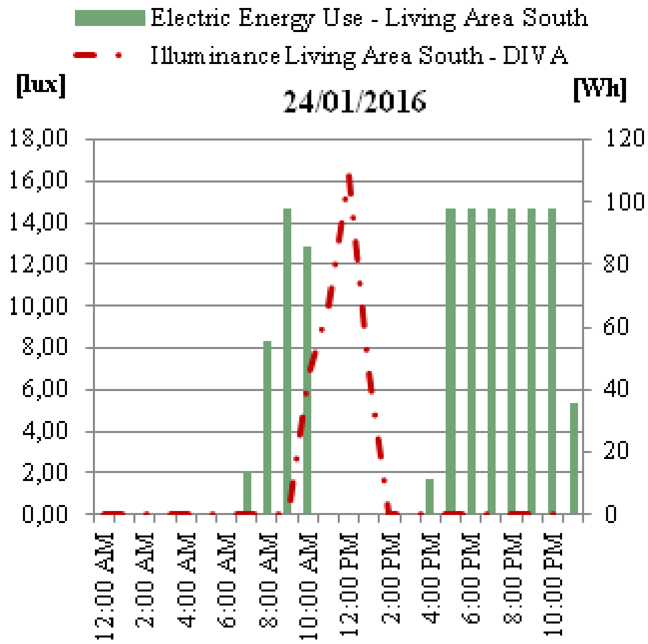
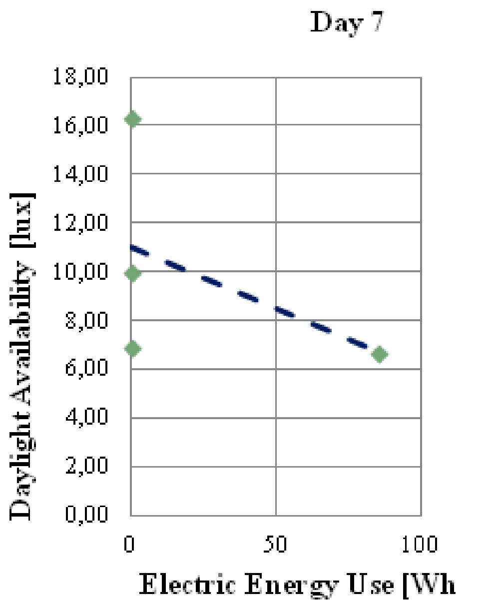


Figure 81. Scatter plot – Electric lighting energy and daylight availability

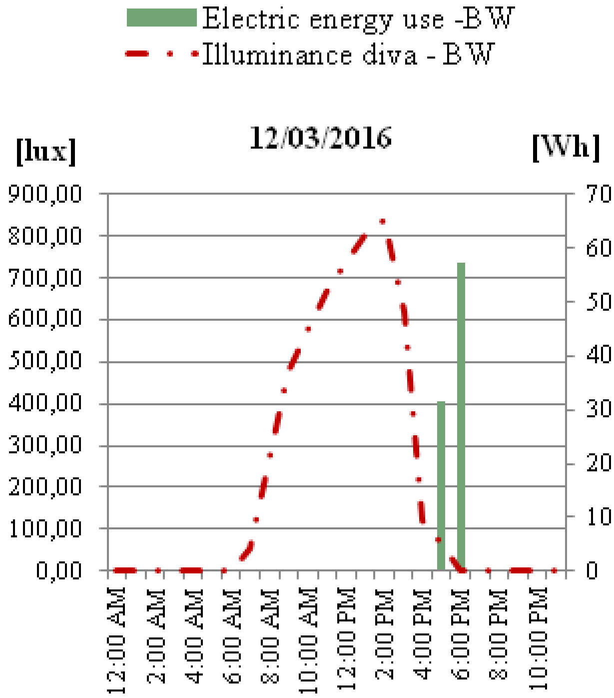
r= - 0,485



Instead, the results of the correlation for the other family show a different behaviour compared with the outcomes of the family that lived in the Living Lab in January. In fact, as the daylight hours increase, it is possible to assess the correlation. However, the results show that it is rather weak.

Day 1 – Family with children - March

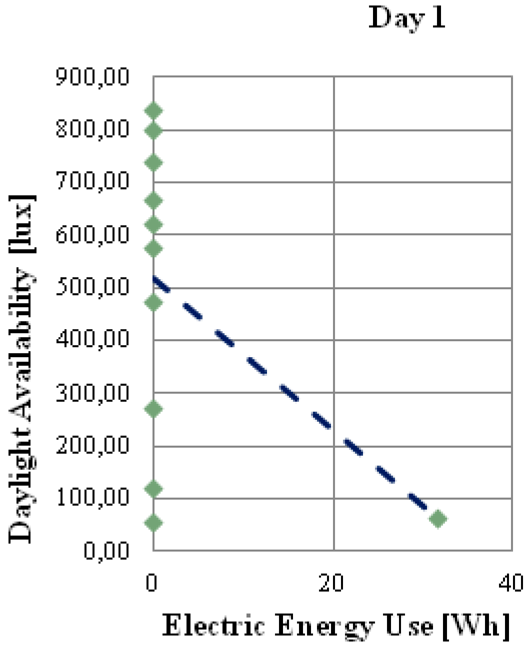
Figure 82. Plot of the illuminance values simulated with DIVA-for-Rhino on day 1 for the Bedroom West in March



Bedroom West

Figure 83. Scatter plot – Electric energy meter for lighting and daylight availability on March, day 1.

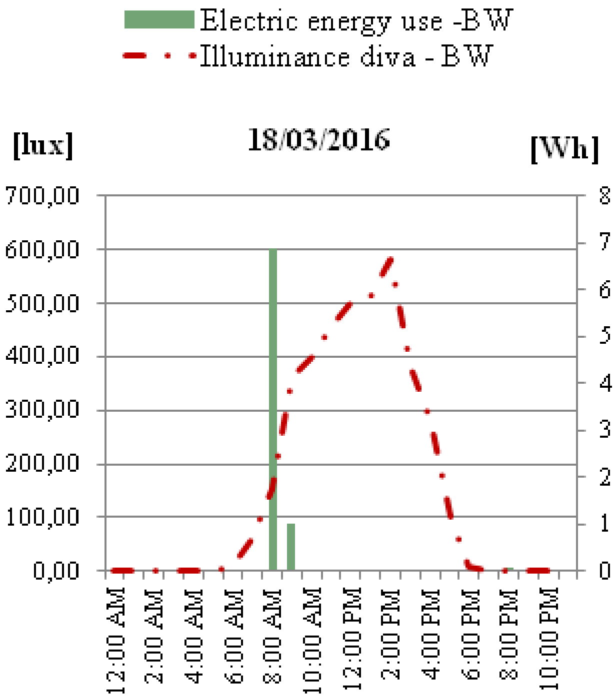
***r* = -0,460**



The graphs above describe the typical situation for this analysed week for the second family with children. The Pearson's coefficient takes a medium value most of the days. The electric lights in the bedrooms are used only in the early morning and late afternoon. Even in this case, the use of electric lights is more dependent on the occupancy schedule than on the availability of daylight.

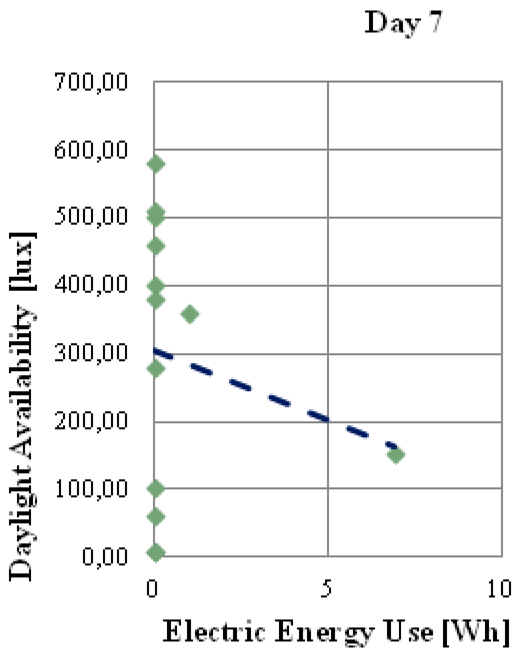
In this case, there are no strong differences between the occupant's behaviour in the bedrooms and in the living area. This means that the artificial lights are switched on and used in conjunction with natural light when the users are in the house.

Day 7 - Family with children - March
Figure 84. Plot of the illuminance values simulated with DIVA-for-Rhino on day 7 for the Bedroom West in March

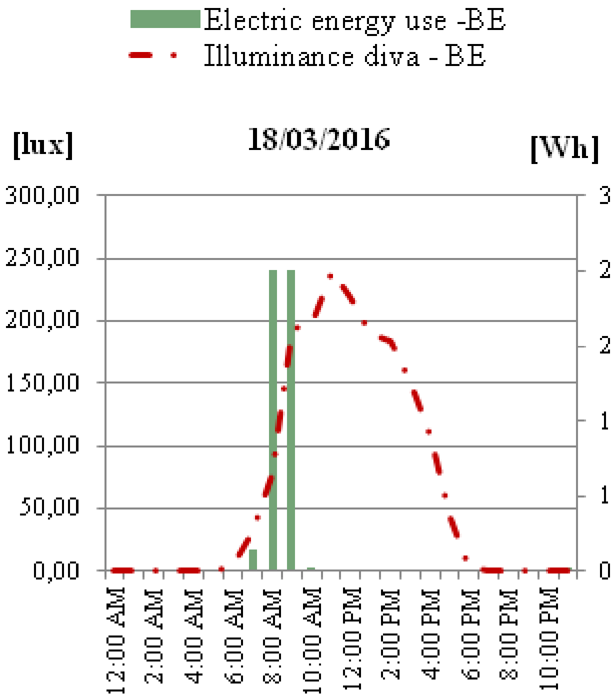


Bedroom West
Figure 85. Scatter plot – Electric energy meter for lighting and daylight availability on March, day 7.

r = -0,192

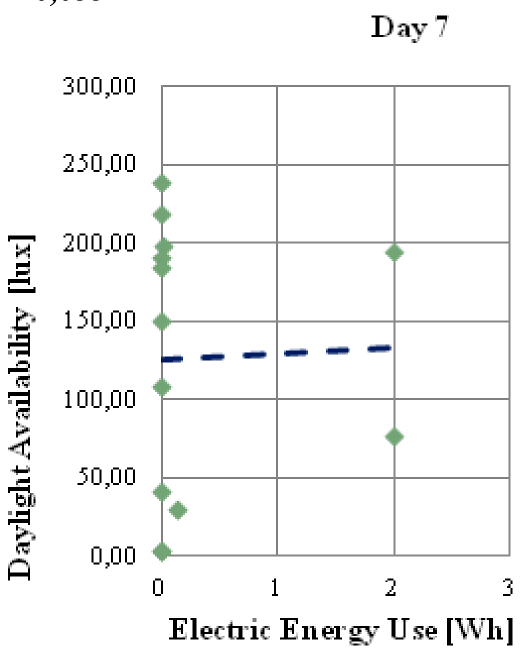


Day 7- Family with children - March
Figure 86. Plot of the illuminance values simulated with DIVA-for-Rhino on day 7 for the Bedroom East in March



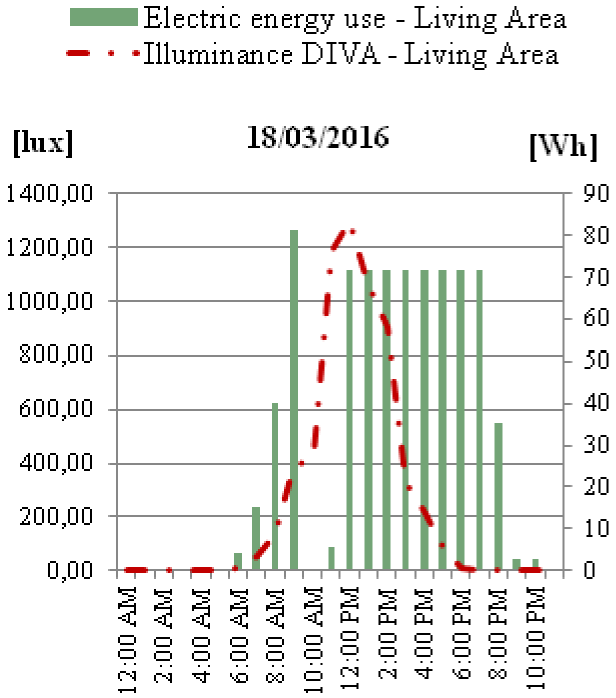
Bedroom East
Figure 87. Scatter plot – Electric energy meter for lighting and daylight availability on March, day 7.

r = 0,033

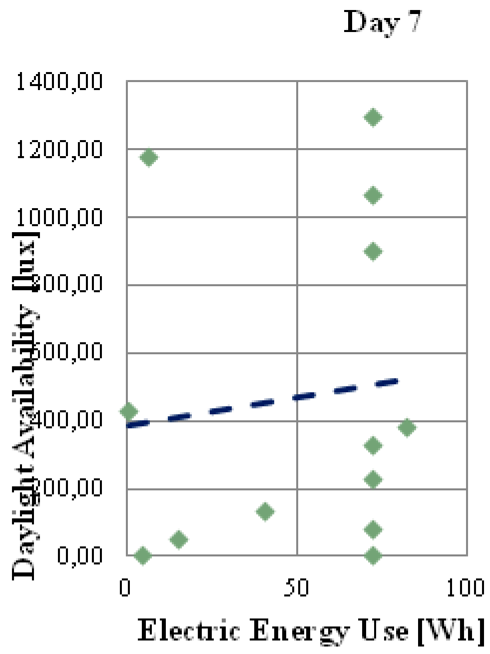


Except some N/A case, meaning that there was no energy use for lighting in the bedrooms, the Pearson's coefficient assesses a medium correlation, this means that users still uses electric light in conjunction with natural light.

Day 7- Family with children - March
Figure 88. Plot of the illuminance values simulated with DIVA-for-Rhino on day 7 for the Living Area in March



Living Area
Figure 89 Scatter plot – Electric energy meter for lighting and daylight availability on March, day 7
r = 0,128



Analysing their behaviour in the sleeping areas, a common pattern in the occupancy schedule emerged, both for the families and for the retired couples.

For the groups that lived in the ZEB Living Lab in February, the bedrooms were unoccupied during the daylight hours and there was no electric energy use for lighting most of the days.

In the group that moved in February, a strong inverse correlation was found between the daylight availability and the electricity used for lighting. Although accountable for that might be the limited hours of daylight and the occupancy schedule that contribute to limit the use of electric lighting to the hours with no natural light available.

In the group that lived in the Living Lab in April, instead the Pearson's coefficient was positive in both of the bedrooms, despite the increasing daylight hours.

Day 2 – Retired couple - February

Figure 90. Plot of the illuminance values simulated with DIVA-for-Rhino on day 2 for the Bedroom East in February

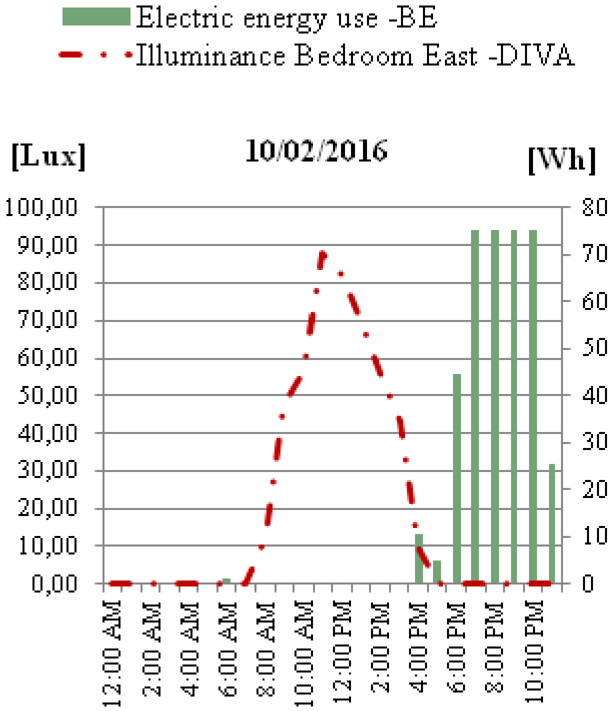
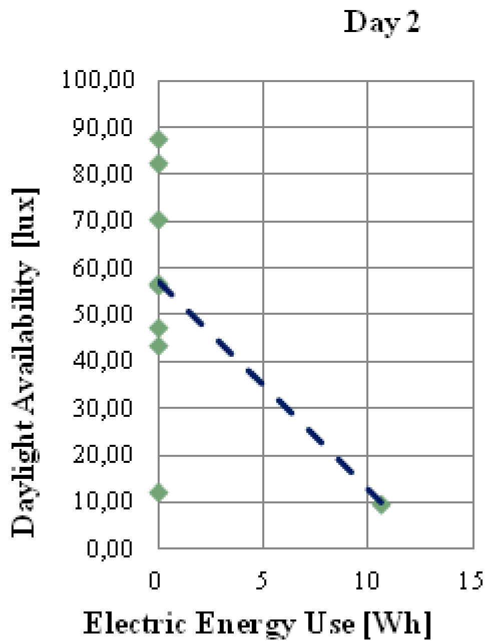


Figure 91. Scatter plot – Electric energy meter for lighting and daylight availability in February

***r* = -0.573**



Day 2 – Retired couple - April

Figure 92. Plot of the illuminance values simulated with DIVA-for-Rhino on day 2 for the Bedroom East in April

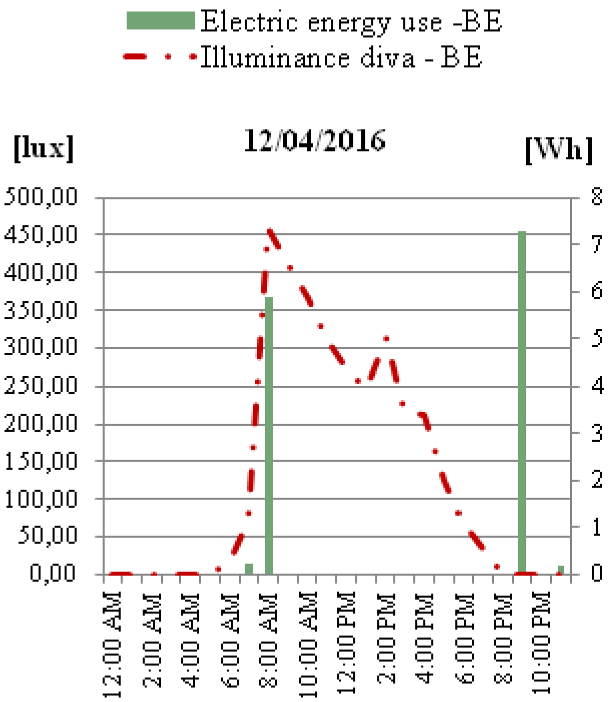
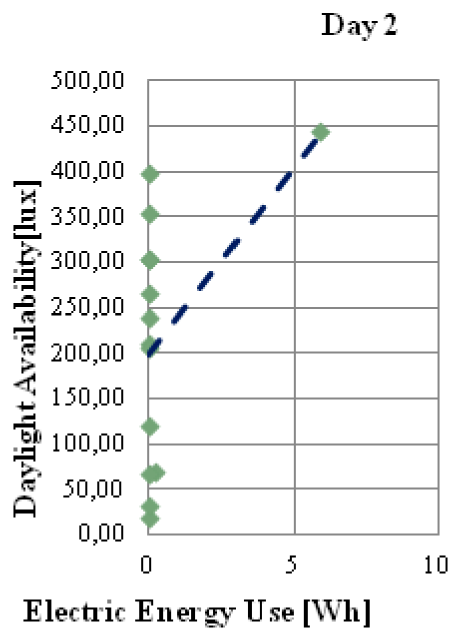


Figure 93. Scatter plot – Electric energy meter for lighting and daylight availability in April

***r* = +0.455**



Day 4 – Retired couple - February

Figure 94. Plot of the illuminance values simulated with DIVA-for-Rhino on day 4 for the Living Area in February

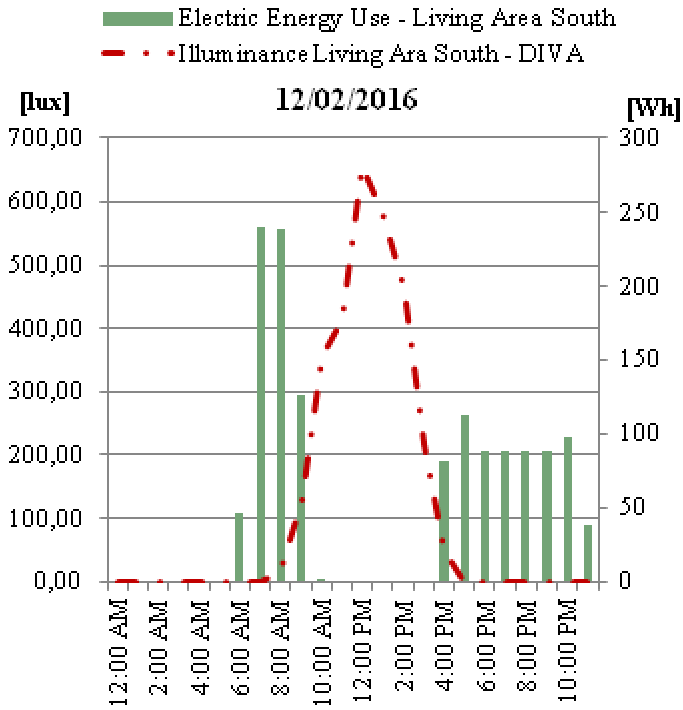
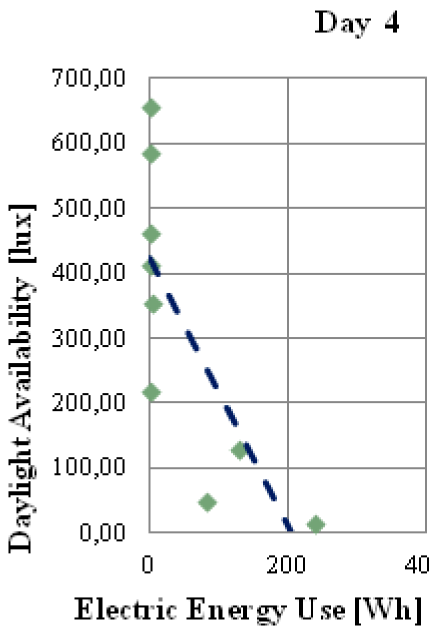


Figure 95. Scatter plot – Electric energy meter for lighting and daylight availability in February

r = -0.761



Day 5 – Retired couple - February

Figure 96. Plot of the illuminance values simulated with DIVA-for-Rhino on day 5 for the Living Area

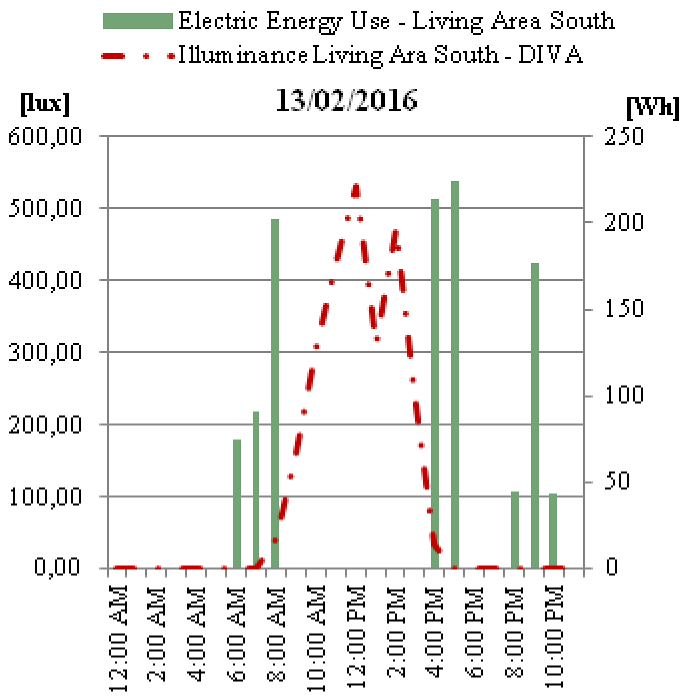
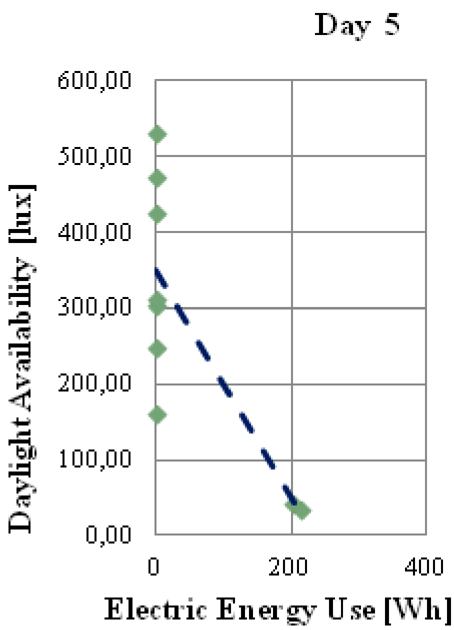


Figure 97. Scatter plot – Electric energy meter for lighting and daylight availability in February

r = -0,771



Day 4 – Retired couple - April

Figure 98. Plot of the illuminance values simulated with DIVA-for-Rhino on day 4 for the Living Area in April.

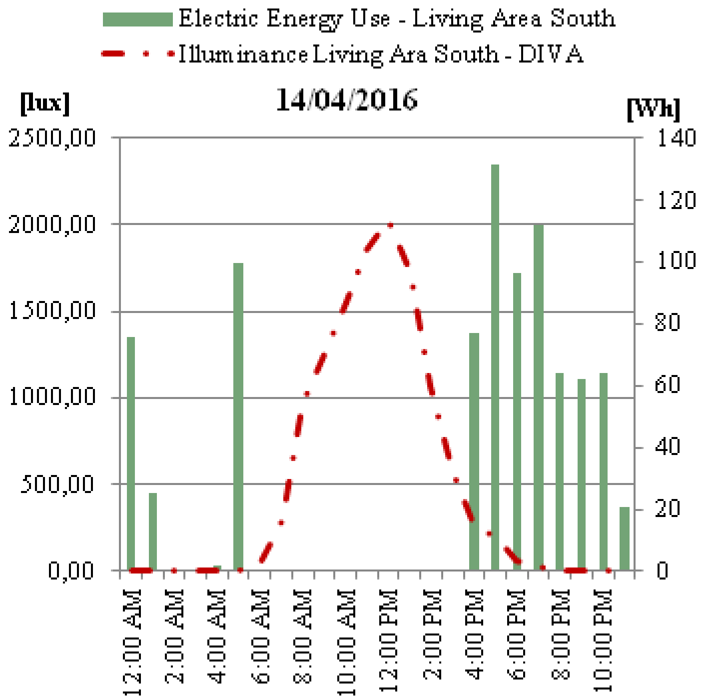
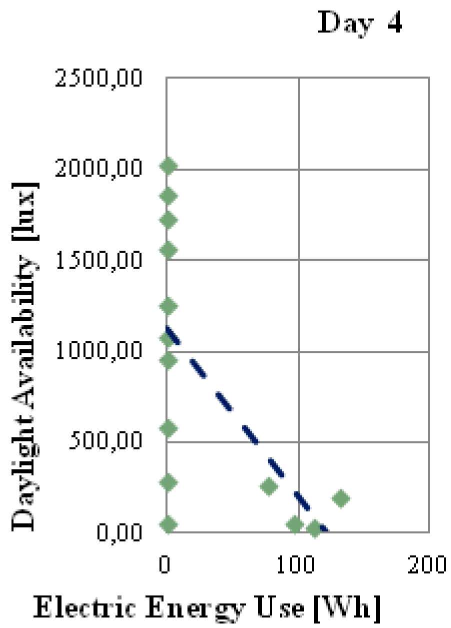


Figure 99. Scatter plot – Electric energy meter for lighting and daylight availability in April

r = -0.629



Day 5 – Retired couple - April

Figure 100. Plot of the illuminance values simulated with DIVA-for-Rhino on day 5 for the Living Area

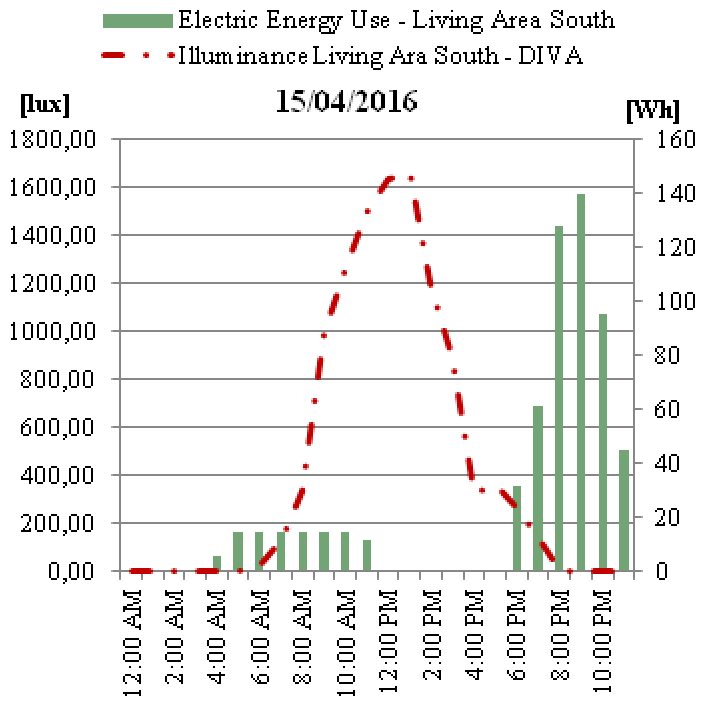
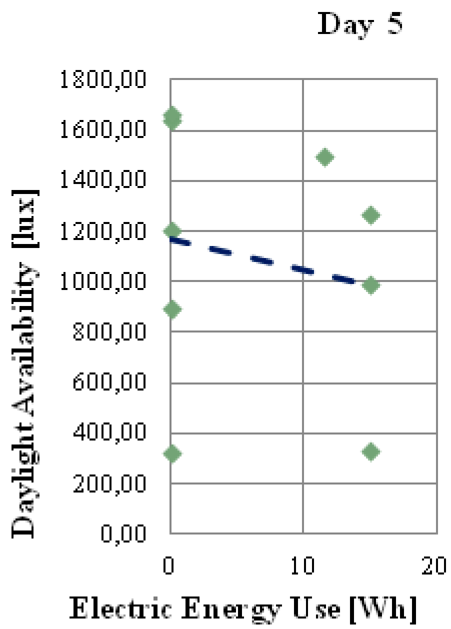


Figure 101. Scatter plot – Electric energy meter for lighting and daylight availability in April

r = -0,467



On this week of February, most of the strong anti-correlations between electric energy use for lighting and the daylight availability were found. Accountable for that are both the limited daylight hours and the habits of the group. In fact, the group that experience the longer days of April show to some extent a similar behaviour, however no such strong negative values of the Pearson's coefficient are found.

5.2 Comparison with the previous study

The results of the correlation for the analysed weeks were compared with the outcomes of the previous study (Esposito, 2017 and Lobaccaro at al., 2017) that assessed the correlation taking into consideration the whole house.

For the retired couples and the student group, no significant deviations between the detailed results and the outcomes of the previous study were observed.

From the comparison of the results obtained in the previous study for the students' couple, no remarkable differences emerge. An exception is the day 1 that shows a weak positive correlation when considering the whole house instead no electric lighting energy use was estimated in the current study.

Table 36. Comparison between the detailed analysis and the whole-house outcomes

			Living Area South	Bedroom West	Bedroom East	Whole House
from November 27th to December 4th, 2015	Couple of students	Day 1	N/A	N/A	N/A	0,097
		Day 2	0,324	0,565	-0,040	0,282
		Day 3	0,300	0,385	0,673	0,388
		Day 4	-0,392	-0,431	-0,420	-0,398
		Day 5	-0,271	-0,302	-0,279	-0,279
		Day 6	0,348	-0,066	-0,147	0,325
		Day 7	-0,473	N/A*	**-0,770**	-0,470
		Day 8	0,579	0,126	0,545	0,520

Remarkable differences, instead, emerged when comparing the outcomes for the two groups of families.

Table 37. Comparison between the detailed analysis and the whole-house outcomes for the family with children that lived in the Living Lab in January

			Living Area South	Bedroom West	Bedroom East	Whole House
from the 18th to the 24th of January, 2016	Family with two children	Day 1	N/A	N/A	N/A	-0,367
		Day 2	N/A	N/A	N/A	**0,331**
		Day 3	N/A	N/A	N/A	**0,008**
		Day 4	N/A	N/A	N/A	**0,380**
		Day 5	N/A	N/A	N/A	**0,290**
		Day 6	**0,599**	N/A	N/A	**0,603**
		Day 7	-0,485	N/A	N/A	-0,490

The results of the detailed analysis carried out are in contrast with the outcome of the previous study for the group that lived in the Living Lab in January.

In fact, in the analysed rooms there is no electric energy use for lighting. Instead, the results of the previous study that took into consideration the overall electric lighting energy show positive correlations. A deeper analysis on the conditions of the switches in the house shows that the reason behind this difference is the use of the external lights that were left. Accountable for that might be the lack of daylight.

Also for the group that lived in the Living Lab in March, the comparison with the results of the previous study shows a slight difference. Accountable for that is the use of lights in other rooms, not taken into account in this study.

Table 38 Comparison between the detailed analysis and the whole-house outcomes for the family that lived in the Living Lab in March

			Living Area South	Bedroom West	Bedroom East	Whole House
from the 12th to the 18th of March, 2016	Family with two children	Day 1	-0,392	-0,46	N/A	**0,376**
		Day 2	0,192	N/A	N/A	**0,172**
		Day 3	-0,435	-0,473	-0,348	-0,474
		Day 4	-0,356	**-0,503**	N/A	**0,002**
		Day 5	-0,473	-0,477	-0,429	-0,490
		Day 6	-0,367	-0,415	-0,248	-0,249
		Day 7	0,128	-0,192	**0,033**	**0,170**

Figure 102. Pie Charts summarizing the results of the Pearson's coefficient for the three different rooms analysed

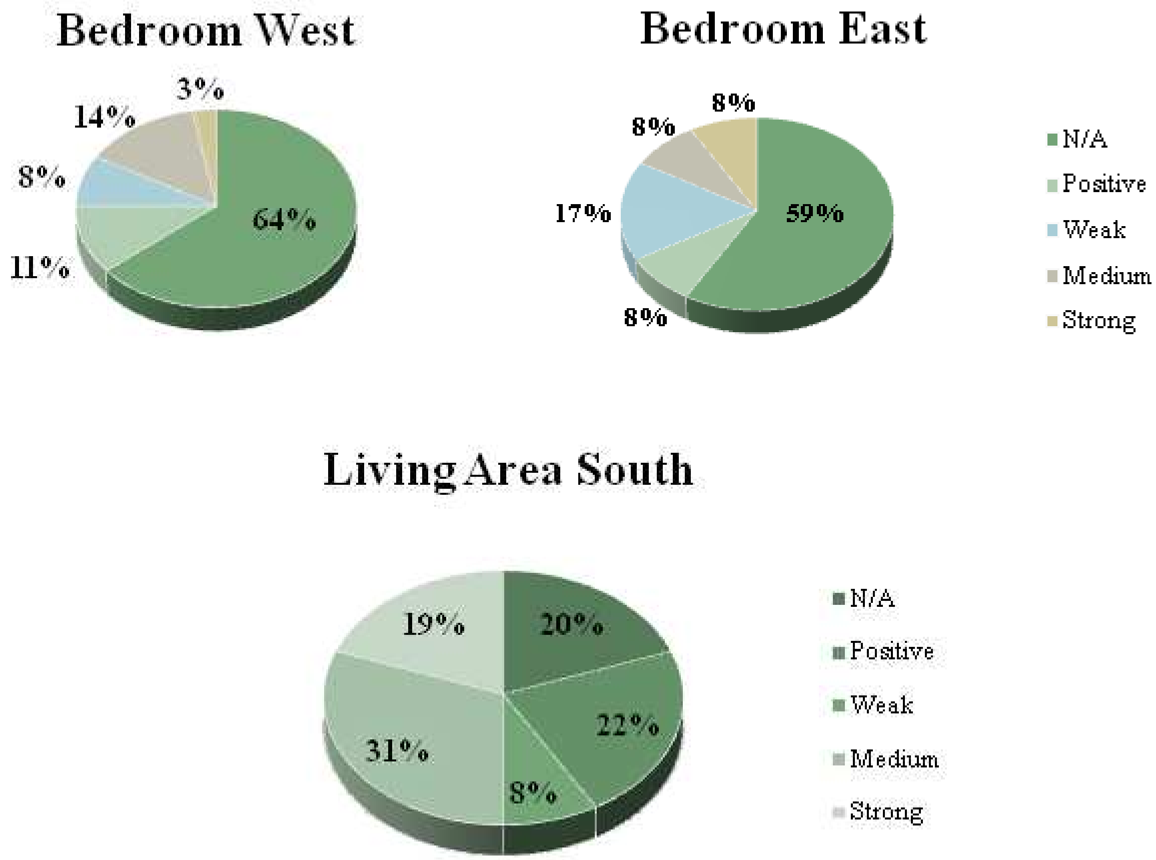
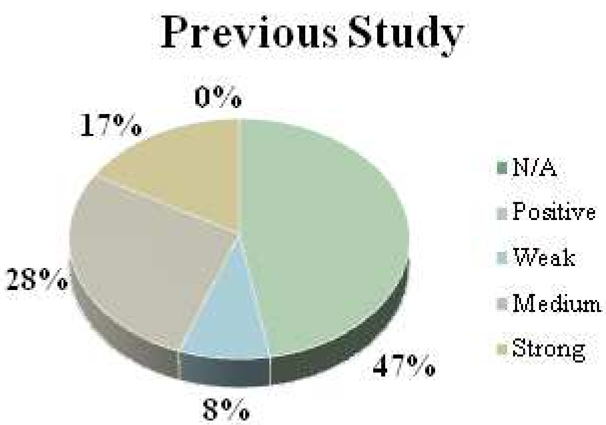


Figure 103. Pie Chart showing the results for the Pearson's coefficient in the previous study (Esposito,2017 and Lobaccaro et al., 2017)



Furthermore, an overall comparison between the population of the results from the previous study and the outcome of the detailed analysis carried out in this thesis pointed out that:

- The number of positive correlations decreases drastically. They were the most frequent cases in the previous study, while this analysis shows a decrease in the number of positive correlation. Unfortunately, this does not go with an increase of negative strong correlation. There are even less cases of strong negative correlations in this study.
- The main result is the emerging of non acceptable results. That is to some extent a good result, showing user's concern and user's carefulness in switching off the light in unoccupied room. Although, the lack of such cases in the previous study proved that in some cases, even though the house is not occupied, there is still energy consumption for lighting. On the other hand, it may indicate that other rooms in the house are occupied and therefore the lights are switched on.

6. Conclusion

Daylight is an important feature in building and it is highly regarded by users. It is generally preferred since it has a positive impact both on visual experience and on the well-being of occupants.

Moreover, the availability of daylight has a strong impact on the building performance in terms of energy consumption for electricity. In fact, electric energy for lighting is accountable for a significant part of the overall energy demand in buildings. Therefore, a good daylighting strategy can help reducing the electric lighting energy use.

However, the studies that support the potentiality of the reduction of the energy use for lighting through more energy efficient lighting and equipment combined with increasing daylight available in the space are based on the assumption that users behave properly and according to certain model. This makes occupants' behaviour a weak link in the energy efficiency and conservation equation (Matoso and Globler, 2010).

This study aims to explore if the users' behaviour towards electric lighting is influenced by the availability of natural light in residential context.

Unfortunately, a few strong anti-correlations between daylight availability in the space and the use of electric lighting were found. This means that in most of the analysed days the availability of daylight has a weak impact on the use of electric lights, showing that artificial lighting is rather used in conjunction with natural light. In fact, habits, routines and users' preferences are some of the factors that concur to influence the user's behaviour at home and therefore also the electric lighting energy use.

Nevertheless, differences in the use of artificial lighting between the sleeping area and the living areas can be observed. From the results emerged that, as one might expect, the living area facing south is actively used during the daytime. Moreover, the positive correlation cases are more frequent in the living area than in the bedrooms. This might reveal that artificial lighting is used in conjunction with daylight to perform the specific tasks and to lit surfaces serving a particular purpose like kitchen work-tops or table.

Furthermore, it seems that the large numbers of positive correlations in the first week analysed are caused by the low level of indoor illuminance (below 200 lux). Although this finding could not be confirmed since the groups that experienced the low indoor illuminances in January and February had a completely different behaviour, it is true that as day get longer, the number of positive correlations decreases.

Moreover, the emerging of Non-Applicable correlation cases is a remarkable result. It means that there is no electric lighting energy use in the room during the daylight hours. On one hand, this result proves the user's carefulness in switching off the lights when leaving the rooms. On the other hand, it is in contrast with the findings of the previous study (Esposito, 2017 and Lobaccaro et al., 2017) since no such cases were found. Even though this study shows some improvements in the results, there is still the need to increase the awareness of the users and find a way to combine the technological improvements and strategies for reducing energy use for electric lighting with occupants' behaviours in order to reduce the environmental impact of lighting is generated during the operation of the lighting system.

These results must be contextualized. In fact, the Living Lab is a peculiar case. This is in part due to Living Lab not being an actual home (Woods at al.,2016), but also supported by the location of the Living Lab, that might suggest that users probably utilized shading device and curtains to secure their privacy.

Moreover, as the architect pointed out, some of the users preferred to keep the lights on for aesthetic reason, saying that the combination of artificial and natural light enhanced the visual experience giving a more dynamic appearance to the interiors.

In the end, it was proved that is not possible to find a universally valid model user's behaviour towards electric lighting in residential context, and that the availability of natural light only marginally influences the use of artificial lighting. The main reason behind that is the residential context itself. In fact, it is a truth universally acknowledged that several factors such as social, psychological, cultural, contribute to define how we behave at home and it is rather difficult to define a pattern in behaviour that can suit us all. We all have different habits, routines and preferences that determine our unpredictable behaviours at home.

However, if there is such a waste, there is still so much potential (Matoso and Globler, 2010). Therefore, increasing the awareness of users about energy consumption and energy waste is an important issue that must be tackled in the immediate future. In addition to that, the introduction of lighting control system such as automatic dimming and automatic switch-off occupancy sensors can provide additional energy savings.

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