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AUTOMATED CONTROL SYSTEMS FOR INDOOR LIGHTING: FROM DESIGN TO ACTUAL PERFORMANCES' ASSESSMENT

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Abstract

In recent years, but already around 1980, many buildings have been equipped with Building Automation and Control (BAC) systems. These systems were applied as a normal upgrade of traditional systems in different field of the industrial sector. In general, they can be applied to the building plants in order to carry out a series of functions. The main benefits of the installation of this kind of system are well known. First of all, it has been shown that BACs systems installation increases the energy savings and because using many typologies of sensors (e.g. presence detectors to control lighting system) and because, by monitoring the data it is possible to modify plant's strategies and also to improve users response. As already cited, with these systems it is possible to monitor the plant and collect data. They can be analysed and results reported the on the system's computer. Lastly, the visual, acoustic and thermoigrometric comfort can be increased using BACs. Unfortunately, even if these systems are no longer so recent, nowadays there is not sufficient attention to some steps of design, installation and commissioning of them. Being the actual performance of these systems affected by many factors, this causes the decrease of the performances in terms of energy and comforts.

Most recent research literature shows that a great potential for energy savings in buildings is in the control and interaction of air-conditioning systems, appliances and, in general, electric devices, also thanks to specific algorithms able to coordinate all the energy facilities in the building. Commercial BACs, installed in residential or small offices, often include functions of lighting control, acting as Daylight-Linked Control Systems (DLCSs). Indeed, this kind of systems can play a key role to achieve a significant reduction of the electrical consumption for lighting and all the well-acknowledged benefits from the daylight (e.g. occupant comfort, health, well-being and productivity). Many authors proposed methods for optimizing BAC systems performance both in terms of energy savings and of comfort. Others investigated both visual and energy performance of lighting control strategies. In recent years, many standards and their updating included more or less simplified methods to preview energy consumption achievable with automated control systems application. Anyway, there is not a consolidated method to analyse how real figures of an existing BAC system differs from the expected ones.

The aim of this thesis is to evaluate, with an original approach, the actual efficacy and achievable benefits of automated lighting control systems and to provide useful suggestions and new tools to design and manage this kind of systems in most effective way. Outcomes have been confirmed through the analysis of data measured in a laboratory set up where three commercial daylight-linked control systems were installed and evaluated for different end uses, operating schedules, control strategy (dimming and ON/OFF) and daylight conditions.

Introduction and structure of thesis

The work follows conceptually during the steps of a lighting control system implementation. For each step, the description of conventional and innovative methods and tools aiming to assess or improve the effective operation of lighting control systems has been analysed and commented.

The first step is about the “predesign-analysis.” It includes chapters 1, 2, 3, 4 and part of 5. In **chapter 1**, a detailed and critical analysis about the methods utilised to preview lighting condition in indoor spaces has been presented. In particular, in this chapter a focus on most popular methods has been done. They have been divided in: mathematical models based on indices, computer simulation, artificial neural network and simplified models (mathematical, graphic and tabled). Some of these methods (i.e. simulations and indices) have been studied and applied also in parallel works published in (Baglivo et al., 2017) and briefly discussed in the thesis. By the way, it must be noted that control lighting system can be applied as well in systems for outdoor environment, but they are not included in this work even if author has been involved in some studies on this topic (Beccali et al., 2017, a) (Beccali et al., 2017, b) (Beccali et al., 2015, c).

Chapter 2, in order to have a clear view of the topic, presents an overview on the building automation systems (including key components, protocols, control strategies). A critical review of relevant cases study presented in literature has been carried out.

Chapter 3 deals with the effectiveness of technical and economic analysis in design. A practical example of an educational building has been chosen to present an application of a method able to select the best retrofit actions of lighting system, selectively analysing the daylight conditions and applying a cost-optimal methodology. With the aim to improve both energy efficiency and visual comfort conditions, the retrofit scenarios included solutions with different combinations of controls. (Bonomolo et al., 2017, a).

The impact of preliminary analysis on the design phase is discussed in **chapter 4**. The importance of the study of daylight distribution is shown through the study of actual measured data for a case in Stuttgart during a research period of the author at Hochschule für Technik of Stuttgart in the first semester 2016. It has been described together with the measurement campaign and different data analysis has been presented. In particular, data has been used to carried out a comparison between illuminance values measured on the desk and illuminance values measured on the ceiling, a shading analysis, a check of the installed commercial photosensors, to study a relationship between energy consumption and meteorological data and the assessment of the existing control system performances and of the potential additional saving related to new control strategies. Finally, some savings prediction methods have been discussed. In order to calculate ideal energy savings, the first one used the measured data and the second one simulation software. This last method has been published in (Dilay et al., 2016).

The laboratory set up (lighting and monitoring system), case study for chapter 6, 7, 8 and 9, and the project of the measurement campaign have been described in **chapter 5**. In a previous work, the laboratory setup has been depicted (Beccali et al., 2015, d).

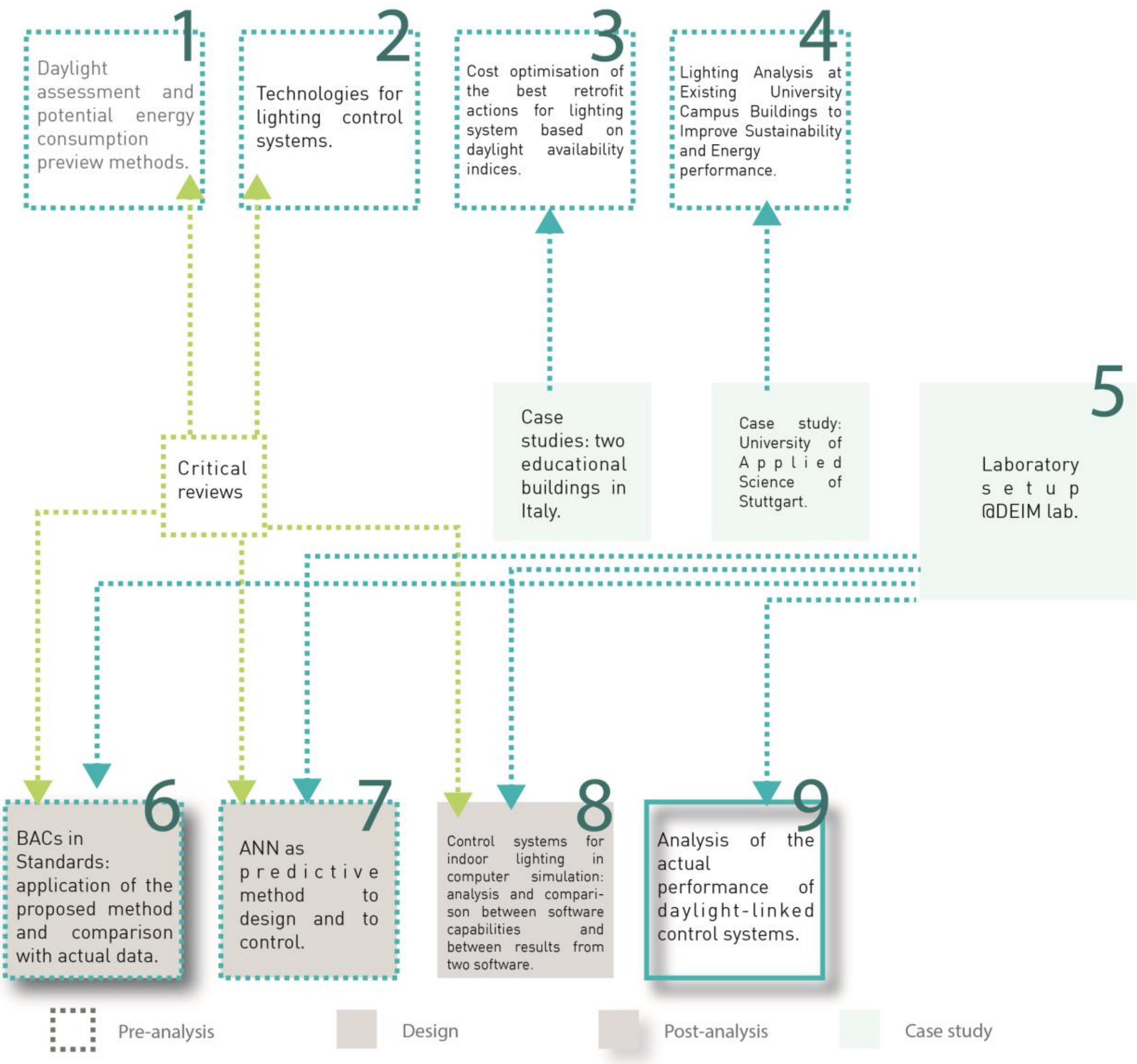
In **chapter 6** an analysis of the most common simplified method proposed by technical standards for energy consumption and saving assessment has been done. The analysis aims to describe the application of this methods (highlighting some critical points) and provide a comparison of the results with actual data. The thesis reports and integrates with new data the original paper (Beccali et al., 2017, e) about the application of the empirical BAC Factor method for the real case study at "Dipartimento di Energia, Ingegneria dell'Informazione e modelli Matematici" (DEIM), of the University of Palermo. To do this, data measured in the case study located in Palermo have been used.

The same data have been utilized to present in **chapter 7** an original method based on Artificial Neural Network as predictive tool to design a BAC system and to implement its control. The aim of it is to find the best location of sensors and a way to correctly model lighting in a room and to control the lighting system. In future works, results will be used for developing a "monitoring kit" that would be able to "learn" the model of illuminance in a room and build a NN correlation between the sensors supporting to choose of their position and configuration. A first original paper has been published in (Beccali et al., 2017, f). A similar original work aimed to develop a decision support tool for a fast prediction of the energy performance of buildings and for a first selection of energy retrofit actions that can be applied is briefly presented (Beccali et al. 2017, g).

Furthermore, a study of the simulation software that include detailed simulations of effects lighting control system as well as simplified calculation of energy consumption have been done and presented in **chapter 8**.

Anyway, this part of the thesis introduces the topic of the evaluation of the real performances that the systems object of this thesis and, in general, every real lighting control system, has. To do this, a set of new indices for the evaluation of the performances and the analysis of the energy effectiveness and of the visual task fulfilment is presented in **chapter 9**. In order to evaluate the efficiency of the systems, it has been developed using the data collected during these years. Results of experimental campaign are extensively presented and commented in **chapter 9**. Coherence and robustness of indices have been studied and tested using different systems, configurations and different daylight condition. Relationships between indices related to visual comfort, energy efficiency and consumption have been found. Main results of their application have been presented in (Bonomolo et al., 2017, b) and (Beccali et al., 2017, h). The measured energy consumption has been also compared with the one calculated through the presented method and other based on Daylight Autonomy and Continuous Daylight Autonomy.

The main conclusions of this research are set out in **chapter 10.**



Original contributions in scientific papers

- a. Beccali, M., Lo Brano, V., Bonomolo, M., Cicero, P., Corvisieri, G., Caruso, & Gamberale, F., A (2017). Multifunctional public lighting infrastructure, design and experimental test, *Journal of Sustainable Development of Energy, Water and Environment Systems,* 5(4), 608-625.
- a. Bonomolo, M., Baglivo, C., Bianco, G., Congedo, P. M., & Beccali, M. (2017). Cost optimal analysis of lighting retrofit scenarios in educational buildings in Italy. *Energy Procedia*, 126, 171-178.
- b. Beccali, M., Bonomolo, M., Galatioto, A., & Pulvirenti, E. (2017). Smart lighting in a historic context: a case study. *Management of Environmental Quality: An International Journal*, 28(2), 282-298.
- b. Bonomolo, M., Beccali, M., Brano, V. L., & Zizzo, G. (2017). A set of indices to assess the real performance of daylight-linked control system. *Energy and Buildings*, 149, 235-245.
- Baglivo, C., Bonomolo, M., Beccali, M., & Maria Congedo, P. (2017). Sizing analysis of interior lighting using tubular daylighting devices. *Energy Procedia*, 126, 179-186.
- Beccali, M., Bonomolo, M., Di Pietra, B., Ippolito, M., La Cascia, D., Leone, G., & Zizzo, G. (2017). Characterization of a small Mediterranean island end-users' electricity consumption: The case of Lampedusa. *Sustainable Cities and Society*, 35, 1-12.
- c. Beccali, M., Bonomolo, M., Ciulla, G., Galatioto, A., & Brano, V. L. (2015). Improvement of energy efficiency and quality of street lighting in South Italy as an action of Sustainable Energy Action Plans. The case study of Comiso (RG). *Energy*, 92, 394-408.
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- d. Beccali, M., Bonomolo, M., Galatioto, A., Ippolito, M. G., & Zizzo, G. (2015, November). A laboratory setup for the evaluation of the effects of BACS and TBM systems on lighting. In *Renewable Energy Research and Applications (ICRERA), 2015 International Conference on IEEE*,1388-1393.
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- f. Beccali, M., Bonomolo, M., Ciulla, G., Lo Brano, V., Mràzek, M. (2017)- Artificial Neural Network to support best configuration of Building Automation Control Systems for lighting, In *12th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES SEE2017)*, October 4th-8th, 2017 Dubrovnik (Croatia).
- g. Beccali, M., Ciulla, G., Brano, V. L., Galatioto, A., & Bonomolo, M. (2017). Artificial neural network decision support tool for assessment of the energy performance and the refurbishment actions for the non-residential building stock in Southern Italy. *Energy*, 137, 1201-1218.
- h. Beccali, M., Bonomolo, B., Lo Brano, V., & Zizzo, G.. (2017). Calculation of energy performance indices of daylight linked control systems by monitored data. In *ISES Solar World Congress 2017, October 28th-November 2nd, 2017 Abu Dhabi (United Arab Emirates)*.
- Zizzo, G., Beccali, M., Bonomolo, M., Di Pietra, B., Ippolito, M. G., La Cascia, D., & Monteleone, F. (2017). A feasibility study of some DSM enabling solutions in small islands: The case of Lampedusa. Energy, 140(P1), 1030-1046.

Honours and Awards

- ***1st Best Paper of the Conference*** for:

Beccali M., Ciulla G., Lo Brano V., Galatioto A., Bonomolo M., Spera E. (2016). *A survey on energy performance of the non-residential public building stock in Southern Italy; toward a decision support tool for refurbishment actions*, Proceedings of: 2nd South East European Conference on Sustainable Development of Energy, Water and environment systems, Volume: 2, June 15th-18th 2016, Piran.

- ***3rd Best Paper of the Conference and selected for a Special Issue of the Journal "Energy"*** for:

Beccali, M., Bonomolo, M., Ciulla, G., Lo Brano, V., Mràzek, M. (2017). *Conference Paper: Artificial Neural Network to support best configuration of Building Automation Control Systems for lighting,* Proceedings of: 12th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES SEE2017), October 4th-8th, 2017 Dubrovnik.

1. Daylight assessment and potential energy consumption preview methods

Lighting represents a large part of building energy use (Xu et al. 2016). For this reason, significant attention has been focused on the contribution of daylight to energy conservation in buildings. The results of correct choices for the design of sustainable buildings involves positive environmental effects, reducing the consumption of natural resources and costs and, especially, ensuring a high quality of service for the end users and the whole community. Several studies have been carried out to give more information about a right choice of technical solutions for high energy performance buildings, focusing on the transparent envelope and on the technical systems (Zacà et al., 2015). M.T. Ke al. (Ke et al., 2013) show that the daylight received through windows can significantly contribute to the reduction of lighting energy use in office buildings. It can be considered as a latent passive strategy for reducing the building energy use and bettering the visual comfort without any expensive operational cost and installation. Daylight access and indoor thermal comfort are key issues for a high design level provided that building occupants spend about 80% to 90% of the time in indoor activities (Ai et al., 2013). Indeed, daylight provides an agreeable and pleasant indoor environment that can foster higher productivity and performance (Plymton et al., 2000).

Also, automated light control systems, are today widespread components of smart buildings. Indeed, this kind of systems can play a key role to achieve a significant reduction of the electrical consumption for lighting and all the well-acknowledged benefits from the daylight (e.g. occupant comfort, health, well-being and productivity) (Klein et al., 2012) (Xu et al., 2015) (Yang and Wang, 2012). Using some typologies of light control systems, it is possible to integrate the daylight contribute with the artificial lighting, when the daylight is not enough.

To preview the daylight in indoor spaces is a very important task first to design the daylight environment of the building, second to estimate the artificial lighting contribution to achieve a good visual comfort and therefore the related energy savings.

In literature many studies about the methods able to preview daylight and the related energy saving achievable using active or passive control lighting systems are presented. Some researchers did an estimation for potential energy savings from daylight condition from field measurement, other used lighting simulation to do that and other present several original algorithms such as empirical formulas or index based calculations.

Each method has advantages and disadvantages. E.g., by the use of the simulation tools the final data are not so accurate as the data available from field measurement, but the costs are lower and the time shorter, even if sometimes it is preferable to validate the simulated results and this process could take more time. Wong (Wong, 2017) did a review of method for daylighting design and implementation in buildings and did a list of strengths and weaknesses of the various which is summarized in following table.

Methods	Strengths	Weaknesses
Scale models	Visualize daylight performance; Assist decision-making process for appropriate design option (CISBE, 2014); Built in desired scales; Studies can be undertaken using artificial sky to represent a specific time, date and latitude (CISBE, 2014); Built in all design stages (CISBE, 2014); Easier and cheaper than real building; Models can be created and handled easily (CISBE, 2014); Apply sensors/camera inside model; Façade configurations and geometrical changes can be easily made (CISBE, 2014);	Rules and considerations in model building (Bodart et al., 2007); Over-estimated illumination (Mardaljevic, 2012); Issues with sky simulators (Mardaljevic, 2012)
Mathematical models	Easier and quick to calculate even without specific design details (e.g. Average DF);	Accuracy needs to be validated and tested compared to experiments
Full scale models/mock-ups	Visualize daylight performance in true sky conditions; True representation of actual design (CISBE, 2014); Real building and systems under real sky conditions; Ability to use real and accurate materials within buildings (CISBE, 2014); Suitable for complex LGS which cannot be replicated at scale (CISBE, 2014);	Large and expensive (CISBE, 2014); Difficult, time consuming and costly to implement technologies; Façade configurations not easily interchangeable; Most assessment limited to real sky conditions (CISBE, 2014); Models should be weather-proofed and orientated correctly if located outdoors (CISBE, 2014);
Computer simulations	Cost effective; User-friendly interface (Laar and Grimme, 2012); Three-dimensional rendering (CISBE, 2014); Easier analysis with variable parameters and complex models; Ability to perform annual simulation (Kittler et al., 2011); Provide 'preview' of daylighting effect (Laar and Grimme, 2012); Dynamic visualization, such as sun animations and time lapse (CISBE, 2014)	Speed of software rendering (Ashmore and Richens, 2001); Accuracy needs to be validated and tested compared to experiments (Gibson and Krarti, 2015); Calculation errors; Certain programs require skilful and well-trained users (Mardaljevic, 2012); Impute quality affects accuracy (Ochoa et al., 2012); Output needs careful expert interpretation (Ochoa et al., 2012)

Table 1. Strengths and weaknesses of the various methods used to investigate daylight performance (Wong, 2017)

Being this thesis focused on the topic of the performances of Daylight Linked control systems, a presentation of the main methods to preview daylight, applied and presented in literature, has been carried out and presented in this chapter.

In particular, following methods have been analysed:

- Mathematical models based on indices;

- Computer simulation;
- Artificial neural network;
- Simplified models: mathematical, graphic and tabled.

1.1 Mathematical models based on indices

Several indices are often used to estimate the quantity of daylight. One of the most famous index is the Daylight Factor (DF). It can be used to determine the illuminance due to daylight contribution. Indeed, the internal daylight illuminance for a particular point can be computed under a simple sky pattern analytically. DF was proposed by Trotter for the first time in 1895 (Walsh, 1951) and can be defined as "the ratio of the daylight illumination at a given point on a given plane due to the light received directly or indirectly from the sky of assumed or known luminance distribution to the illumination on a horizontal plane due to an unobstructed hemisphere of this sky" (Hopkinson et al., 1966).

$$DF = \frac{E_{P,obs}}{E_{P,unobs}}, \tag{1}$$

where $E_{P,obs}$ is the horizontal illuminance at a point P due to the presence of room's construction elements that obstruct the view of the sky and $E_{P,unobs}$ is the horizontal illuminance at the same point P if the view of the sky is unobstructed by the room. It is based on such ratio in order to avoid the dependency of the daylight performance on the instantaneous sky conditions (Reinhart and Fitz, 2006) given that the daylight would be variable over time. DF values are often very low. As an example, for an office space the recommended DF value is %5% as ratio of an outside illuminance value that lies around 10 000 lx and an illuminance value of 500 lx on the work plane.

It must be noted that the DF is estimated at a given point, but it is almost always used to evaluate daylight in larger surface (e.g. a room) as average value. For "not too deep or obstructed office rooms" are suggested DF of 5% (CIBSE, 1999) and of 2% for residences. According to the British Standard, a DF of 1% is sufficient for the bedroom, of 1,5% for living and 25 for the kitchen (BS 8206-2, 2008). But, some authors affirmed that the DF metric can have several limitations. Mardalievic (Mardaljevic et al., 2009), e.g., noted that the main limits are that it cannot represent non-overcast skies since, basically, the actual daylight illumination conditions significantly differ from the overcast sky model and it is expressed as a percentage; hence the absolute illuminance values are not taken into account.

Furthermore, in building design there is often a trend to maximize DF that leads to admit as much daylight as possible by means of building envelopes with a large ratio of glazed area over opaque area (Reinhart and Fitz, 2006), influencing the thermal comfort performance of the building or inducing glare effects. Furthermore, the orientation of a building has no effect on DF calculation (Kota and Haberl, 2009).

In 1975, Longmore proposed the concept of average daylight factor (DF_{ave}), which indicates the sufficiency daylighting in a space as a whole rather than at any particular point, for daylighting calculations (Longmore, 1975).

Some authors tried to find a correlation between sky conditions and daylight and propose method to predict the illuminance indoor accordingly. Alshaibani (Alshaibani, 1997) e.g., for clear sky condition, proposing the DF_{ave} concept for clear skies and assuming the vertical illuminance on the window plane is equal to the horizontal sky illuminance and Tregenza did the same for cloudy sky (Tregenza, 1982) (Tregenza et al., 1984) (Tregenza, 1987). Moreover, Tregenza and Waters have also developed the concept of Daylight Coefficient (DC) (Tregenza and Waters, 1983). It depends on the geometry of the room and its exterior environment, the reflectance of the surfaces and the transmittance of the windows and it considers dynamic changes in the luminance of the sky elements under various sky conditions and solar positions. For this reason, is more accurate than the DF method.

Another index widely used is the Daylight Autonomy (DA). It is more precise than DF and it has been proposed by the Association Suisse des Electriciens in 1989 (ASE, Éclairage intérieur par la lumière du jour. 1989, Association Suisse Des Electriciens: Zurich (CH)). Reinhart (Reinhart, 2002) developed it. It represents the percentage of the occupied hours of the year when a minimum illuminance threshold is met by the sole daylight. It is calculated as follows:

$$DA = \frac{\sum_i (wf_i \cdot t_i)}{\sum_i t_i} \in [0,1]$$
$$\text{with} \quad wf_i = \begin{cases} 1 & \text{if} \quad E_{Daylight} \geq E_{limit} \\ 0 & \text{if} \quad E_{Daylight} < E_{limit} \end{cases}, \tag{2}$$

where t_i is each occupied hour in a year; wf_i is a weighting factor depending on values of $E_{Daylight}$ and E_{limit} that are, respectively, the horizontal illuminance at a given point due to the sole daylight and the illuminance limit value. The threshold value is not indicated. It is expressed as a percentage and it is calculated for one-year time and takes into account the weather condition of the site. Bian and Ma (Bian and Ma, 2017) in order to compare Daylight Factor and Daylight Autonomy performed a study based on long-term continuous measurements of daylight illuminance in a test room under real climate, combined with scale model tests under an artificial sky and computational simulations. Contextualizing the results to their case study, they found a rather good agreement (deviation <20%) between the DA measure in the test room and the simulated value by the software Daysim for a north facing side-lit room under the daylight climate in Canton, South China, particularly within the distance from façade of window head height. In addition, they affirmed that the scale model tested DF levels have a proportional relationship with the test room measured daylight level on the work task plane and that DA is a more applicable daylight performance metric than DF.

Bonomolo et al. (Bonomolo et al., 2017) proposed a methodology able to select the best retrofit action for lighting system, selecting the spaces according to the Daylight Autonomy and applying the cost-optimal methodology for different scenarios proposed for two existing educational buildings located in Italy. This method is extensively presented in chapter 3.

Another example of its application in building design is given by Raimondi et al. (Raimondi et al., 2016). The aim of their work was to optimize existing building shapes and facades configurations for increasing natural lighting levels in office spaces. In particular, their idea was to get an extension of useful working space just in those areas in which luminance levels are acceptable for a longer time while, at the same time, buildings get slimmer where natural light conditions are worse. To do this, authors considered the Daylight Autonomy as a more effective parameter in zones with a high amount of radiation: the higher the percentage, the more the building extends its area.

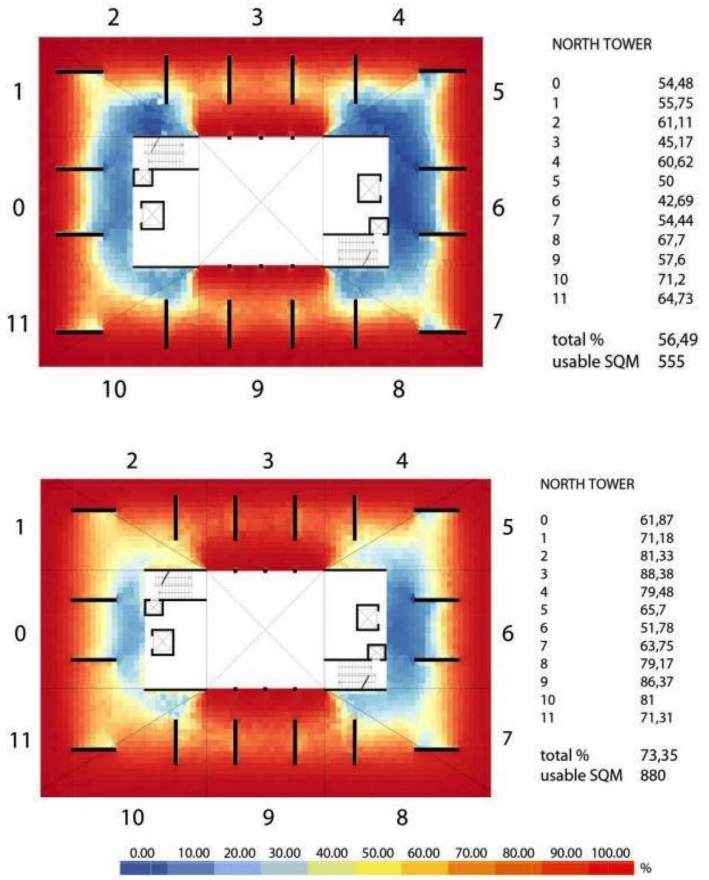


Figure 1. Upper picture: before and, lower picture, after the floor surface increment. The increase of usable surface with a DA value (300 lux for 70% of operational time) higher than the set threshold

Nabil and Mardaljevic (Nabil and Mardaljevic, 2006) found some limits as well for this index. Indeed, it does not take into account the amount of light that is above and below the threshold value. This percentage of lighting is still perceived from the users and could be cause of visual discomfort (e.g. in terms of glare). Moreover, it could be important for the evaluation of the energy consumption of ancillary artificial lighting. Anyway, it gives an idea on how the daylight penetrates into the space taking into account the hours of actual operation and the real weather conditions. Furthermore, it can be used to select fixtures that can provide benefit from daylight harvesting daylight-linked control systems.

For this reason, Rogers and Goldman (Rogers and Goldman, 2006) proposed an evolution of it: Continuous Daylight Autonomy (cDA). It attributes a partial credit to time-steps when the measured daylight illuminance ($E_{daylight}$) lies below the limit (E_{limit}). It is calculated as follows:

$$cDA = \frac{\sum_i wf_i \cdot t_i}{\sum_i t_i}$$

$$\text{with} \quad wf_i = \begin{cases} 1 & \text{if} \quad E_{Daylight} \geq E_{limit} \\ \frac{E_{Daylight}}{E_{limit}} & \text{if} \quad E_{Daylight} < E_{limit} \end{cases} \qquad (3)$$

A limit of the cDA is that sometime the calculated values could not provide a univocal information. E.g., having a value of 0.100 for an area can mean or that there were 300 lx for 10% of the time, or 30 lx for 100% of the time.

Being DA and cDA both referred to a single point, their values can be reliable only by selecting representative points of a space or by doing the calculation on a spatial grid.

To this end, other DA derived indices aim to give an overall essay of the spatial daylight availability. The index called Spatial Daylight Autonomy (sDA) is defined as "the percent of an analysis area […] that meets a minimum daylight illuminance level for a specified fraction of the operating hours per year" (IES, 2012).

Kazanasmaz et al. (Kazanasmaz et al., 2016) explained it saying that "it reveals the adequate daylight on workplane area throughout the year. sDA considers not only the temporal but also the spatial dynamics of daylight in buildings. It has been recommended for the evaluation of entire occupied spaces in combination with another index, the Annual Sunlight Exposure (ASE)".

The first one, is calculated as:

$$sDA_{x/y\%} = \frac{\sum_i (wf_i \cdot DA)}{\sum_i p_i} \in [0,1] \\ \text{with} \quad wf_i = \begin{cases} 1 & \text{if} \quad DA \geq DA_{limit} \\ 0 & \text{if} \quad DA < DA_{limit} \end{cases}, \tag{4}$$

where x is the task illuminance level, y is the time fraction, p_i are the points of the grid where the DA is calculated. An sDA 300/50 % is suggested by the Illuminating Engineering Society (IES) for analysis of daylight sufficiency, expressing the percentage of points of the analysed area which meets or exceeds the horizontal illuminance threshold of 300 lx for at least 50 % of the occupied hours (evaluated from 8 a.m. to 6 p.m. of the local clock time) over a typical meteorological year (IES). Comparing to the DA and the cDA, it gives a single value for the whole space. Moreover, the sDA is calculated for one-year long time. It can be used to evaluate daylight in a whole area, but it is characterized by the same limit of DA. Cammarano et al. (Cammarano et al., 2015) used sDA to define the daylight performance of rooms. Their work had the aim to estimate through a parametric study based on dynamic, climate based annual simulations, the influence of daylighting on the energy demand for a large number of space configurations and combination of building features. The rooms were divided in classes according to the energy results and potential savings. In the study above-cited, Kazanasmaz et al. (Kazanasmaz et al., 2016) evaluated the performance of a window in terms of spatial Daylight Autonomy (sDA) of the room where it is installed and utilised this index as an optimisation parameter for selecting best windows geometry and optical properties. They applied such optimization approach by using the Climate-Based-Daylight-Modeling tool, EvalDRC (Bauer and Wittkopf, 2015), which is also able to figure out the necessary area for a daylight redirecting micro-prism film (MPF) while minimizing the glazing area. The goal was to achieve an sDA of at least 75% with a South-facing window of a classroom in Switzerland.

As mentioned before, the sDA is often combined with the Annual Sunlight Exposure (ASE). It represents the percentage of the illuminance measured on a workplane for which illuminance levels related to the direct component of daylight exceed the value of 1000 lx for at least 250 h in a year (IES).

Reinhart (Reinhart, 2015) believes that this illuminance threshold, prescribed for annual sunlight exposure is too strict, and it may lead to prevent direct sunlight from entering a space, resulting in “dull spaces”.

Useful Daylight Illuminance (UDI) is another well known index that considers three ranges of annual illuminance distribution and can be defined as the fraction of the time in a year when indoor horizontal daylight illuminance at a given point falls in a given range (Nabil and Mardaljevic, 2005). In particular, three bins have been defined: the first, that is the highest, indicates the percentage of the time when an oversupply of daylight might lead to visual discomfort, the second, that is the lowest, is the percentage of the time when there is too little daylight, and the third represents the percentage of the time with appropriate illuminance level. In comparison with DA and cDA, UDI gives additional information useful to assess glare and thermal discomfort risks. Anyway, provided that it is the combination of three values, it is not immediate to communicate how well the space performs. It is calculated by the following equation:

$$UDI = \frac{\sum_i (wf_i \cdot t_i)}{\sum_i t_i} \in [0,1]$$

$$\begin{cases} UDI_{Overlit} \quad \text{with} \quad wf_i = \begin{cases} 1 & \text{if} \quad E_{Daylight} > E_{Upper\ limit} \\ 0 & \text{if} \quad E_{Daylight} \leq E_{Upper\ limit} \end{cases} \\ UDI_{useful} \quad \text{with} \quad wf_i = \begin{cases} 1 & \text{if} \quad E_{Lower\ limit} \leq E_{Daylight} \leq E_{Upper\ limit} \\ 0 & \text{if} \quad E_{Daylight} < E_{Lower\ limit} \vee E_{Daylight} > E_{Upper\ limit} \end{cases} \\ UDI_{Underlit} \quad \text{with} \quad wf_i = \begin{cases} 1 & \text{if} \quad E_{Daylight} < E_{Lower\ limit} \\ 0 & \text{if} \quad E_{Daylight} \geq E_{Lower\ limit} \end{cases} \end{cases} \quad (5)$$

Illuminance threshold values can vary. Table 2 reports how several authors have interpreted them.

Source	**Lower illuminance limit [lx]**	**Upper illuminance limit [lx]**
Nabil and Mardaljevic (Nabil et al., 2006)	100	2,000
Mardaljevic, Heschong (Mardaljevic et al., 2009);	100	2,500
Olbina and Beliveau (Olbina and Beliveau, 2009);	500	2,000
David et al. (David et al., 2011);	300	8,000

Table 2. Different UDI thresholds assumed in literature (Carlucci et al., 2015)

So, about the UDI calculation there is not full agreement on illuminance limit values. Last but not least, it must be noticed that the UDI provides three values for each point of the space resulting less synthetic than the other indices.

Berardi and Anaraki (Berardi and Anaraki, 2015) evaluated the efficacy of light-shelves on the illuminance levels in a south facing office building in Toronto taking into account the UDI. They simulated the building with four different window-to-wall ratios (WWR) with and without lightshelves and found that the presence of the lightshelves provide high values of UDI mainly in the first six meters in front of the windows and ensure a more homogeneous daylight distribution.

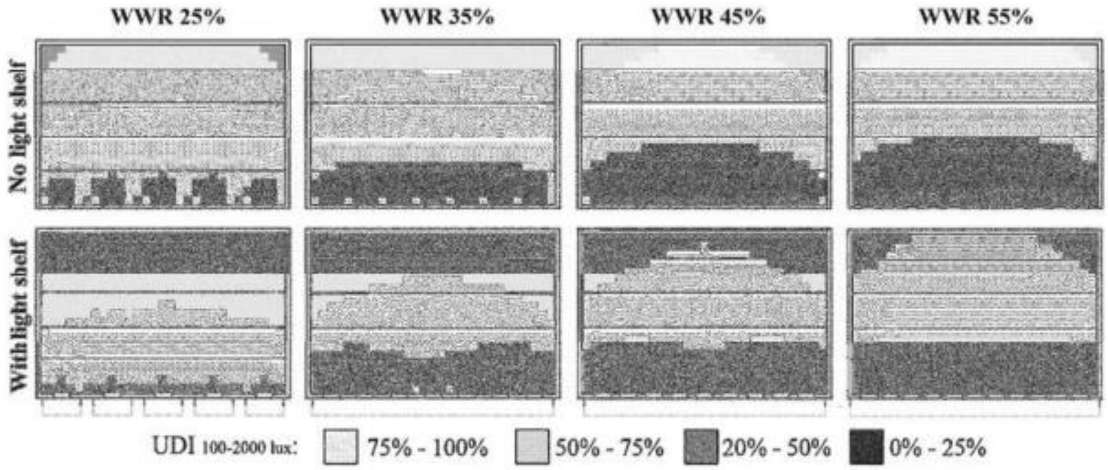


Figure 2. Comparison between UDI maps for all WWR with/without light shelves

Not very well-know is the Frequency of Visual Comfort (FVC). It is the percentage of the time within a given period during which daylight alone delivers appropriate values of illuminance (Sicurella et al., 2012). It is assumed that in order to have an adequate visual comfort from the daylight, the average illuminance must range between two threshold values. It is defined by the following equation:

$$FVC = \frac{\sum_i (wf_i \cdot t_i)}{\sum_i t_i} \in [0,1] \quad \text{with } wf_i = \begin{cases} 1 & \text{if } E_{Under} \le E_{Daylight} \le E_{Over} \\ 0 & \text{if } E_{Daylight} < E_{Under} \vee E_{Daylight} > E_{Over} \end{cases} \tag{6}$$

Whenever illuminance is below E_{Under} daylighting is insufficient, if it above E_{Over} glare may occur. The visual comfort depends on many factors, such as the actual working context, the visual task, the background luminance etc. Authors define a value of FVC higher than 0.8 for a situation where illuminance values are outside the range (E_{Under} = 150 lx, E_{Over} = 750 lx) at most for 20 % of the time. It is a long-term, two-tailed and zonal index useful to evaluate the assessment of daylight and to compare the global visual effectiveness of different technical solutions and systems (for daylight control and exploitation) on a monthly or annual basis. The definition is similar to UDI one, but the values of E_{Over} and E_{Under} are different in respect to what is proposed in (Nabil and Mardaljevic, 2006), i.e., 2,000 lx and 100 lx, respectively. It is because Sicurella (Sicurella et al., 2012) work on a spatial-averaged daylight illuminance and not on a spatial distribution of values, thus a narrower range could better guarantee to avoid too high or too low values locally. However, the averaging procedure is not described.

Also, Sicurella et al. defined the Intensity of Visual Discomfort (IVD). It is based on two indices: IVD_{Over} and IVD_{Under}. They result from the time integral of the difference between the spatial average of current daylight illuminance and the upper limit of visual comfort (E_{Over} is set at 750 lx) or the lower limit of visual comfort (E_{Under} is set at 150 lx). The calculation is performed as:

$$IVD = \int_P \Delta E(t)\,dt$$

$$\begin{cases} IVD_{Over} \quad \text{with} \quad \Delta E(t) = \begin{cases} E(t) - E_{Over} & \text{if} \quad E(t) \geq E_{Over} \\ 0 & \text{if} \quad E(t) < E_{Over} \end{cases} \\ IVD_{Under} \quad \text{with} \quad \Delta E(t) = \begin{cases} 0 & \text{if} \quad E(t) \leq E_{Under} \\ E_{Under} - E(t) & \text{if} \quad E(t) > E_{Under} \end{cases} \end{cases} . \qquad (7)$$

High IVD_{Over} or IVD_{Under} indicate that there is visual discomfort. Each individual index gives an idea about this occurrence, but it is better to consider the IVD approach as a two-tailed method. The authors propose a limit of the 30 % for both. Since the averaging procedure is not explicitly described, it would be advisable to make it explicit and/or to accompany this index with an assessment of the light uniformity.

Nowadays, most of these indices can be easily calculated using software tools, as shown in following paragraph. A good example of their use it is reported in the work by Handina et al. (Handina et al., 2017). They calculated DA, DF and UDI by the software Daysim and compared them with “contour daylight lines”. They were drawn by forty bachelor students to asses a large daylit space, namely the West Hall, in Institut Teknologi Bandung, Indonesia, that has side-lighting on four different sides of the facades. The results showed that $DA_{300lx,\ 50\%}$ is more suitable, compared to other daylight metrics, for predicting daylight availability because, for the analysis case, the percentage of area enclosed with the contour lines of DA of 50% with target illuminance of 300 lx in the space is 55%, close to the third quartiles of the daylit areas according to the participants' preference (56%). Moreover, they also affirmed that DF of 2% can be used to predict the minimum daylit area.

	Metric	Percentage area [%]
Subjective (occupant perception)	Minimum area	13
	Fully daylit (Q1) area	22
	Partially daylit (Q3) area	56
	Maximum area	75
Objective (computer simulation)	DF 2%	15
	DF 1%	62
	$DA_{300lx,\ 50\%}$	55
	$DA_{150lx,\ 50\%}$	96
	$UDI_{100\text{-}200lx,\ 50\%}$	100

Table 3. Percentage of daylit area according to subjective perception and simulation (Handina et al., 2017)

1.2 Computer simulation

As anticipated, a very common way to preview daylight, and in many case as well artificial lighting, is to use lighting simulation software. Nowadays, many software exists and they are always more sophisticate and precise. For this reason, they are utilised to support researchers and designers.

A detailed overview of most famous lighting simulation software and their features is carried out in chapter 8 and a particular focus on the implementation of the lighting control systems in some software have been done.

Reinhart et al. (Reinhart et al., 2006) presented a work based on a web survey about the use of daylight simulations in building design. The majority of respondents was between energy consultants and engineers (38%) followed by architects and lighting designers (31%) as well as researchers (23%).

The above-mentioned Daylight Factor and the indoor illuminances were the most commonly calculated simulation outputs. Shading type and control were the most common design aspects influenced by a daylighting analysis. Participants named a total of 42 different daylight simulation programs that they routinely used, over 50% of program selections were for tools that use the RADIANCE (Ward and Shakespeare, 1998) simulation engine, revealing the program's predominance within the daylight simulation community. Following graphs show how the participants answered.

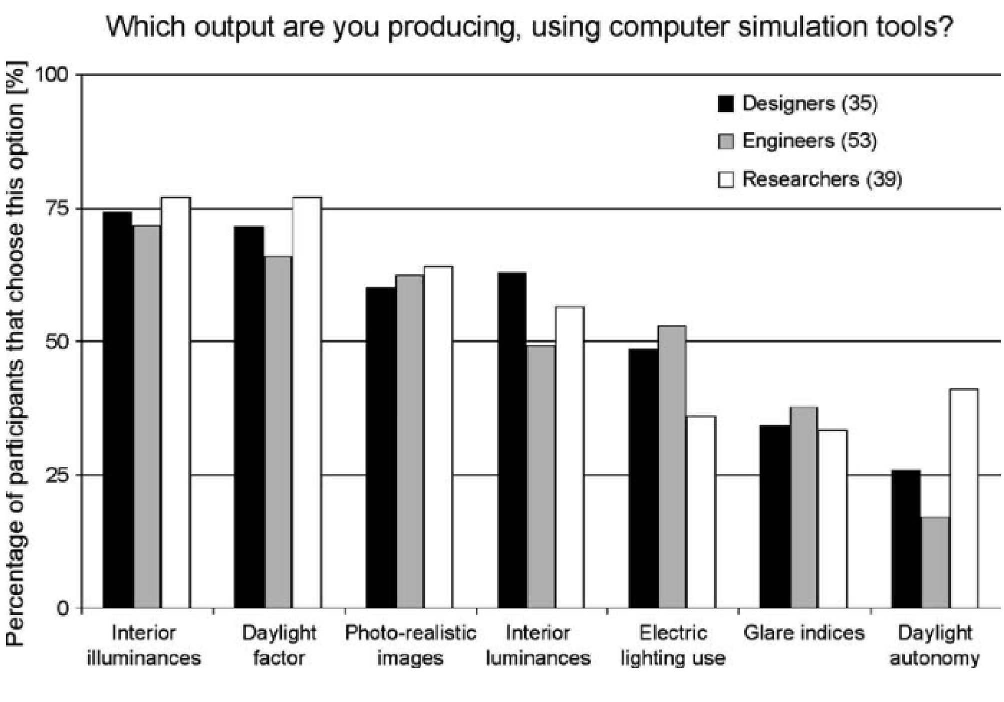


Figure 3. Responses given by 35 designers and 53 engineers which outputs they produced computer simulation programs

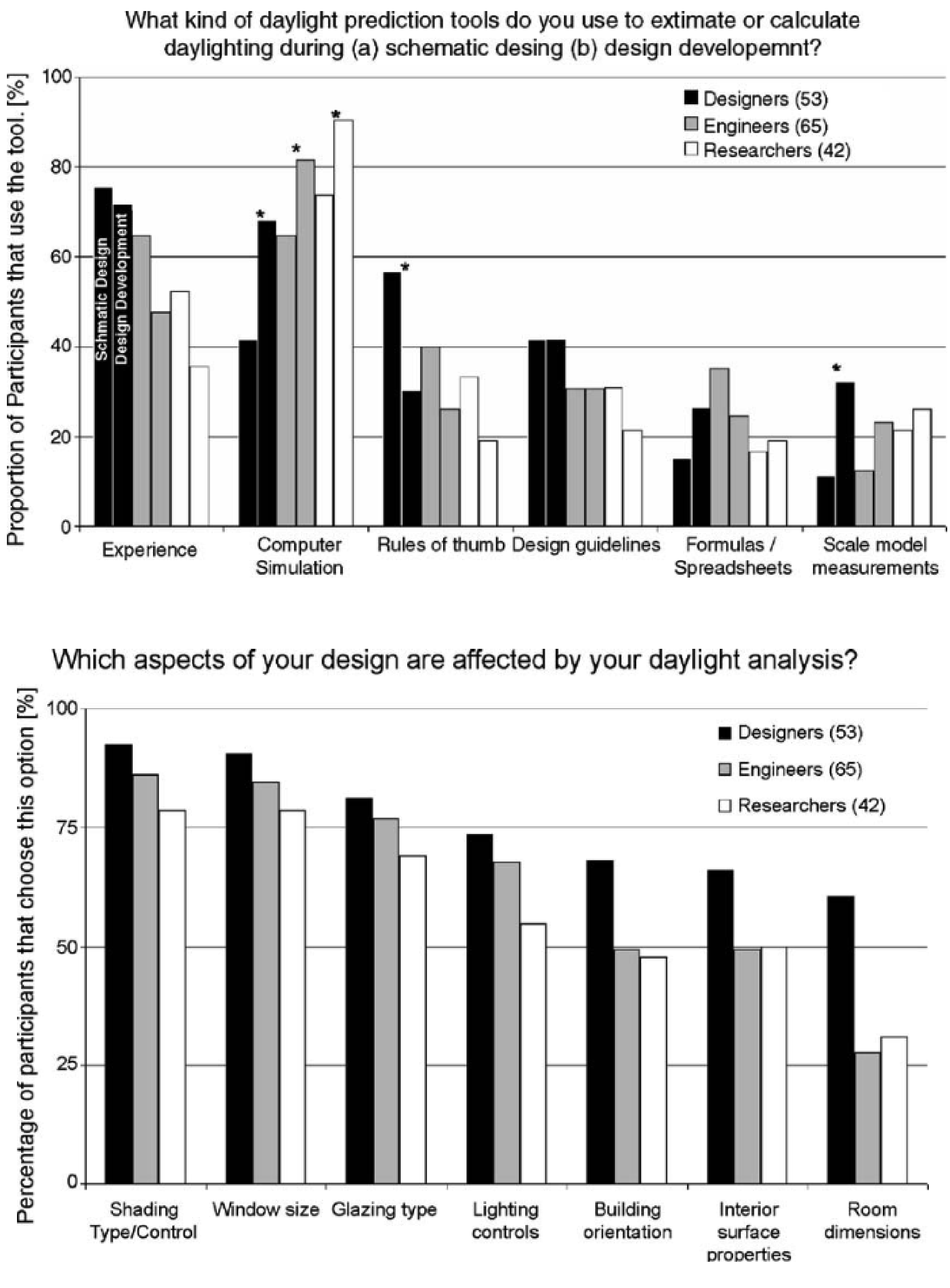


Figure 4. Responses given by 53 designers, 65 engineers and 42 researchers about the building design aspects affected by their daylighting analysis

Li et al. (Li et al., 2004) presented a study about the daylight factor and daylight coefficient approaches using simulation software. Comparing simulated data by RADIANCE with indoor daylight illuminance data measured in a scale model of a classroom, authors found that, in general, the daylight coefficient approach performs better than daylight factor approach. Both methods estimated the daylight illuminance less accurately when the measurement points in the classroom are far away from the window facade. Li and Tsang (Li and Tsang, 2005) used RADIANCE to elaborate methods to estimate indoor daylight and apply it for a daylit corridor.

Roisin et al. studied the potential of lighting energy savings in office rooms by using different control systems for three locations in Europe and the four main orientations. To do this, they applied a method based on DAYSIM (Reinhart, 2011) simulations, to perform daylight calculations, on laboratory measurement to evaluate precise system energy consumptions and on the implementation of a new algorithm to simulate a close-loop daylight dimming system (Roisin et al., 2008).

Li et al. used the computer simulation tool, DOE-2 (DOE-2, 2017), to illustrate the energy performance of a generic commercial building due to various daylighting schemes and OTTV designs (Li et al., 2002) (Li et al., 2005). In another study (Li et al., 2008) authors, through building simulations performed by the software EnergyPlus (Crawley et al., 2001), studied how the annual building electricity consumption and peak electrical demand is influenced by the input parameters including window-to-wall ratio, visual transmittance of glazing, overhangs and side fins dimensions. In order to predict the incremental electricity use (IEU) and of the incremental peak electricity use (IPEU), a regression models and energy equations has been developed, using both linear and non-linear multiple regression techniques.

Energy Plus, e.g., has been used in another work by Li and Wong (Li and Wong, 2007) to estimate energy consumption of a building in Hong Kong and of an industrial building in Tianjin.

Yang and Nam (Yang and Nam, 2010) e.g. studied and evaluated the energy and economic performance of an on-off lighting control system in an office in Seoul. The simulations have been carried out with the software 3Ds Max 8.0 Radiosity (3Dstudio, 2017) to calculate the “lighting ratio”, which accounts for the percentage of lights being turned off so that the minimum illuminance level of 400 lux and average of 500 lux for working plane in each zone is ensured. The results of the simulations have been put into the building energy consumption simulation program DOE-2.1E.

With the software SUPERLINK (Szerman, 1993) it is possible to calculate the internal load of artificial lighting according to room properties and lighting management system. It has been used by Bodart and Herde (Bodart and De Herde, 2002) to calculate the hourly artificial lighting consumption of a building with different façade configurations (with different parametric settings such as glazing transmittance, building orientation, room width, and wall reflectance, etc.). Also, authors addressed that, according to the previous research (Reinhart, 2000) (Opdal and Brekke, 1995), the accuracy of the simulation results by SUPERLINK (Szerman, 1993) seems to be uncertain and needs to be validated. On the other hands, it could be confirmed from the simulation results that the integration of daylight could save large amount energy.

The software DAYSIM (Reinhart, 2011) is able to simulate lighting energy consumption by modelling a photosensor control as it will perform in a real space. The control algorithms of several commercially available lighting control systems, the directional sensitivity and the mounting position of photosensor, the daylight aperture geometries, the shading device configuration, the control zone, etc. have been modelled with the software DAYSIM by Mistrick and Casey (Mistrick et al., 2011). Reinhart (Reinhart, 2002) used the DAYSIM to simulate the use of the blinds. Indeed, sometime they could give an error of overestimation, if the blinds are completely open for all year, or of underestimation, if they are completely closed for all year, in the evaluation of the energy saving.

The study has been performed for a case study of an office with a southern façade located in New York City. Chiogna et al. (Chiogna et al., 2012) performed a study using ADELINE Software (Erhorn and Szerman, 1994). The aim was to evaluate energy savings achievable using different typologies of automated controls installed in two groups of south-exposed lecture rooms located in the Faculty of Engineering of the University of Trento. Results showed that using an occupancy-based control coupled with a daylight-linked on-off switching system it is possible to have energy savings equal to 40% and till 65% by integrating occupancy strategy also with a dimming control.

Bellia (Bellia et al., 2015) performed three studies aimed to analyse the topic of the daylight preview and, in particular, of the relationships with the performance of dynamic daylight simulations. The author said that the main problems are essentially related to the availability of different weather data files and software to perform such simulations. The first study evaluates the impact of using four format of weather data files (IWEC, Meteonorm, TRY and Satel-Light) on daylight simulations' results carried out for a North-oriented office located in five European locations (Copenhagen, London, Nancy, Milan and Rome). The second one was developed basing on the findings of the first study. This time the results of daylight simulations were performed for the same office located in two European locations (Copenhagen and Rome), exposed according to the four main orientations (North, East, West and South) and using three different weather data files (IWEC, Meteonorm and Satel-Light). The last study compared the results of dynamic daylight simulations carried out for the same office located in four European cities (Copenhagen, Nancy, Milan and Rome) and exposed toward North, East, West and South, using DAYSIM and 3ds Max Design®.Table 26 reports the climatic data related to the cities for which the abovementioned studies were carried out. She analysed the weather data file and the abovementioned software and the simulations results.

In these described case studies many authors used software in order to simulate the daylight distribution and/or calculate indices with the explained aims. But, it must be noted that some simulation software can be used to calculate directly energy consumption. Indeed, many software, as it will be explained better in chapter 8, include simplified methods proposed by standards (as described in chapter 8). E.g. RELUX energy (Relux, 2017), that embeds the standard EN15193 method calculation avoiding the complicated manual calculation. Shailesh and Tanuja (Shailesh and Raikar, 2010) used this last lighting simulation software to study the interaction between the natural and artificial light and the energy consumption under various lighting control schemes in an under-construction commercial building in Mumbai, India. Comparing the original lighting design in building where does not take into account the daylight, about 70% of lighting energy could be saved by using the combined occupancy and daylight dimming sensors.

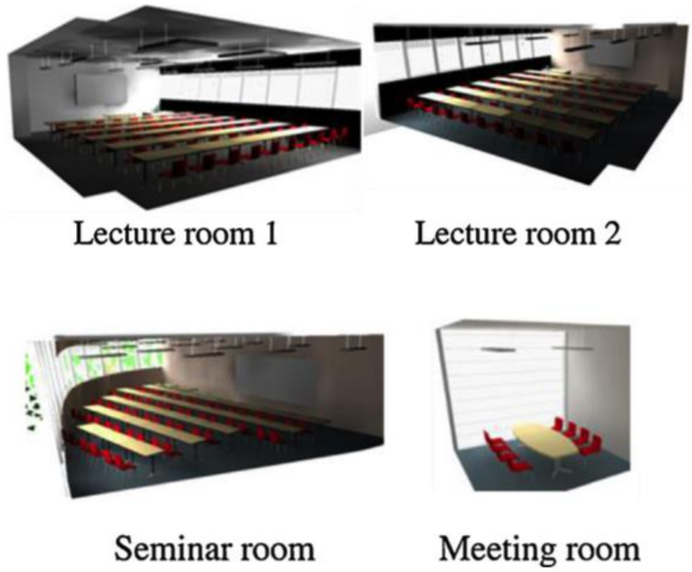


Figure 5. Relux simulations (Yu and Su, 2014)

1.3 Artificial Neural Network

Many daylight studies are based on the application of Artificial Neural Networks (ANN). A more detailed explanation of this method is resented section 7 which includes also an original application proposed by the author. ANN found successful application on the area of energy modelling. Many researchers demonstrated the great capability of the ANN method over the other conventional well know methods in problems characterised by complex phenomena and large number of parameters.

Karatasou et al. (Karatasou et al., 2006) affirmed that the main advantage of the ANN is the high potential to model non-linear processes. In particular, they used a neural network to predict energy consumption in buildings and in particular hourly load profiles. They valuated the performance of the model using two data sets: the energy use data of the Energy Prediction Shootout I contest and of an office building, located in Athens. They demonstrated that the integration of ANN with statistical data can provide a tool for designing efficient buildings.

Kazanasmaz et al. (Kazanasmaz et al., 2009) developed a model based on neural network for office building with daylighting for subtropical climates. Considering eight variables as input, they elaborated a model to predict daylight illuminance indoor. In particular: four variables were related to the external weather conditions (daily average dry-bulb temperature, daily average wet-bulb temperature, daily global solar radiation and daily average clearness index), four to the building envelope design (solar aperture, daylight aperture, overhang and side-fins projections). Finally, they validated the neural network model with simulations carried out by Energyplus. The output layers estimated daily electricity use for cooling, heating, electric lighting and total building as the output.

As well da Fonseca et al. evaluated a method based on ANN to predict the impact of daylighting on building final electric energy requirements (de Fonseca et al., 2013). The results were obtained by the simulation of 216 models then used to develop a Multi Linear Regresion (MLR) equation. DAYSIM was used to perform the daylighting simulation and Energyplus for energy simulation.

Aydinalp et al. (Aydinalp et al., 2002) used ANN to calculate the energy consumption for Canadian residences, also due to the lighting system. Several researches tried to preview the radiance distribution with this methodology. Pattanasethanon et al., e.g., presented a study on all sky modelling and forecasting daylight availability for the tropical climate in the central region of the north-eastern part of Thailand. They estimated the required components of sky global and diffuse horizontal irradiance and global horizontal illuminance to calculate saving energy (Pattanasethanon et al., 2008).

In the study carried out by Lam et al. (Lam et al., 2008), the effect of relative humidity on the potential of solar radiation exploitation is investigated using artificial neural-networks. Authors used meteorological and geographical data (latitude, longitude, altitude, month, mean sunshine-duration, and mean temperature) in the input layer of the neural network net. (Model 1). In Model 2 relative humidity values are added to one network. Formulae were used to determine the solar energy potential in Turkey using the networks' weights for both models. Scaled conjugate gradient (SCG) and Levenberg-Marquardt (LM) learning algorithms and a logistic sigmoid transfer-function were used in the network. Results showed that the humidity has only a negligible effect upon the prediction of solar potential using artificial neural-networks.

In order to train the neural network, Sözen et al. (Sözen et al., 2004) used meteorological data for the last 3 years (2000–2002) from 17 stations (namely cities) spread over Turkey as training (11 stations) and testing (6 stations) data. As well geographical data (latitude, longitude, altitude, month, mean sunshine duration, and mean temperature) have been used as inputs to the network. As well in this case, the trained and tested ANN models show greater accuracies for evaluating solar resource possibilities in regions where a network of monitoring stations has not been established in Turkey. They elaborated a monthly map of the predicted solar-potential values. They affirmed that it can be used by scientists, architects, meteorologists, and solar engineers in Turkey.

Koca et al. (Koca et al., 2011) and Sözen et al. (Sözen et al., 2004) used Neural Network method to estimate solar radiation in Turkey. Koca et al., in particular, used the data measured during 2006-2007 from the Turkish State and Meteorological Service to calculate the data of 2008 (Figure 6). The number of input layer parameters changed from 2 to 6. Authors affirmed that the method could be used by researchers or scientists to design high efficiency solar devices. Moreover, it was also found that number of input parameters was the most effective parameter on estimation of future data on solar radiation.

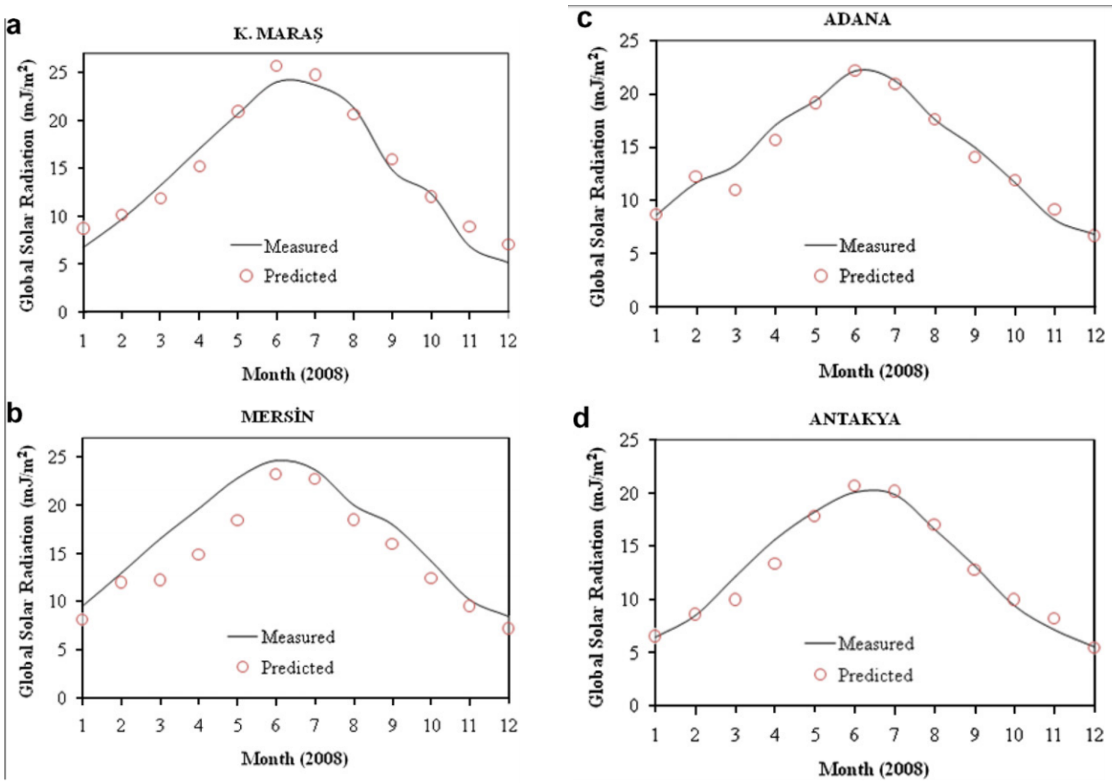


Figure 6. Variation of predicted and measured values of global solar radiation for different cities along the year of 2008: (a) K. Maras, (b) Mersin, (c) Antalya, and (d) Antakya. (Koca et al., 2011)

Mohandes et al. (Mohandes et al., 1998) introduced a neural network technique for the estimation of global solar radiation in any location using available data, collected from 1971, from 31 locations in Arabia Saudita for training the neural networks and the data from the other 10 locations for testing. Results indicated the viability of this approach for spatial modeling of solar radiation.

Tíba and Leal (Tíba and Leal, 2012) took collected data measured in meteorological stations in Brazil (dew temperature, precipitable water, sky brilliance index, clearness index of Perez and clearness index) in order to evaluate the potential contribution of natural illumination in commercial buildings. They elaborated different models known as luminous efficacy, which made possible the estimation of illuminance in regions where there only existing information is on solar irradiation. In particular authors found the relationship between illuminance and solar irradiation with other meteorological variables and/or sky conditions with statistical models. MLP (multilayer perceptron) artificial neural networks (ANN) have been used to estimate the hourly luminous efficacy. The results were compared with the statistical models of Perez et al. (Perez et al., 1993), and Robledo (Robledo and Soler, 2001), adjusted with local coefficients. Other researches used the way of the empirical formulae.

Krarti et al. (Krarti et al., 2005), e.g., determined with a simplified method, the percent of savings in annual use of artificial lighting due to daylighting implementation using daylighting controls in office buildings for several combinations of building (by changing geometry, window opening size, and glazing type for four geographical locations in the United States). To verify and validate the ANN model's predictions, authors used results from building energy simulation as well as experimental data. Moreover, they found a direct correlation that has been established between window transmittance and window area on annual lighting reductions.

Danny et al. (Li et al., 2004) elaborated a method of controlling lighting energy consumption for two categories of systems: one considers the on-off control system and the second allows the level to be set between maximum and minimum by dimming. For the sake of simplicity, only standard on±off control is considered in the present study.

Ihm et al. (Ihm et al., 2009) improved the equation used by Krarti et al. They considered the effects of pre-set illuminance level, number of steps in stepped control, the minimum setting for dimming control on the values of two indexes, "a" and "b". The value of "a" depends on the location of the building and the control strategy, and the value of "b" depends on percentage of time in a year that daylight level can provide the setpoint of illuminance. The data have been compared with the data measured in a small office in Brulder, USA. The results indicated that annual energy savings of up to 64% associated with lighting can be achieved using dimming control strategy, which agrees with the results estimated using the equation. In another study (Şahin et al., 2016), authors modelled a neural network based on measurement of the illuminance in order to estimate in real-time the illuminance distribution in an environment. Also, they calculated the mean illuminance in the environment and obtained the depreciation multiplier of the system. In order to improve the system behaviour and to prevent energy waste and light loss, finally, the percentage of energy in the system that was not transformed into light was determined.

1.4. Simplified models: mathematical, graphic and tabled

In order to calculate the Daylight Factor, presented in section 1.1, it is necessary to know the how light can reach a point inside a room through glazed windows. In particular, the light can come from the patch of sky visible at the point considered (sky component (SC)), (b) can be reflected from opposing exterior surfaces and then reached the point (externally reflected component (ERC)) or can enter through the window but reaching the point only after reflection from internal surfaces (internally reflected component(IRC)). The sum of these components is equal to the Daylight Factor.

$$DF = SC + ERC + IRC \tag{8}$$

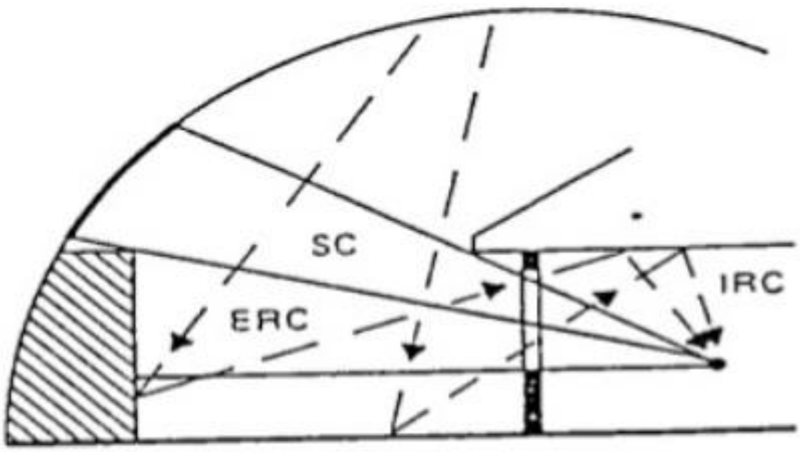


Figure 7. Scheme of the three radiation components

Benjamin Geebelen (Geebelen, 2003) did a detailed review on daylight calculation methods, categorized the “Graphical, tabular and hand-calculation methods”:

- According to treatment of the direct and reflected components: do they produce one or both, or do they produce the total daylight factor in a single step?
- According to applicability: can they handle vertical, horizontal or sloping windows? Can they handle saw-tooth roof lights?
- According to daylight conditions: which kinds of sky luminance distributions can they handle? Typical for simplified methods is that they cannot handle complex sky luminance distributions. They are only applicable to azimuthally invariant sky models, mostly uniform or overcast.
- According to output: do they produce mean, minimum or maximum values, or can they handle arbitrary reference points?
- According to “form”: do they consist of tables, equations, protractors, nomograms, dot charts or diagrams?
- According to underlying light transfer model: are they based on the Flux Transfer method, the Lumen Method, or do they have another foundation?

In order to compute the direct and the indirect components it is possible to use different methods. These methods can be combined them or used for both components.
Regarding the direct component, it depends on the shape of the windows, their transmission characteristics and their four positions relative to the reference point and its calculation it is often captured in graphical or tabular form.

Waldram diagram is one method that consists of a grid of squares. Each square represents an equal portion of daylight factor, on which it is possible to draw the projections of windows and obstructions as seen from the reference point. In order to know the direct component of the daylight factor, one simply needs to count the squares within the outline of the projection. The Waldram diagram has been designed to have vertical edges, which remain vertical in the projection. In order to consider the cosine law of illumination and the nonuniform luminance of the sky vault, the horizontal edges, however, need to follow the shape of the so-called "droop lines". In Figure 8 an example in Waldram diagram for a vertical glazed aperture, including corrections for glazing losses, with a large window and an obstructing tower proposed in (Geebelen, 2003) is shown.

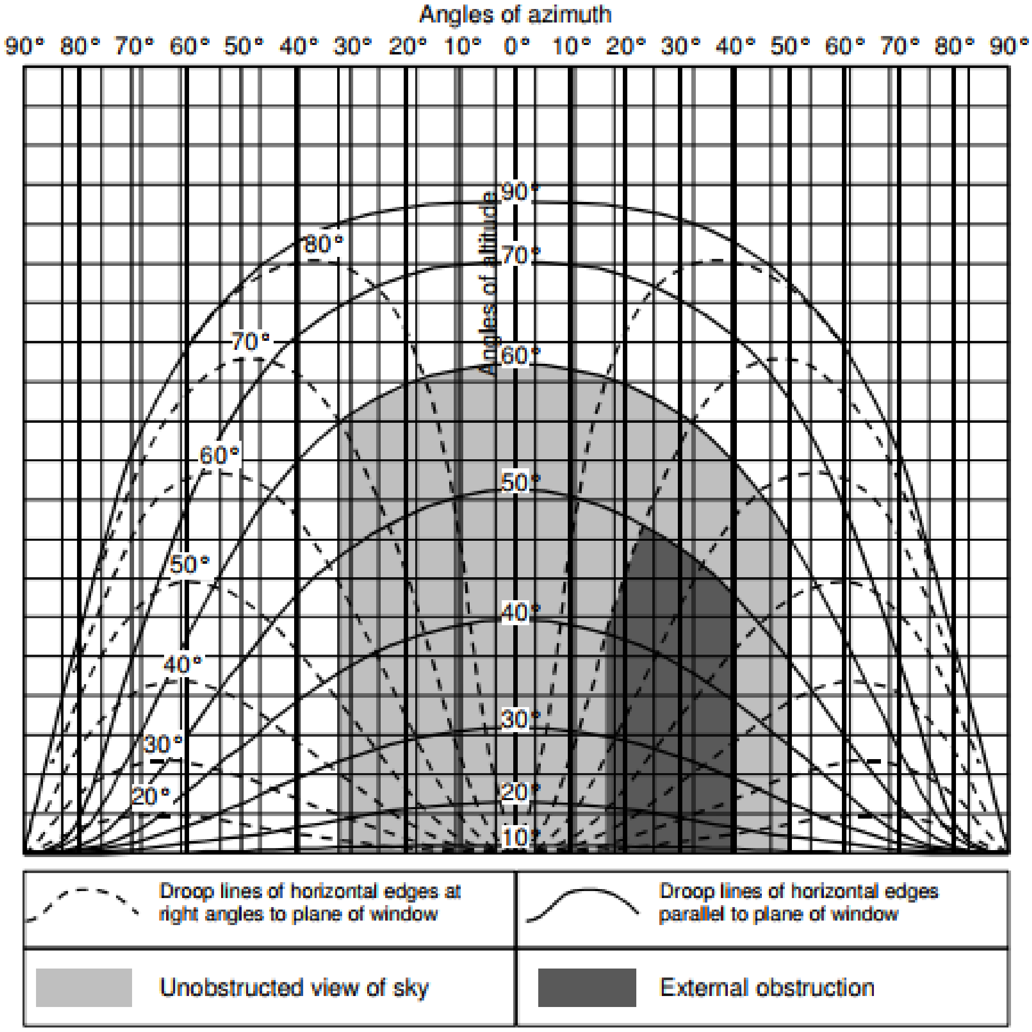


Figure 8. Example in Waldram diagram for CIE Overcast Sky and vertically glazed apertures, including corrections for glazing losses, with a large window and an obstructing tower (Geebelen, 2003)

The method is based on the luminance distribution of an overcast sky and allows for accounting glazing losses. Even if it is an old method, it can be tedious, but an accurate way to obtain the direct contribution of skylight in a particular point in the room.

The diagram designed by Pleijel (Pleijel, 1954) is similar. It is composed by dots. The direct component of daylight can be obtained by counting the dots that fall within the contours of the projection. One advantage of this method is that the density of the dots in the graph accounts for the non-linearity of the illumination, so that projections can be made without deformations. The drawback, however, is that counting the dots can become a very tedious task.

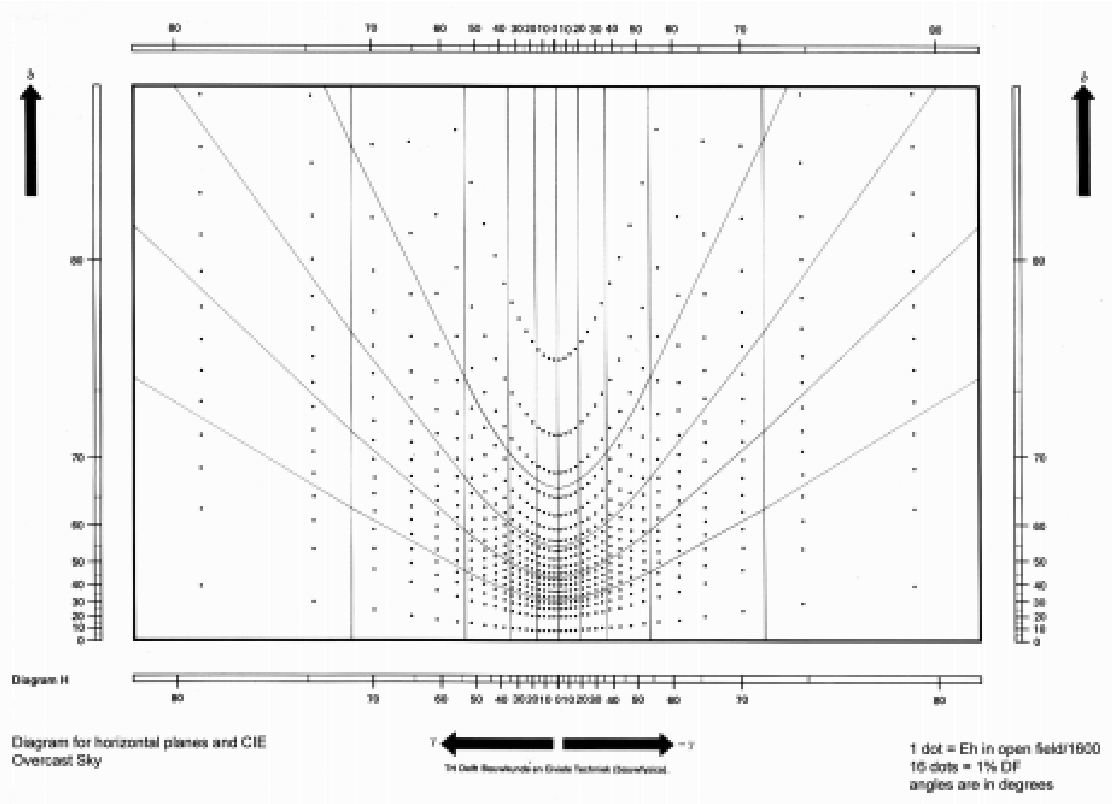


Figure 9. "Pepper-pot diagram or dot chart for the sky component of the daylight factor on horizontal planes (Pleijel, 1954) (Geebelen, 2003)

The BRS Daylight Protractors are probably the most widely used (Building Research Establishment, 1986). In order to apply this method, two graphical tools are used. The first one is a primary protractor or daylight scale, and one auxiliary protractor or correction scale. They are available for different sky types and various slopes of glazing. Moreover, they can be used straight onto plans and sections of the proposed room. Figure 10 and Figure 11 show the Component Protractors for Vertical and Horizontal Glazing. The primary protractor is placed onto a section drawing. By the difference between the readings of the top and bottom edge, it is possible to know the sky component or the equivalent sky component of an external obstruction. The secondary one is placed onto a plan and provides the correction factors (in general equal to 0.2) for windows of finite length. It is not so easy to use this method for irregular compositions. However, it can be assumed as an average simple outline.

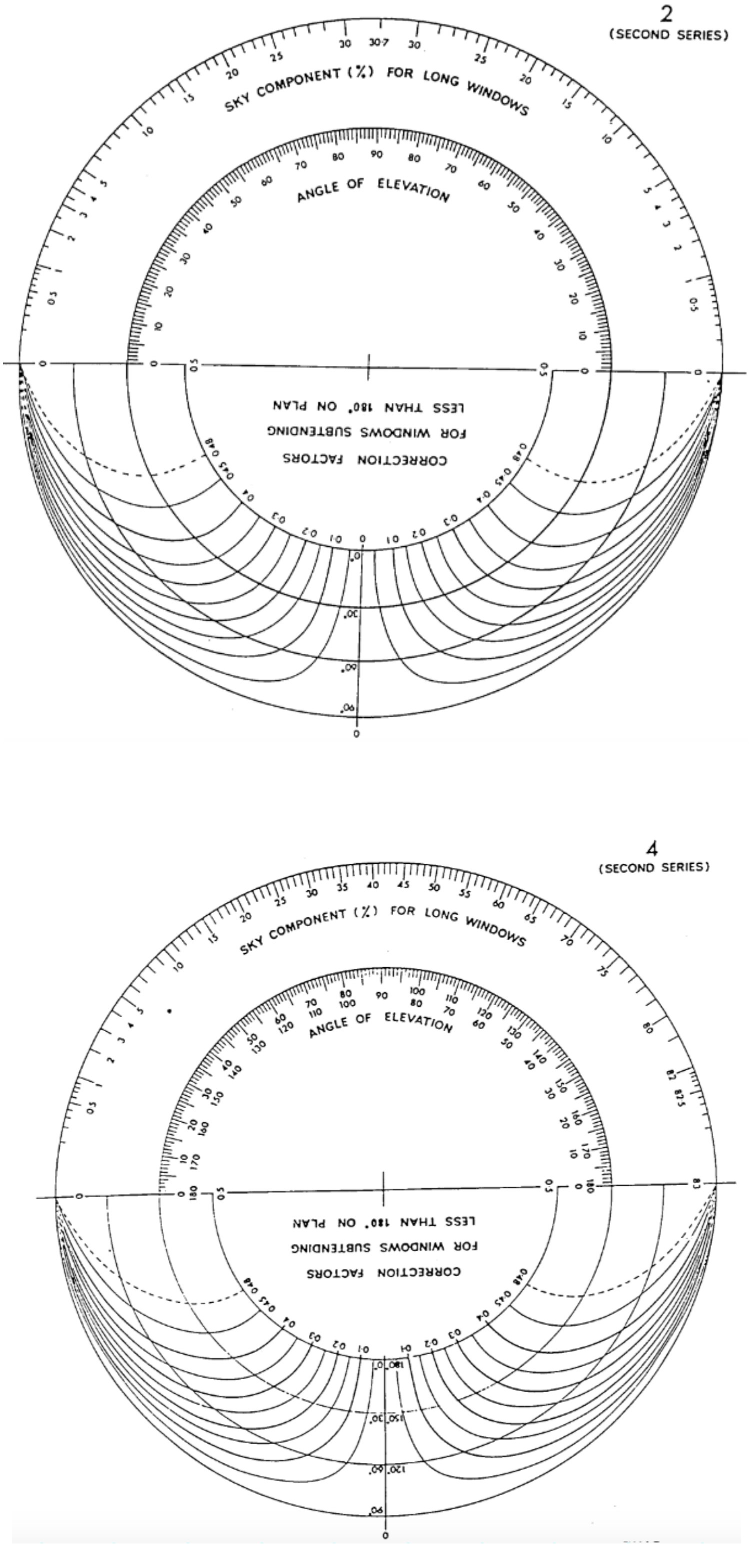


Figure 10. BRS Sky Component Protractor for Vertical (above) and Horizontal (below) Glazing (CIE Overcast Sky)

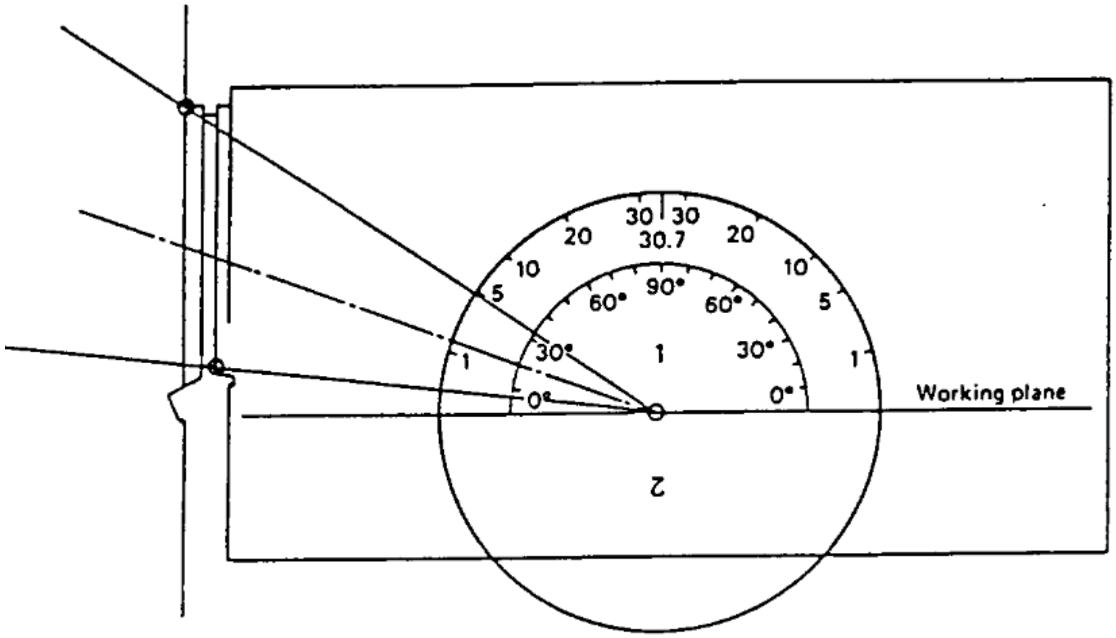


Figure 11. Example of positioning of BRS protractors for the CIE Standard Overcast Sky and vertical windows

Sky component of the daylight factor [%]

Ratio height of window above working plane : distance from window [-] \ Ratio width of window to one side of normal : distance from window [-]	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.2	1.4	1.6	1.8	2	2.5	3	4	6	∞
∞	1.30	2.50	3.70	4.90	5.90	6.90	7.70	8.40	9.00	9.60	10.70	11.60	12.20	12.60	13.00	13.70	14.20	14.60	14.90	15.00
5	1.20	2.40	3.70	4.80	5.90	6.80	7.60	8.30	8.80	9.40	10.50	11.10	11.70	12.30	12.70	13.30	13.70	14.00	14.10	14.20
4	1.20	2.40	3.60	4.70	5.80	6.70	7.40	8.20	8.70	9.20	10.30	10.90	11.40	12.00	12.40	12.90	13.30	13.50	13.60	13.70
3.5	1.20	2.40	3.60	4.60	5.70	6.60	7.30	8.00	8.50	9.00	10.10	10.60	11.10	11.80	12.20	12.60	12.90	13.20	13.20	13.30
3	1.20	2.30	3.50	4.50	5.50	6.40	7.10	7.80	8.20	8.70	9.80	10.20	10.70	11.30	11.70	12.00	12.40	12.50	12.60	12.70
2.8	1.10	2.30	3.40	4.50	5.40	6.30	7.00	7.60	8.10	8.60	9.60	10.00	10.50	11.10	11.40	11.70	12.00	12.20	12.30	12.30
2.6	1.10	2.20	3.40	4.40	5.30	6.20	6.80	7.50	7.90	8.40	9.30	9.80	10.20	10.80	11.10	11.40	11.70	11.80	11.90	11.90
2.4	1.10	2.20	3.30	4.30	5.20	6.00	6.60	7.30	7.70	8.10	9.10	9.50	10.00	10.40	10.70	11.00	11.20	11.30	11.40	11.50
2.2	1.10	2.10	3.20	4.10	5.00	5.80	6.40	7.00	7.40	7.90	8.70	9.10	9.60	10.00	10.20	10.50	10.70	10.80	10.90	10.90
2	1.00	2.00	3.10	4.00	4.80	5.60	6.20	6.70	7.10	7.50	8.30	8.70	9.10	9.50	9.70	9.90	10.00	10.10	10.20	10.30
1.9	1.00	2.00	3.00	3.90	4.70	5.40	6.00	6.50	6.90	7.30	8.10	8.50	8.80	9.20	9.40	9.60	9.70	9.80	9.90	9.90
1.8	0.97	1.90	2.90	3.80	4.60	5.30	5.80	6.30	6.70	7.10	7.80	8.20	8.50	8.80	9.00	9.20	9.30	9.40	9.50	9.50
1.7	0.94	1.90	2.80	3.60	4.40	5.10	5.60	6.10	6.50	6.80	7.50	7.80	8.20	8.50	8.60	8.80	8.90	9.00	9.10	9.10
1.6	0.90	1.80	2.70	3.50	4.20	4.90	5.40	5.80	6.20	6.50	7.20	7.50	7.80	8.10	8.20	8.40	8.50	8.60	8.60	8.60
1.5	0.86	1.70	2.60	3.30	4.00	4.60	5.10	5.60	5.90	6.20	6.80	7.10	7.40	7.60	7.80	7.90	8.00	8.00	8.10	8.10
1.4	0.82	1.60	2.40	3.20	3.80	4.40	4.80	5.20	5.60	5.90	6.40	6.70	7.00	7.20	7.30	7.40	7.50	7.50	7.60	7.60
1.3	0.77	1.50	2.30	2.90	3.60	4.10	4.50	4.90	5.20	5.50	5.90	6.20	6.40	6.60	6.70	6.80	6.90	6.90	6.90	7.00
1.2	0.71	1.40	2.10	2.70	3.30	3.80	4.20	4.50	4.80	5.00	5.40	5.70	5.90	6.00	6.10	6.20	6.20	6.30	6.30	6.30
1.1	0.65	1.30	1.90	2.50	3.00	3.40	3.80	4.00	4.30	4.60	4.90	5.10	5.30	5.40	5.40	5.50	5.60	5.60	5.70	5.70
1	0.57	1.10	1.70	2.20	2.60	3.00	3.30	3.60	3.80	4.00	4.30	4.50	4.60	4.70	4.70	4.80	4.80	4.90	5.00	5.00
0.9	0.50	0.99	1.50	1.90	2.20	2.60	2.80	3.10	3.30	3.40	3.70	3.80	3.90	4.00	4.00	4.00	4.10	4.10	4.20	4.20
0.8	0.42	0.83	1.20	1.60	1.90	2.20	2.40	2.60	2.70	2.90	3.10	3.20	3.30	3.30	3.30	3.30	3.40	3.40	3.40	3.40
0.7	0.33	0.68	0.97	1.30	1.50	1.70	1.90	2.10	2.20	2.30	2.50	2.50	2.60	2.60	2.60	2.60	2.70	2.70	2.80	2.80
0.6	0.24	0.53	0.74	0.98	1.20	1.30	1.50	1.60	1.70	1.80	1.90	1.90	2.00	2.00	2.00	2.10	2.10	2.10	2.10	2.10
0.5	0.16	0.39	0.52	0.70	0.82	0.97	1.00	1.10	1.20	1.30	1.40	1.40	1.40	1.40	1.50	1.50	1.50	1.50	1.50	1.50
0.4	0.10	0.25	0.34	0.45	0.54	0.62	0.70	0.75	0.82	0.89	0.92	0.95	0.95	0.96	0.96	0.96	0.97	0.97	0.98	0.98
0.3	0.06	0.14	0.18	0.26	0.30	0.34	0.38	0.42	0.44	0.47	0.49	0.50	0.50	0.51	0.51	0.52	0.52	0.52	0.53	0.53
0.2	0.03	0.06	0.09	0.11	0.12	0.14	0.16	0.20	0.21	0.21	0.22	0.22	0.22	0.22	0.23	0.23	0.23	0.23	0.24	0.24
0.1	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.08	0.08

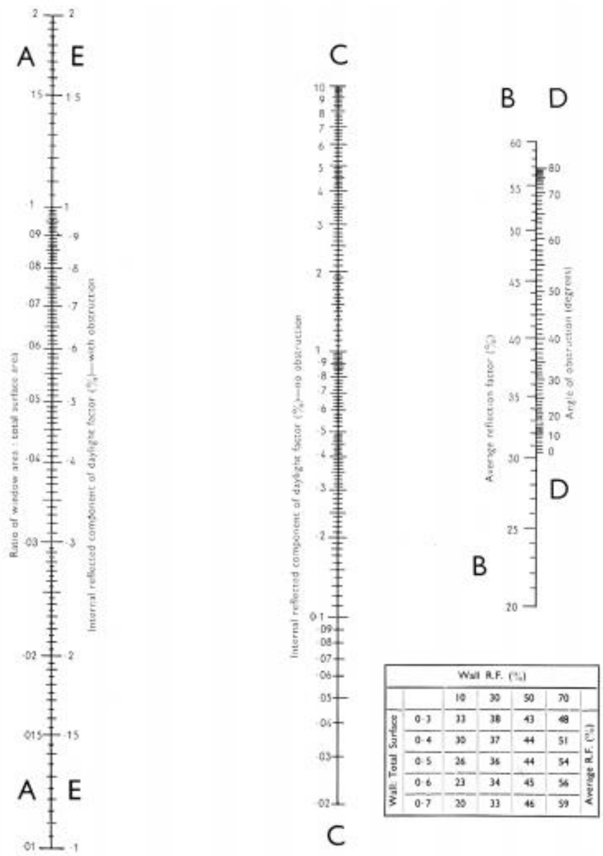
Table 4. BRS Simplified Daylight for vertical glazed rectangular windows. (Building Research Establishment, 1986)

The BRS Simplified Daylight Tables can be used without scale drawings. For very simple geometric compositions these tables provide the sky component.

On the contrary, it is not easy to estimate of the reflected component, because it depends on scene geometry and material properties of all surface finishes in the scene that are not easily parametrizable and translate them into graphical form. Most simplified methods for the internally reflected component therefore consist of equations and nomograms. The internal reflections are described by a formulae series, but most of them can be traced back to only a few basic ways of abstracting the scene.

The Split-Flux Method considers a scene with only two surfaces: the floor with the part of the vertical walls below the centre of the window and the ceiling and the part of the vertical walls above the centre of the window. In this case it is assumed that the light from the sky is distributed over the lower part and the externally reflected light over the upper part (Baker et al., 3013).

Another alternative to equations are the nomograms. An application example of this method is shown in Figure 12. It allows the computation of the average internally reflected component for side-lit rooms. It is not adequate to use this method for complex case. Furthermore, each nomogram is based on an assumption of the distribution of reflectance values. It is not possible to differentiate the upper and lower part of the scene. This can cause discrepancies with the values that are computed using an equation.



	Wall R.F. (%)				
Wall: Total Surface	10	30	50	70	
0·3	33	38	43	48	Average R.F. (%)
0·4	30	37	44	51	
0·5	26	36	44	54	
0·6	23	34	45	56	
0·7	20	33	46	59	

Figure 12. Nomograms (Building Research Establishment, 1986)

Several authors studied method and models to predict illuminance values from daylight contribution (Littlefair, 1985) (Kittler, 1999) (Moon, 1942) and even today, many traditional methods, e.g. physic models under an artificial sky or CIE sky models, are used to quantify the daylight contribution.

Tsangrassoulis and M. Santamouris (Tsangrassoulis and Santamouris, 2000) presented a practical methodology to estimate the round skylight efficiency and hence the amount of daylight that reaches the interior of a room equipped with these devices. Their method is based on a model of the distribution of the luminous energy inside the round skylights for various height-to-width ratios (H/r), wall reflectance and transmittances of the glazed cover under diffuse skylight and sunlight.

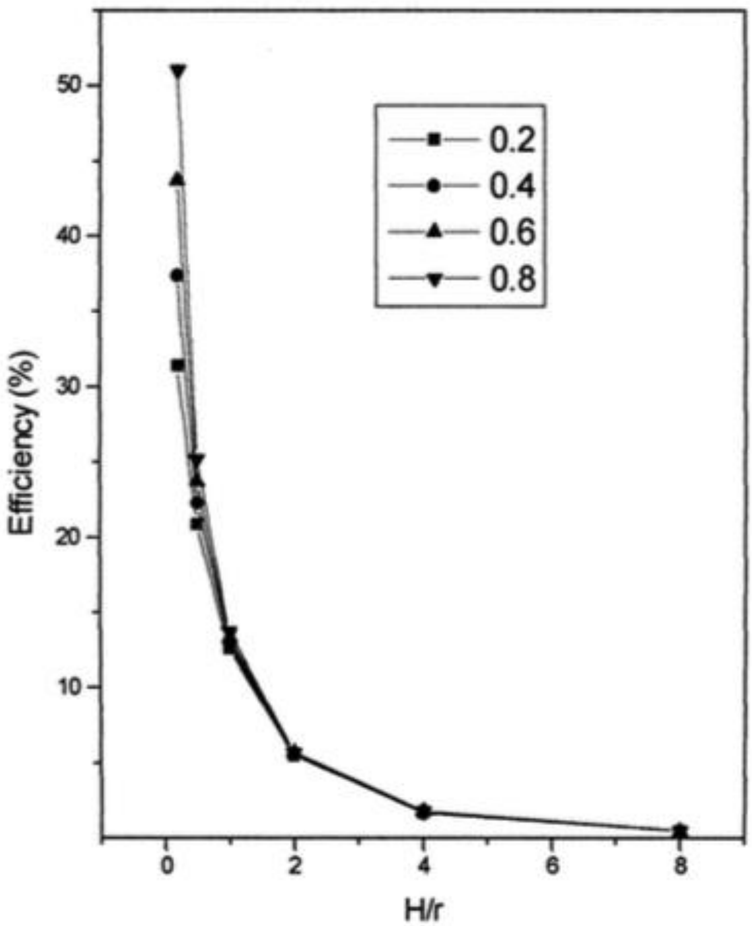


Figure 13. Round efficiencies as a function of the aspect ratio H/r for various values of reflectance ρ_2 (Tsangrassoulis and Santamouris, 2000)

Other researchers used physical models. They are also common to assess daylighting performance of buildings using sky simulators for purpose of research as well as practice. But there is a tendency of scale model assessments to over-estimate the performance. In general, they are expressed through work-plane illuminance and daylight factor profiles. Indeed, as well known, there are several sources of experimental errors, such as modelling of building details, mocking-up of surface reflectance and glazing transmittance, as well as photometer features They can cause discrepancy between buildings and scale models.

Thanachareonkit (Thanachareonkit et al., 2005) analysed the main sources of errors comparing a full-scale test module designed for experimentation of daylighting systems and its 1:10 scale model, placed within identical outdoor daylighting conditions. Authors noted many discrepancies between the performance figures (some caused by slight differences in surface reflectance and photometer cosine responses). In particular, they lead, on average, to a relative divergence of +60% to +105% in favour of the scale model for different points located in the side lit room. By increasing the effort to carefully mock up the geometrical and photometrical features of the test module, discrepancies have been reduced to a +30% to +35% relative divergence.

Li et al. studied a calculation model to preview the daylight illuminance in a heavily obstructed environment under overcast and non-overcast skies (Li et al., 2009) (Li et al., 2010). They affirmed that the sunlight reflected by vertical facades and ground can represent an important source in the illumination of buildings. In their study, authors examined the fraction of sunlit surface and presented it in terms of solar geometry. Finally, they developed a calculation tools in the form of simple equations and diagrams through computer simulation analysis. Furthermore, they validated the developed method against the daylight illuminance obtained by other independent computer simulations and full-scale measurements under real sky conditions. In this nomograph approach, they considered the sky divided in several patches that contributes to the internal illuminance level at a point, using a chart and two scales A and B to determine the daylight illuminance for the CIE standard skies (Li DHW et al., 2004).

Unfortunately, this method is long and complicated for the computer process. The results showed reasonably good agreement with the measured data and showed that the DC approach could give satisfactory results especially for the sun-shaded surface and sun-facing surface receiving a large amount of direct sunlight.

Reinhart and Herkel (Reinhart and Herkel, 2000) by applying six Radiance-based methods, simulated the annual indoor illuminance distribution for two office geometries located in Germany. As demonstrated by the results, two of these methods based on daylight coefficient, showed the lowest relative root mean square errors (RMSEs) for the straightforward office geometry.

Mardaljevic (Mardaljevic, 2000) examined the DC approach with the software RADIANCE (Radiance) and using measured data from the office of the Building Research Establishment (BRE) (Building Research Establishment, 1986). Yu and Su (Yu and Su, 2014) compared the DF method and DC method in the case study of an educational building in Nottingham, UK. Each method has vantages and disadvantages. The study of Yu and Su demonstrated indeed that the real annual energy saving potential might lie between the values obtained by DF and DC methods. The DF method represents the worst case, but e.g., the DC method does not consider the possible occupant reaction to oversupply of daylight.

Tregenza also proposed simple calculation procedures for determining the daylight illuminance in rooms facing sunlit streets (Tregenza, 1995).

Regarding the use of mathematical methods applied to evaluate automated control systems, Athienitis and Tzempelikos (Athienitis and Tzempelikos, 2002) developed a method for numerical simulation of daylight. In particular, they considered an office space equipped by an advanced automated shaded system. The aim was to calculate dimming levels for electric lights to provide the additional illuminance required so as to minimise electric energy consumption for lighting. Furthermore, they estimated daylight transmittance equations for the window system from experimental measurements. Researches of ENEA Institute studied a more accurate method to know the needed electrical energy for artificial lighting when the daylight level is not suitable. They tested this method and the standard EN 15193 one for an office building and presented the comparison of results (Zinzi et al., 2014).

Finally, other works present some manual calculation algorithms to estimate the potential energy saving from daylight. Li DHW et al. apply one of these in several researches (Li and Lam, 2001), (Li DHW et al., 2010), (Li and Lam, 2003), (Li et al., 2006). Authors used cumulative frequency distribution of daylight illuminance. It is based on field measurement of the illuminance and so of the daylight availability that is presented graphically in the form of frequency of occurrence. Converting it graphically into the cumulative frequency distribution of the daylight availability, it could determine the necessity of using artificial lighting and possible energy saving from on–off or top-up lighting control. For the on–off control, the energy saving could be observed directly from the cumulative frequency distribution of the daylight availability as it is simply given by the fraction of time when the daylight illuminance exceeds the threshold illuminance level. While for the top-up control, which varies the light output in accordance with the prevailing daylight level, the process of determining the potential energy saving is a bit more complicated and is shown in researches by Li et al.

Another algorithm, developed by Alzoubi and Al-Zoubi (Alzoubi and Al-Zoubi, 2010), contrary to the first one, uses the average indoor daylight illuminance and does not consider the illuminance variance in accordance to the distance from the window.

It can be used to calculate the energy consumption for both cooling load and artificial light when the room is lit with daylight. They simulated the lighting by LIGHTSCAPE and calculated the illuminance level at different distances from the window. Comparing these values with the values suggested by the standards, it is possible to know the excessive or insufficient amount of light, which leads to the artificial lighting consumption as a supplement.

The disadvantage of this algorithm is that it is only available to calculate the energy consumption for a time point. The third advantage is that it considers the arrangement of the luminaire and sensor position.

In following section, a study of Roisin et al. (Roisin et al., 2008), where it has been applied to study the energy savings in a single office room, is presented. This algorithm has been coupled with another one that includes the algorithm of the control system. This is an important improvement because the energy saving from daylight is directly related to the properties of dimming control system.

Doulos et al. (Doulos et al., 2008.) applied it considering the operation equations of different control algorithms. By the software DAYSIM the illuminance values on the workplane has been simulated. Through the equations it is possible to determine the required dimming percentage, then converted into the consumed light power, using the simulating data. The potential energy saving, achievable in a simulated office, was quantified by the above method for two control algorithms. The first was integral reset and the second one was a closed loop. The results showed that the annual energy saving for different pairs of ballasts various from 66.91–72.82% and 70.35–76.09% for closed loop and integral reset, respectively. It seemed that the integral reset algorithm performed better than closed loop on the aspect of energy saving, but the closed loop algorithm could provide more constant designed set illuminance level during the day.

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2. Technologies for lighting control systems

The main “materials” used to implement a lighting system are obviously luminaires and lighting sources. The selection of them is important and can affect and compromise the efficiency of the whole system. But, with the market diffusion of the automated control of lighting system, the number of technologies typology is increased and there are always more and more sophisticated. Indeed, these systems differ in their control method, parameters, algorithm, cost of installation, complexity of operation, maintenance and commissioning. It is important to know how to correctly manage design and operation variables because they can strongly affect the system performances in terms of energy savings as well as visual comfort and user acceptance.
The aim of this chapter is to investigate among the existing lighting control systems, to have a picture of their applications and an overview of their performances in real conditions and case studies.

Bellia et al. (Bellia et al., 2015) mentioned the factors that can influence the performance, in terms of the energy savings achievable, of lighting control systems for each category of controls.

Affecting factors category	**Affecting factors**	**Timers**	**Occupancy-based controls**	**Daylight-linked controls**
Factors depending on the control system’s typology	Control strategy	x	x	x
	Occupation pattern	x	x	-
	Sensor’s typology	-	x	x
	Sensor’s location	-	x	x
	Sensor’s spatial response	-	x	x
	Sensor’s spectral response and sensitivity	-	x	x
	Sensor’s time-delay	-	x	x
	Control algorithm	-	-	x
	Calibration process	-	-	x
Factors depending on the lighting system’s characteristics	System efficacy	x	x	x
	Variation in absorbed power depending on systems’ setting (total installed power, stand-by power, power corresponding to different luminous scenes, etc.)	x	x	x
	Relationship between power consumption and related light output	-	-	x
	Relationship between sensor signal and related light output	-	-	x
	Location and zoning of luminaires	-	x	x
Factors depending on the indoor daylight availability	Outdoor daylight availability (site’s latitude or longitude, day of month and time of day, sky cover)	-	-	x
	External obstructions	-	-	x
	Room’s typology (geometric and optical characteristics, orientation)	-	-	x
	Glazing and shading typology	-	-	x

Table 5. Control systems' performances affecting factors (Bellia et al., 2015)

The factors depending on the control system's typology are: control strategy, occupancy pattern, sensor's typology, sensor's location, sensor's spatial response, sensor's spectral response and sensitivity, sensor's time-delay, control algorithm and calibration process. As factors that depend on system' characteristics there are: the lighting system's absorbed power, depending on systems' setting (total luminous scenes, etc.), the relationship between power consumption and light-output, the relationship between sensor signal and light output, location and zoning of luminaires and the overall system efficacy. Authors summarized in Table 5 these factors.

Ul Haq et al. (ul Haq et al., 2014) did an interesting review on lighting control technologies in commercial buildings. They classified such systems in four categories of operation:

- Occupancy-based control schemes;
- Daylight-linked lighting controls;
- Lighting control by time scheduling;
- Mixed control systems.

In particular for the first category, authors identified as factor that can influence the performance the effect of Time Delay (TD) and the effect of occupancy pattern. The time delay is a pre-fixed time before it turns off the lights after a space is unoccupied in order to avoid frequent switching of lights if the users leaving the room for a short period. Setting a short delay time, the luminaires would be turned on for shorter time and so it would be achieved higher energy savings, but this could provide disturbing for occupants (Maniccia et al., 1999), technical problems to the control system and decrease the lamps lifetimes.

Von Neida et al. (Von Neida et al., 2001) investigated on the impact on energy savings due to changes in time delay. To do this, they investigated a set of buildings located in 24 states, characterized by different end uses (offices, classrooms, restrooms, break rooms and conference rooms) an occupied by different people in age, ownership, occupancy type, etc.. Authors carried out simulations of system's behaviour using different time delay settings (5, 10, 15 and 20 minutes). The results showed significant differences in savings between the maximum (20 min) and minimum (5 min) time delay setting. They ranged between the 17 and the 50%.

In some studies, has been demonstrated that setting a fixed TD for all time in not suitable, because the activity level of occupants can be different occupant by occupant, as well as time by time. Indeed, as observed by Garg and Bansal (Garg and Bansal, 2000) the activity level of a user changes over the time of the day and the activity level of different users is different. In their research presented the design of smart occupancy sensors that can change TD being able to learn the variation in activity level of the occupants with respect to time of the day. Experiments conducted have shown that about 5% more energy can be saved by using smart occupancy sensor as compared to non-adapting fixed TD sensors.

Leephakpreeda proposed an adaptive TD system (Leephakpreeda, 2005) controlled via Grey (Zhao and Magoulès, 2012) using data about the users' past activity modelling the occupancy behaviour by the Pareto distribution for determining such delay time based on probability of no false off-switch. The real-time control implementation for lighting an office room is used to illustrate a viability of the proposed methodology in practical use for energy saving.

As well, the occupancy pattern in the room plays a key role for the energy performance of this kind of lighting control systems. In particular, higher energy saving can be achieved with a less frequent or irregular occupancy of a room, e.g. a classroom. Having said that, it is important to underline that a simple timer switch can substitute an occupancy detector if the room is constantly occupied by people without any significant breaks throughout the activity period.

Between the factors that can affect the performances of the Daylight linked control systems, first of all there is the daylight availability in the room that in turn, as well known, depends on many parameters, e.g. sky conditions (Serra, 1998), windows optical properties (i.e. visual transmittance), orientation and position and obstruction (e.g. trees, buildings, billboards, etc.).

Another factor is the control method. It must be selected carefully. As it will be explained in following session, lamps could be switching or dimming and the sensor can be controlled by different algorithms (e.g. closed or open loop). Finally, it must be pay attention selecting the proper tuning of control parameters, i.e.:

- the task illuminance levels, that has to be set to make sure that adequate level of light is provided to the users at all time notwithstanding daylight availability;
- the delay settings, that must be set paying attention to the 'dead band', a range of lux levels through which lamps will not be switched, to make sure the switching is not frequent or disturbing to the users (Li et al., 2010)
- the placement of the sensor, that would be ideally the task plane, even if not practically suitable. In general, the photosensor are located on the walls, on the ceiling or directly integrated in the lamps. So, it is important to select the exact point that can provide higher performance of the system, according to the characteristics of the room, lighting conditions and photosensor algorithm, trying to select a point where photosensor detects a sample of daylight that best represents the daylight availability of the task surface in the control zone (DiLouie, 2008), where there is not direct light (even if high reflections of the room surface can provide problems even in absence of direct light).

2.1 Control systems hardware devices

The devices of a lighting control system have to be able to receive a signal, to elaborate it and to send a command to the so-called actuators. The main devices are:

- Control unit;
- Active devices;
- Passive devices;
- Actuators;
- Controlled devices.

2.1.1 Control Unit

The control unit is a switchboard able to manage the control system. It receives the input signals from the active and passive devices, elaborates and sends them to the actuator to define the actions. It is able to identify the devices of the systems, to define the actions to perform and identify the controlled device.
The complexity of the control system depends on the unit characteristic. It works to send the signals using software and drivers. Furthermore, it can control simple or complex automation systems and send the signals to one or many actuators.

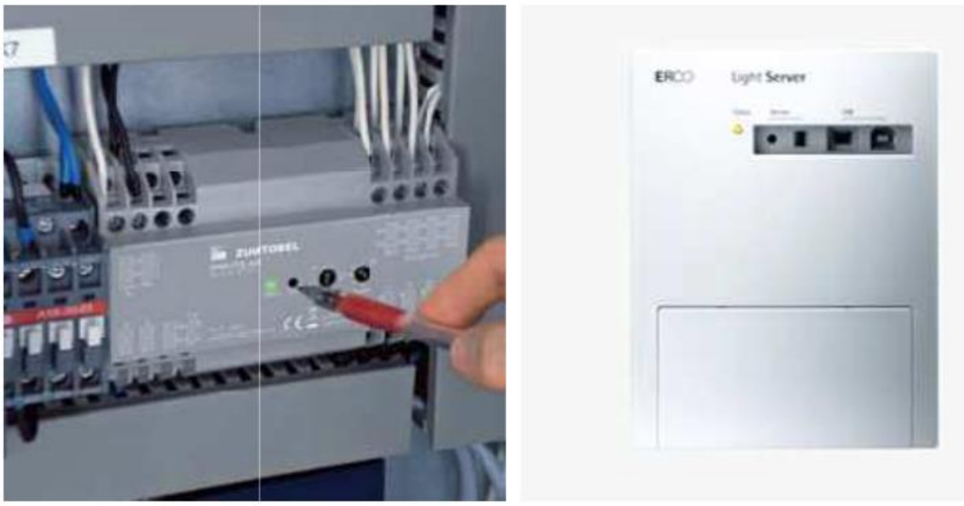

Figure 14. Central unit examples

The control unit can manage different functions and can communicate with other parts of the plants. This communication is based on a language, called protocol.

In following sections, a briefly description of the most famous protocols will be done.

2.1.2. Active devices

The active devices are able to work automatically according to the conditions of the environment where they are installed (i.e. photosensors, motion detectors, heliometers and twilight sensor) or according to the pre-set time (i.e. timers).

2.1.2.1. Sensors typologies

The sensors can be divided according to the functions for which they have been produced:

- Photosensor;
- Motion detectors;
- Image processing devices.

2.1.2.1.1. Photosensors

Photosensors can detect the quantity of daylight contribution in the point where they are installed.

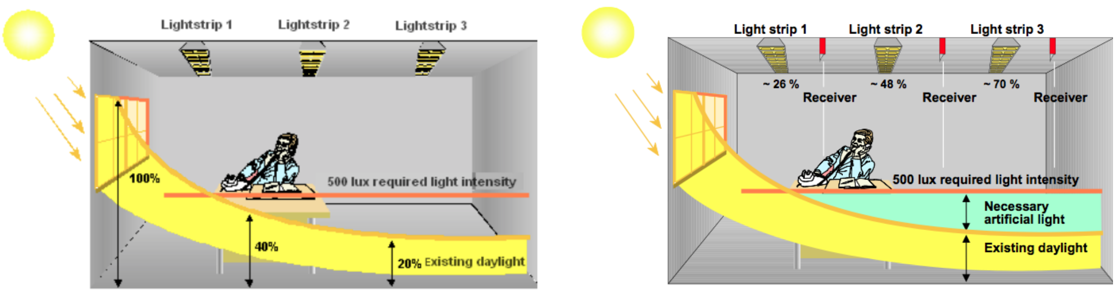

Figure 15. Brightness control optimised for all areas of the room (Source: Konnex)

They are equipped by an electric circuit and a photosensitive element.
The first part is able to convert the visual signal to the electric signal. It determines the management of the electronic ballast of the luminaries. The photosensitive element can be a sensor or a photoconductor. The first is a diode and produces a voltage quite proportional to the visual signal in order to dim the lamps. While, in the second case the sensor can send a voltage inversely proportional to the visual signal linked by an exponential relation. The diode is more precise to translate the signal and can be equipped by spectral filter based on the luminous efficiency function V (λ). It works to filter only the visible wavelength in order to select only the natural lighting component. The

photoconductor is less precise and for this reason is often used for outdoor application (not object of this thesis).

Daylight-linked systems can elaborate the signals measured by the photosensors by using two different algorithms and, in particular:

- Closed Loop;
- Open Loop.

The open loop manages the luminous flux considering only the daylight contribution from outdoor or the luminance of the window. Based on the level of available daylight, it sends corresponding signal to the controller to provide corresponding lamp output. It works with a photosensor able to measure external brightness value, which is independent of the internal illuminance that is to be set. According to this value, the internal illuminance control value is determined via any calculation function, which the room illuminance uses to reach the required task point illuminance. The feedback loop for this system is missing because it only detects available daylight levels. It can have advantages and disadvantages. One advantage is that they can never oscillate since the feedback loop has been omitted as mentioned. So, it is possible to have many different control curves with the measured value of a single sensor. But, many adjustments must be done for continuous control, which takes at least one day.

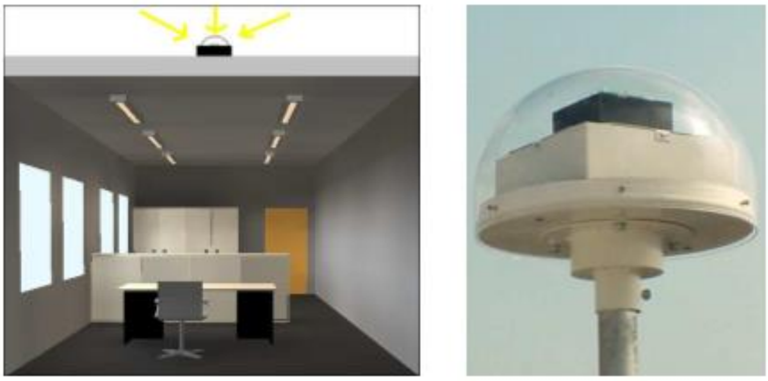

Figure 16. Openloop sensor located on the roof

Figure 17. Open loop photosensor located indoor on the ceiling

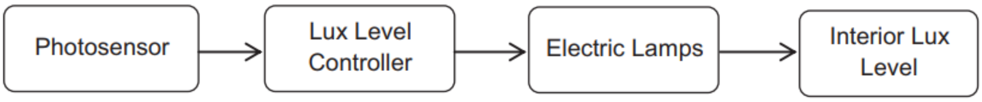

Figure 18. Daylight linked open loop control system

In general, they can be located or on the roof or inside the room, oriented toward the windows.

General guidelines give some suggestion to locate the photosensors:

- Photosensors have to detect correctly the daylight;
- It is necessary to pay attention there are not objects and structures which can obstruct the external photosensors (they could read the shade as cloudy conditions);
- When there are skylight systems it is necessary to locate the photosensors under them and to protect them from the weather;
- When sensors are on the ceiling, with daylight from the sides, it is necessary to locate them at a distance calculated as 2/3 of the whole room depth.
- When there is only one workplane, the photosensor should be located upon it;
- When there are more than a workplane, photosensor should be locate on the part that receives a more neutral daylight or the luminaires should be separated in different control groups;
- If it is possible, the sensors should be placed where there is not the direct flux of the luminaires.

The open-loop can be often divided in continuous control and two-step control systems as better explained in "Strategies" section.

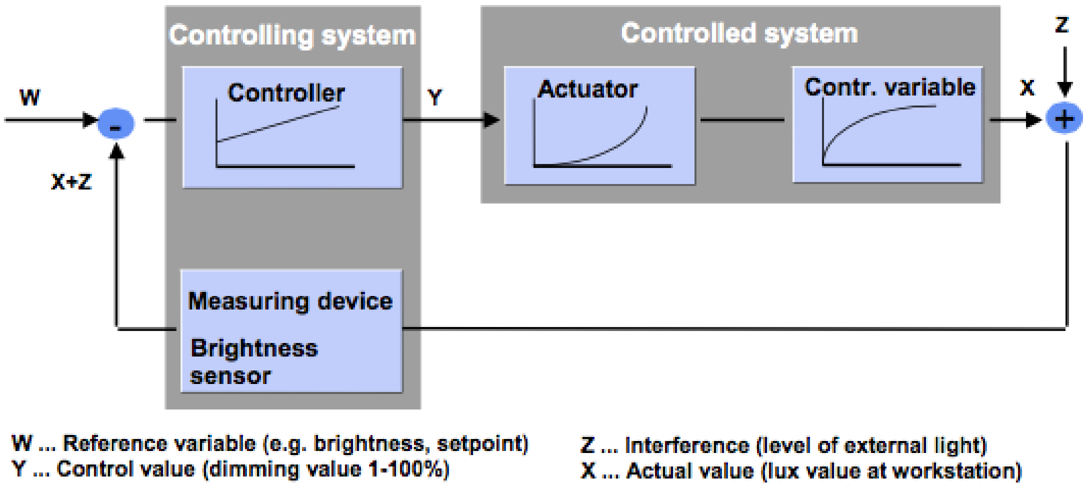

Figure 19. Constant lighting control scheme (Source: Konnex)

The closed loop sensors are installed always in the room and consider both the natural and the artificial components of light. It is also called "constant lighting control". Indeed, the required level of brightness in the room or the level of lighting at the desk, is measured as a controlled variable together with the interference from the external light and then fed back to the actuators in the appropriate manner.
It could control more precisely, but if it is not configured correctly it can decrease the performance of the system. In general, installation guidelines suggest installing them on the ceiling and at a distance from the window as 2/3 of room depth.

Figure 20. Closed-loop photosensor (Aghemo et al., 2009)

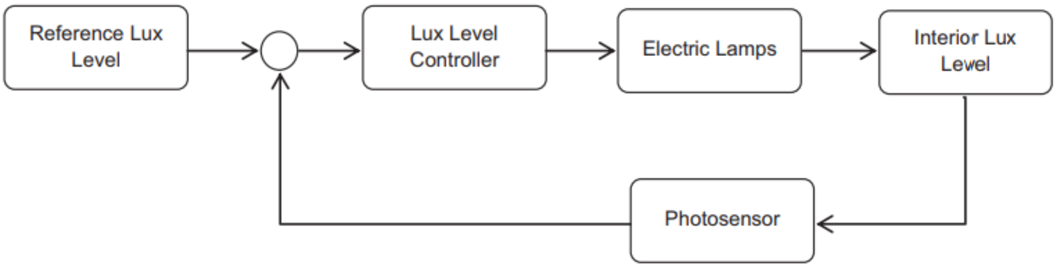

Figure 21. Daylight-linked closed loop algorithm flowchart (ul Haq et al., 2014)

Sometime the manufactures guideline suggests to choose position and configure the photosensor by recommending that the surface should be as undisturbed as possible and that it should not receive direct light from outside and from the luminaires. Furthermore, in case of several strips of luminaires, the placement of one sensor for each strip is suggested. If it is not possible, the position should be optimised to control the strip closer the window, which is the most sensitive to daylight changes. The other strips can be interfaced via a control function (e.g. offset adjustment through master/slave circuit). In general, it can be affirmed that with this kind of systems, the more external light comes in, the greater the measuring error, because the natural light also is picked up by the sensor rod directly instead of only from the controlled surface by reflection. Indeed, they work on the one hand according to the different lighting spectrum of natural light and artificial light and, on the other hand, to the different angle of illumination. As shown in following figure, a curve of the controlled variable is produced. It depends on the external brightness which reaches its minimum in a ratio of 50:50 between the proportion of external and internal light. The system must always be balanced under these lighting conditions (Konnex).

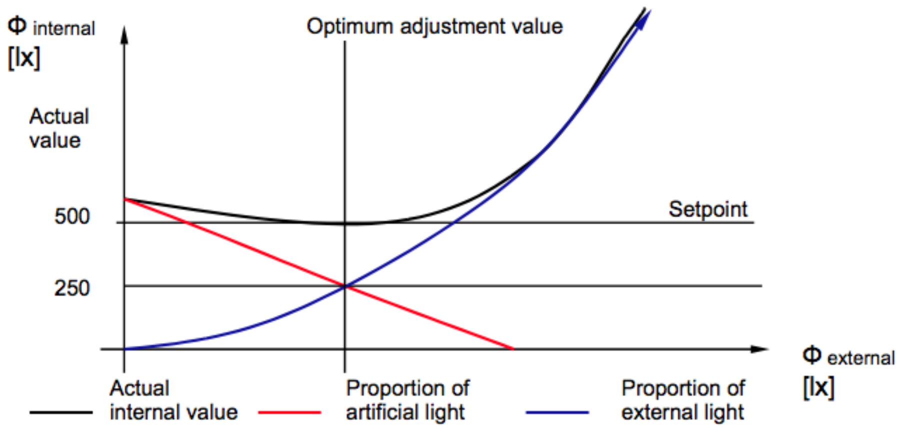

Figure 22. Behaviour of the actual values dependent on the level of external light (source: Konnex)

Anyway, in general, the choice of installing an open or a closed loop depends on the specific situation and could be important for planning commissioning operations. The installation of a closed loop can be more appropriate if there is a single zone to control. While an open loop sensor is more adequate to control multiple zones, e.g. open space for an open plan office spaces.

Other advanced algorithms have been developed in last years. Fischer et al. (Fischer et al., 2012) proposed an illumination model-based method and an algorithm for intelligent open-loop lighting control. Authors presented the results of a simulation study using a simplistic virtual office model to demonstrate the validity of the method. In particular, they addressed the challenges of meeting users' individual lighting preferences using a highly accurate illumination model to enable balancing the various lighting requirements among spatially grouped task areas, while minimizing the energy needed to do so.

2.1.2.1.2. Motion detectors

Motion detectors are able to detect the presence of someone in the room in order to switching on or off the luminaries. They can be divided in categories according to the occupancy detection technique.

Passive Infrared (PIR) sensors detect the temperature variation due to the presence of human. The closer is the presence, more sensible is the sensors to detect the temperature in the detection zone (Guo et al., 2010). Unfortunately, this kind of sensors can give problems, e.g. the so-called "false-off", i.e. the lights are switched off despite occupancy because there are gaps in the sensing zone of PIR sensors, which can be significantly wide as they go further from the sensor. This can happen due to detection principle of the PIR sensors. Movements within these gaps may not be detected properly by the sensors (Serra, 1998). The field of view of the sensor must be clear and without objects that can obstruct the view or indentations. Furthermore, a common detector it is not able to detect slight motion of a sedentary activity.

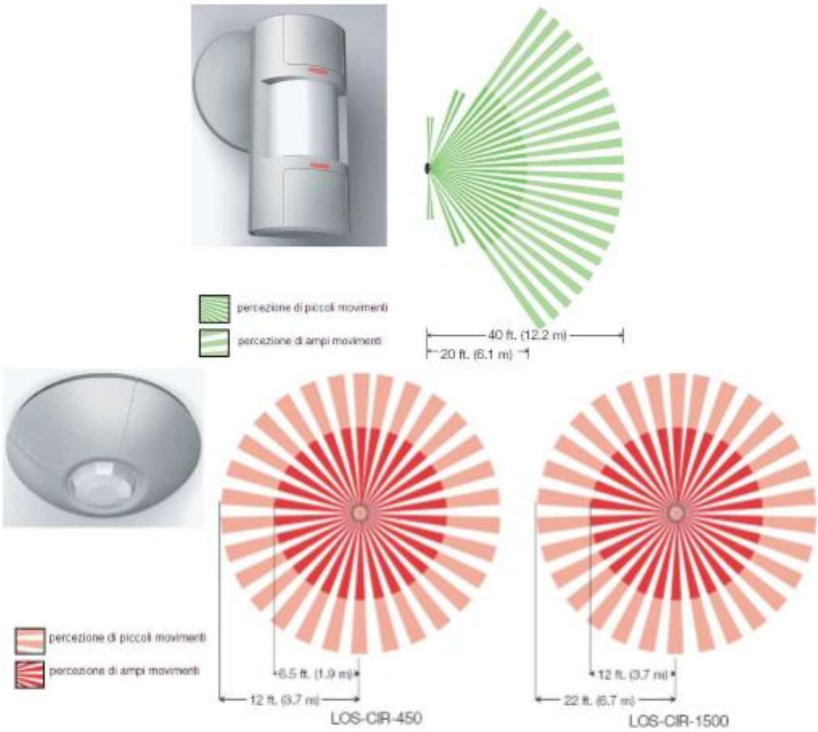

Figure 23. Some examples of field of view of infrared motion detectors and of their sensibility (source: LUTRON)

The second type of motion detectors is called "ultrasonic". It works emitting ultrasounds to the space basing on the principle of "Doppler Effect". When someone is in the room the normal wave of these ultrasounds changes.

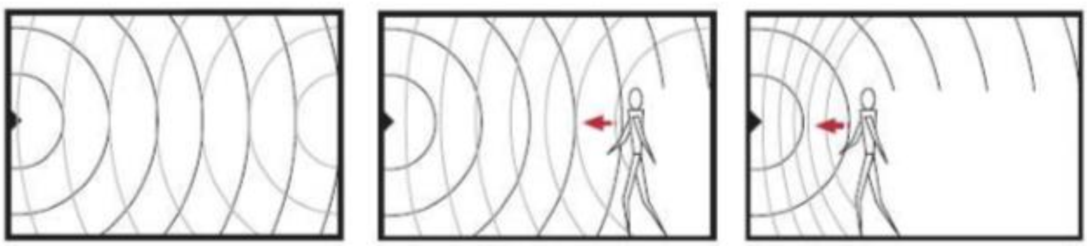

Figure 24. Concept scheme of how an ultrasound motion detector works.

This kind of sensors are much more effective in detecting occupant motion as well because is that ultrasonic waves are reflected by room surfaces, so ultrasonic occupancy sensors do not require a field of vision as compared to the PIR sensors. Unfortunately, the added sensitivity causes problems in this type of sensors and movements coming from activities in the room other than occupant movement can trigger the sensor. Furthermore, like for the PIR sensors, the detection accuracy gets lower when subjects are further from the sensors, due to the gradual weakening of the reflected ultrasonic waves.

Radio Frequency Identification (RFID) lighting control works using Radio Frequency Identification (RFID) to detect occupancy and is gaining focus in lighting research. In general, they are inserted in ID cards and can be used to identify people in office or public buildings, but some researchers suggested to use RFID as a supportive technology to existing occupancy detection scheme.

By the aid of the added information from the RFID system, the shortcomings of the existing system can be minimized. Manzoor et al. (Manzoor et al., 2012) investigated the use of passive RFID detection to aid the detection process of the Passive Infrared (PIR) system already installed in an open plan office space. Authors proposed a methodology to minimize the Time Delay (TD) setting of lighting control scheme to further increase energy savings by fusing occupancy data with that of PIR (Passive Infrared) sensors used to control a building's indoor artificial lighting. The method showed improvement of building lighting control in comparison to the *PIR-Only* method which relies only on PIR sensors. Observational and empirical analysis results show that up to 13% of electrical energy can be saved in one day (13 hours) from only one office area with regular office occupants or users. Practical implementation of RFID gateways provides real-world occupancy profiling data to be fused with PIR sensing towards analysis and improvement of building lighting usage.

2.1.2.1.3. Image processing devices

The last typology of motion detector uses imaging techniques. The research focus on this kind of systems in order to develop a novel occupancy detection approach to minimize false detection and non-detection in occupancy-controlled lighting systems starting from the problem that the conventional occupancy detection techniques are still not free from false errors. To do this, it is possible to use cameras as sensors to detect presence of occupants.

Liu et al. studied a system (Liu et al., 2012) that would take advantage of surveillance cameras installed in many rooms. Authors proposed an algorithm, which takes image frames from the static surveillance cameras, installed in open plan office room and detects presence of human heads. Results proved the efficiency of the system and that it is accurate in determining human presence.

The similar system, developed by Benezeth et al. (Benezeth et al., 2011), uses video information to subtract the background and develop a background model. In this way, system can recognize occupants in the video frame.

Newsham and Arsenault (Newsham and Arsenault, 2009) and Sarkar (Sarkar et al., 2008) developed an image based control systems using CMOS based cameras that can provide luminance information. It is more flexible on usage besides just occupancy detection, providing luminance information of a space for proper daylight harvesting and shading control. Moreover, installed camera can be further used for security purposes and fire detection. Also, authors suggested that a single camera can combine the applications of multiple separate sensors effectively. As well for the motion detectors, there are some typical installation guidelines. According to these, it can be located on a vertical surface (on a wall) or on a horizontal surface (i.e. on the ceiling) and it is necessary to know its view field.

Some sensors are able to work both as photosensors and as motion detectors. If the daylight is not enough to achieve the task illuminance the luminaires switch on, but only if someone is in the space.

2.1.2.2. Timers

Timer is a device that opens or closes the relay of the electric circuit to turn on and turn off the luminaires according to pre-set time schedules. In this way the luminaires are turned on only during the occupancy time. The scheduling could be daily, weekly or yearly and based on different seasons.

2.2.2 Passive devices

Passive devices need manual operations to be set (i.e. switches, touchscreens, remote controls devices, keyboards, etc.). Switches work to switch on and off the luminaires manually. Traditional ones open and close the electrical circuit acting on the 1-10v signals. Nowadays, the switches interface on digital signals (DSI-DALI-BUS) and do not interrupt the circuit, but control the output signals.

Figure 25. Picture of some switches

Keyboard, remote control device and touch screen work to manage several functions and scenarios. The third one has a more sophisticate and technologic interface.

Figure 26. Picture of some keyboards

The actuators are devices that have to receive the information elaborated by the controller and translate them in actions sending to the terminal devices, i.e. the luminaires. Luminaires can be controlled by their ballast that switch on, switch off or dim the lamps (Montoya et al., 2017). As well luminaires and lamps have to be selected according to the application, the space and the end use, and, mainly the electronic ballasts compatible with the Protocol. A long review could be done about the lighting sources and the luminaires, but it is not useful to the aim of this thesis.

2.2. System architecture

According to the logic that controls the system, its architecture can be categorized as:

- basic systems and/or able to be integrated with other systems (stand-alone);
- centralized systems;
- centralized systems integrated with building automation systems.

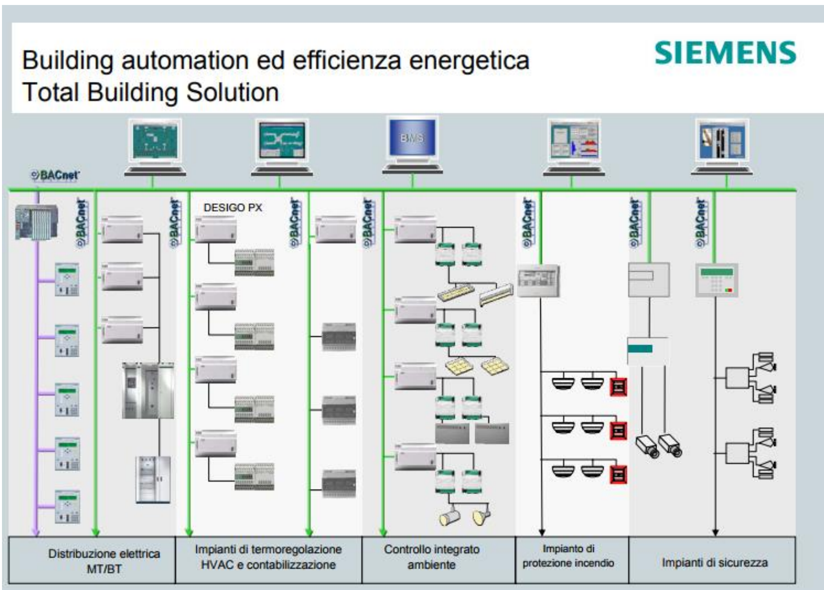

Figure 27. Conceptual scheme of a Total Building Solution functions (source: Siemens)

The first type of systems is composed by some devices, which receive input data from the environment or from the user and translate them to signals for the luminaires. Their architecture scheme is hence simple because there is not a hierarchy. They can work alone and are often integrated into the luminaires. In this case it is not necessary a control unit because signal is sent directly to the ballast of the luminaires. Obviously, in general these systems have limited number of functions.

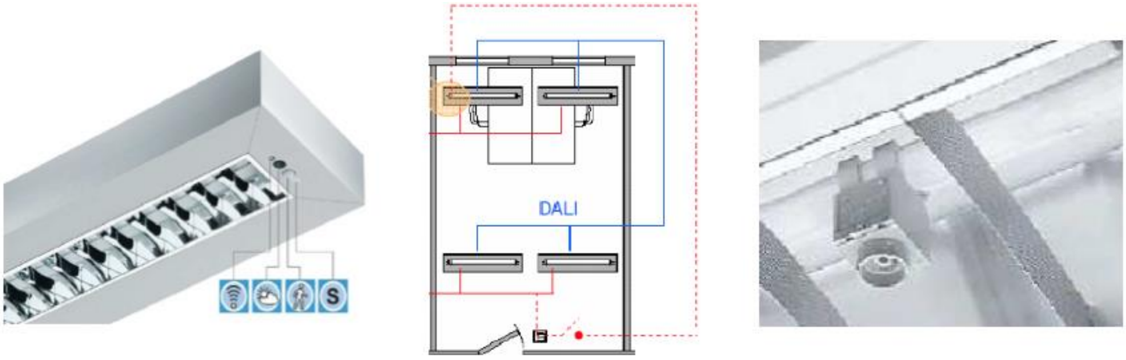

Figure 28. Example of basic system (source: Philips)

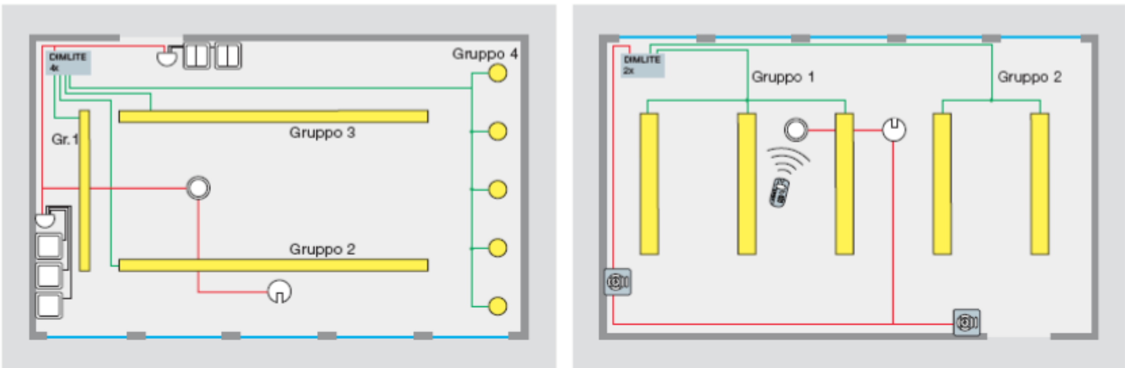

Figure 29. Stand-alone schemes examples (source: Zumtobel)

A centralized system is based on a central unit that works as a "supervisor" on different part of the whole system by managing them and processing the signals sent by sensors. The data are received by the control unit. It translates them and send the command to the actuators that control the terminal devices according to their functions. These systems, bigger than the stand-alone ones, are able to manage different functions. Sometime the centralized system can be part of a building automation systems. These are large systems that can be controlled in different complexity layers (e.g. HVAC, lighting systems, telecommunication devices, systems for safety, etc.). Lighting control systems are only a part of these systems. They can work independently or communicate with the other subsystems (e.g. automated shading systems).

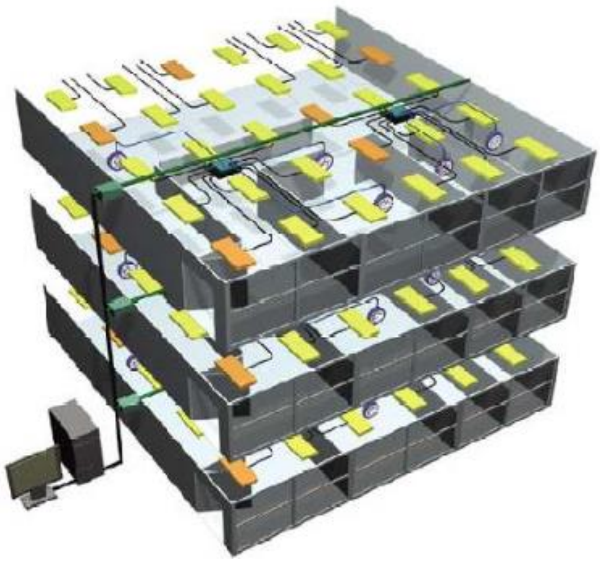

Figure 30. Centralized system architecture (source: PHILIPS)

Furthermore, based on the communication protocols used by the system, the architecture can change, also according to the manufactures standards. E.g., in figure 31 the scheme of the architecture used for the protocol EIB/KNX (following described) is shown. The system is divided in areas (with a maximum of 15) and lines. A central line connects areas. In each area there is a main line and, where can be connected, second lines (with a maximum of 15 lines). Sensors and actuators are connected to the lines with a maximum of 256 for each line divided in 4 segments of line where a maximum of 64 devices are connected. An Area Coupler connects the main lines to the central line and the Line Coupler connects the second lines to the main line. For each line it is necessary to provide a bus line to supply the connected devices (29V DC SELV).

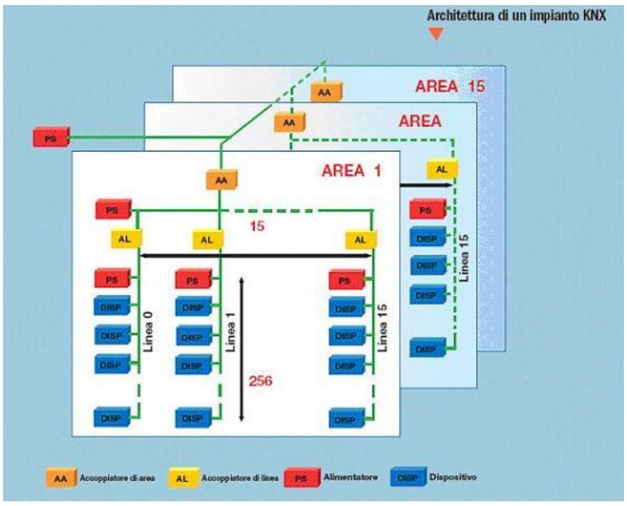

Figure 31. Conceptual scheme of the architecture used by the Konnex protocol (source: Konnex)

The couplers are necessary in order to isolate electrically the parts of the system in case of failure of a single device and to “filter” the message sent from a single device in order to avoid that they are sent to the whole network system.

2.3 Protocols

The protocols can be defined as the "language" that control systems speak. They work to manage and control input and output data flow from/to CU and field devices (sensors, luminaries or other kind of equipment). In order to communicate and to be able to understand the data associated to signals, the different parts of the system must speak the same language. It is necessary to select the protocols according to the devices and the size of the system. So, it is possible to say that protocols are procedures used by automated systems for communication between all devices with the ability of “controller”.

Also, protocols can be classified as "open standard" (free use for all), under license standard type (open to all licensed) or owner type (solely for the manufacturer or manufacturers owners) (The Cambridge, 2012).

In case of lighting control systems, the signals can be analogic or digital. The first kind of signal is generally related to the voltage of a DC circuit between the CU and the device (Figure 32). They are usually called “1-10V”. They are characterised by continuous values in a certain interval and the codification is done by an electromagnetic wave that change continuously. Usually this communication is adopted for simplified lighting systems.

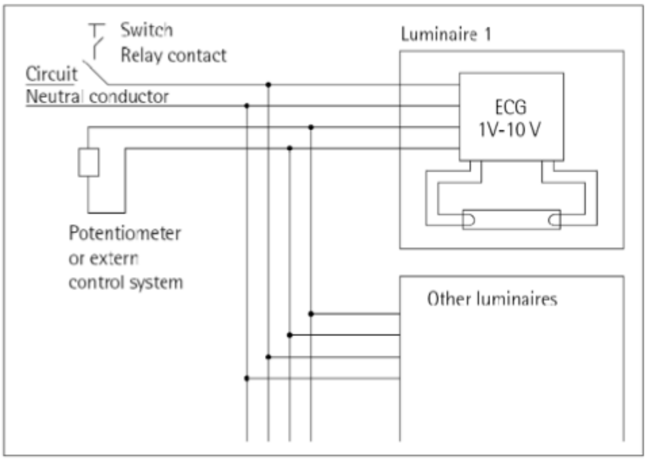

Figure 32. Communication scheme of 1-10V (source: ERCO)

Management of electronic signals is a more complicated task. Data have discrete values represented in binary form. Nowadays, there are many existing automation standards for communication by electronic signals. The more common are: DALI, DMX, Konnex o EIB and LonWorks. DALI (Digital Addressable Lighting Interface) is a communication interface that has the advantage to be a product used only for lighting control. For this reason, the communication speed has been decreased in order to contain production costs and to make easier the installation operations. A DALI based CU is able to manage 64 electronic ballasts and 16 power supply devices groups. In general, it is used for centralized systems and stand-alone ones.

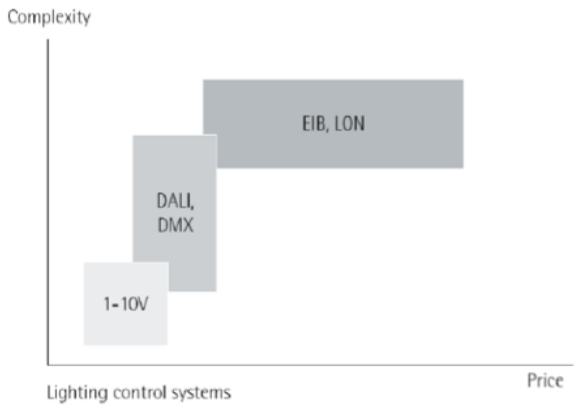

Figure 33. Relation between price and Complexity of communication protocols and data management (Source: ERCO)

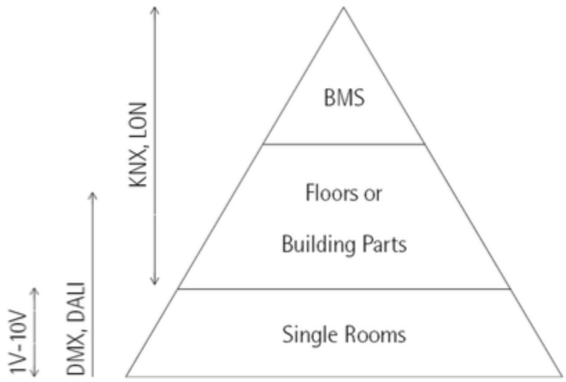

Figure 34. Some example on how to use protocols for different dimensions and typologies of spaces (Source: ERCO)

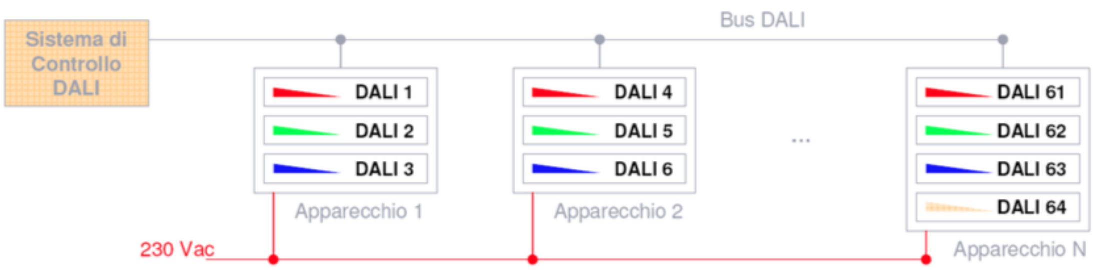

Figure 35. DALI protocols scheme (source: PHILIPS)

The Digital Multiplex Signal (DMX) is a high-speed protocol. In general, it was used for lighting for shows on stage. Nowadays, it is used as well to control the lighting system used to lit the architectural facades or for special lighting effects. For long years, the signals were unidirectional: it controlled the lamps, but it was not able to give information about the lamp status (e.g. to report a problem). This limit has been exceeded with the new version DMX 512. This protocol permits to control an unlimited number of luminaires thought a maximum of 512 addresses with the possibility to use the same address for more channels and by making colour group of luminaries.

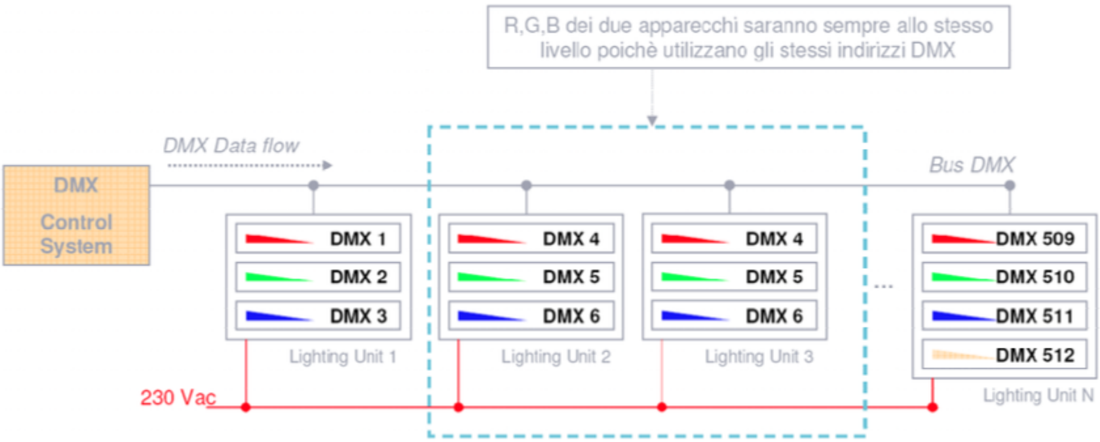

Figure 36. DMX protocol scheme (source: PHILIPS)

The DMX-RDM (Remote Device Management) represents a further evolution. The RDM protocol is able to identify the type of modules (e.g. the kind of lamps or luminaires), to set the module parameter (e.g. the address) and to check the module status (e.g. percentage of dim). It is possible to select many functions, e.g. select the colour or the luminous flux or to program scenarios.

Konnex protocol (KNX) is an open standard for home and building control. It covers the full range of in-house communication options, including twisted pair (TP), power line (PL), radio frequency (RF) and Ethernet (IP). This protocol joins and enhances three legacy bus standards, EIB, EHS, and BatiBUS (Ruta et al., 2014). KNX has a free and decentralized topology with distributed intelligence that can detect, control and monitor the functions and sequences through a unified line of communication. The ANubis (Advanced Network technology for Unified Building Integration) is an initiative to develop an open standard to provide KNX integration to the Internet standards. Its goal is the cost-effective implementation, from small homes up to large buildings, using hierarchical buses. Twelve lines can be used by a BUS and each line can have 255 devices. Furthermore, one coupler can connect up to 15 buses (Toschi et al., 2017). Thanks to this, KNX is very suitable for home automation (Miori et al., 2006) (Miori et al., 2010). In order to implement automated systems in residential buildings, Siemens Instabus is focused on residence energy consumption and provides solutions such as light control, HVAC (heat, ventilation and air conditioning) management and security devices. User can configure, program and manage the system devices with a PC connected by the serial interface RS 232 and the EIB software.

Ruta (Ruta, 2011) proposed backward-compatible enhancements to one of the most widespread building automation standards, i.e., EIB/KNX ISO/IEC 14543-3, able to support advanced, knowledge-based and context-aware functionalities, grounded on the semantic annotation of both user profiles and device capabilities. Authors identified benefits as: determining the most suitable services/functionalities according to implicit and explicit user needs and allowing device-driven interaction for autonomous adaptation of the environment to context modification. They presented a case study to better clarify the proposed framework also highlighting main characteristics, while performance evaluation is provided to assess its effectiveness. Authors introduced a semantic based extension of application layer in KNX standard, preserving legacy applications and opening possibilities for further enhancements, and in (Ruta et al., 2012) a semantic-based approach able to interface users and devices (whose characteristics are expressed by means of annotated profiles) within an advanced home infrastructure.

KNX can be used to configure the system by a PC that has to be connected by BUS. In this way, it is possible to have a graphical interface to program the devices and mainly to identify easily the position of them. As well in this case the signal is bidirectional and it is possible to include also other plants (e.g. HVAC, photosensors and motion detectors, monitoring systems, weather stations, or an actuator controlling building equipment, such as blinds or shutters, safety appliances, energy management, heating, ventilation and air-conditioning systems, and multimedia devices (Toschi et al., 2017)) by permitting the “interoperability” of the parts, even if they are produced by different manufactures (if the companies have adopted the KNX protocols). Furthermore, the KNX is scalable (Bolzani, 2004) and permits to the system growing by adapting to home or building needs and providing an end-to-end communication, enabling sensor and actuators to communicate with low response time in dynamic control situations.

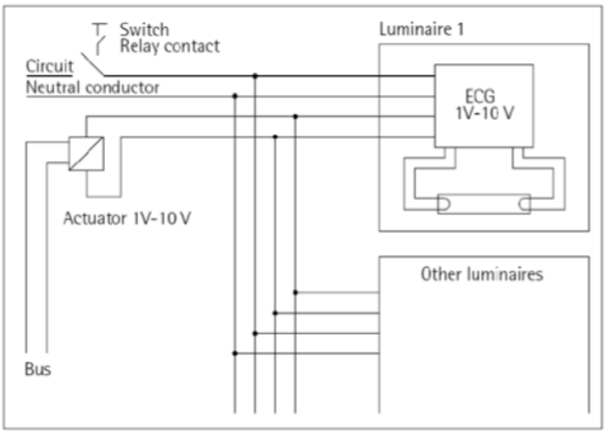

Figure 37. Konnex scheme (Source: ERCO)

Basically, KNX is based on of "datapoints". Inputs, outputs and parameters are datapoint instances from object containers, groups or properties. Those datapoints are standardized and grouped into functional blocks and receive a name, a type and a data format.

Protocol LonWorks (Local Operation Networks), has been developed by Echelon Corporation Company in 1991 in order to support control applications (Lai et al., 2012) and to address the needs of control applications connecting command instruments, measurement instrument, regulation, etc. It is a platform that uses an affiliated Internet Protocol (IP) tunnelling standards in use by a number of manufacturers to connect the devices on previously deployed and new LonWorks platform-based networks to IP-aware applications or remote network-management tools. It is open and permits the interoperability of the system. It has grown in popularity as a protocol for home networks after developing it for building automations or production automations. However, the LnCP was developed as a control network to implement it using a cheap microcontroller, which is installed in home appliances. It can be a good solution for a wide range of networked control systems with a dedicated LonTalk communication protocol (Echelon Corporation), and lighting automation is one of the most important applications (Wen and Agogino, 2011).

Lee et al. (Lee et al., 2009) evaluated its performance by developing a simulation model using state diagram of LonWorks and LnCP, and simulated conditions through analysis of message to be generated in the smart home. While, Tse et al. (Tse et al., 2003) applied it to develop a distributive monitoring system with several features and integrating a low-cost electronic circuit board and a LonWorks control module with an existing emergency lighting circuit to form an intelligent control node in which the maintenance test is performed automatically. The devices of LonWorks includes (Nowak et al., 2011):

- Neuron Chip: a system-on-a-chip with multiple microprocessors, RAM, ROM and IO interface ports;
- Transceiver: an electronic module that provides the physical interface to communicate with other devices;
- Application electronics.

This technology is based on the idea to divide the devices or the systems into different groups (nodes). They are linked by means of communication medium (twisted pair, etc.) creating a network (Tozlu et al., 2012). The LonWorks protocol follows the OSI model and provides services on all the OSI seven layers. It is a complex and complete protocol and has functionalities on each layer (Tolosa, 2014). However, according (Aslam and Lukkien, 2012) if the manufactures add functions to their systems would lose the right to bear the LonMark mark. Anyway, they could convince a “gold member” to endorse their extensions. Moreover, unfortunately not all systems are LonMark systems, but LonWorks right now continue to be used by some vendors who do not wish to be part of the LonMark consortium.

Layer	Name	Characteristics
1	Physical	• Multiple physical mediums • For example, RS-485, free topology (FT), or power line (PLC), wired or wireless technology, and fiber optics
2	Data Link	• MAC algorithm: - Independent control from MAC, based on enhancements of the CSMA, concepts of p-persistent CSMA and non-persistent CSMA - Predictive p-persistent CSMA to support access periodization • Bit encoding: - The cynic redundancy check (CRC) using the CCITT CRC-16 standard
3	Network	• Hierarchical addressing follows the mask: - The node domain - The sub network - The identity number of the node • Simple addressing mechanism allows simple package routing and maintaining a small routing table
4	Transport	• Packet retransmission and duplicate detection • Enables reliable: - Point-to-point transmission - Point-to-multiport transmission • The communication is transparently perceived by the application • Response time control to meet application requirements
5	Session	• Devices and application perform service request and response • Retrieve time control to meet application requirements
6	Presentation	• The Echelons publisher-subscriber • Message header encodes the semantics of the data passed to the application layer following the Echelon's standards
7	Application	• Device logic and core • Internal control of the device • Input processing • Action taking • Peripheral management

Table 6. LonWorks protocol stack summary table (Toschi et al., 2017)

2.4 Control strategies

Lighting control systems can work according to different control strategies. As already said, they can work according to the daylight contribution or according to the presence of occupants in the space. Furthermore, they can be switching or dimmable. In Figure 38, the schemes of the most common control algorithms are shown.

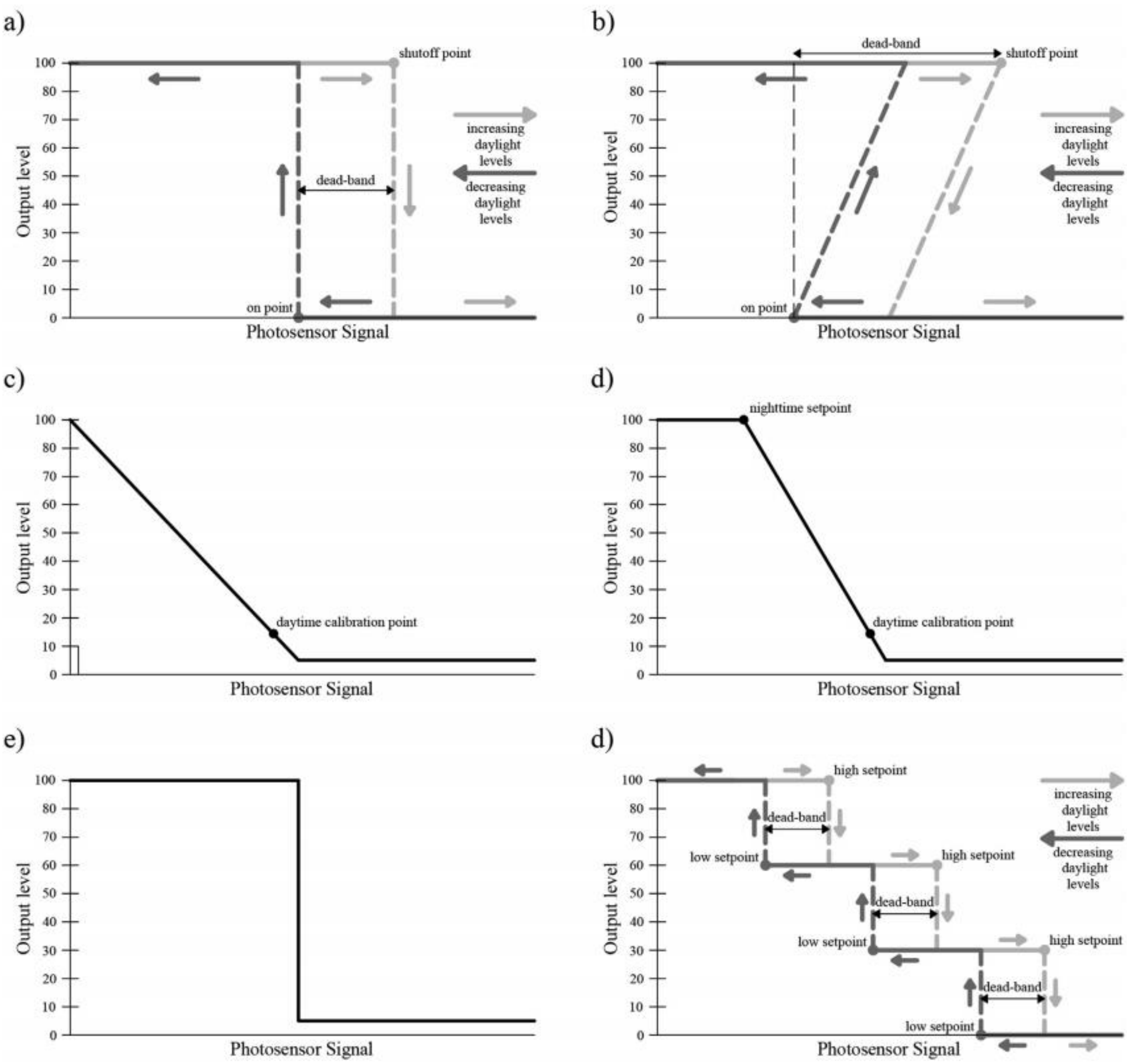

Figure 38. Typical control algorithms: a) Open-loop switching algorithm; b) Closed-loop switching algorithm; c) Open-loop dimming algorithm; d) Closed-loop linear proportional control (or sliding setpoint control) algorithm; e) Closed-loop constant setpoint control (or integral reset control) algorithm; f) Tri-level control algorithm (Bellia et al., 2016)

Talking about the systems that work according to the daylight contribution (Daylight-linked lighting controls) they can control the lights by switching between 'On' and 'Off' states based on available daylight or dim the lamps. In the first case the luminaires turn on when the photosensor measures an illuminance value lower than the pre-fixed task illuminance. In this case, the power absorbed by the system will be the 100% of the

installed one. In case of open loop systems, as already mentioned, it can be often divided in continuous control and two-step control systems. The continuous typology works using dimmers or dimming actuators, which can be infinitely adjusted.
Given that, it is not possible to adjust automatically the control value (due to the missing feedback loop), and it is necessary to select a control function. In the simplest case, it can be a straight line determined by two pairs of values:

- maximum external brightness above which there should be 100% interior lighting;
- minimum brightness level above which the light should be switched off.

Furthermore, it is necessary to locate the control module in a position to carry out a hysteresis in order to ease control in the extreme range between switched on and switched off (Konnex).

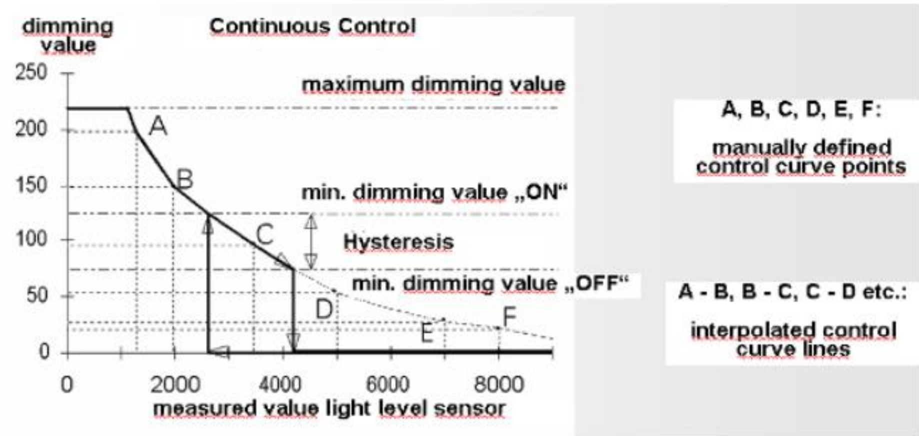

Figure 39. Typical curve for brightness control - a hysteresis is advisable (Konnex)

This curve is further simplified for the "two-step control" because only two states are possible for the controlled lamps: ON or OFF

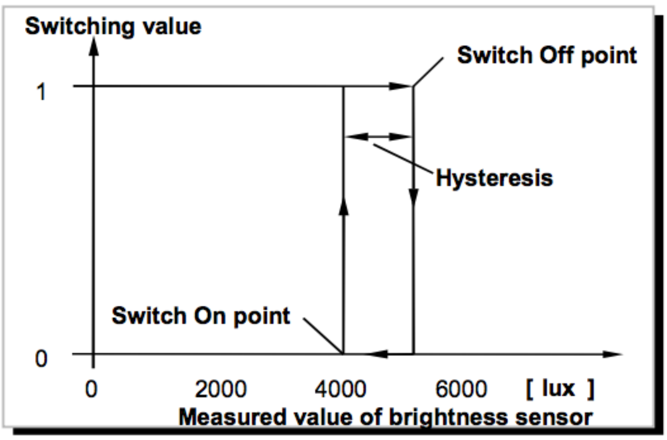

Figure 40. Principle of two step control (Konnex)

In closed-loop systems, the operation procedure can contain three different feedback logics:

- Proportional (P): a direct control output ‘y’ is calculated for the dimming actuator from the setpoint/actual value differential ‘x’ via simple, linear conversion function according to the function y = a.x (Figure 38)
- Integral (I): the control output is integrated with a specific rate i.e. it is zero at the beginning and reaches the calculated value y = a.x.t only after a certain period (Figure 38)
- Differential (D): the control output is determined from the rate of change of the system deviation y = x/t (Figure 38)

The proportional controller can be used directly by these basic functions of control technology. However, it leads to a systematic deviation which cannot be reduced because the requirement to avoid oscillations. In this case, an integrating controller could work better because it could find stability after a certain period in which it remains while there are no changes to the external light intensity.
A differential controller works more quickly if some parameter change. Furthermore, for an adequate visual confront it could be fulfil that the change in the brightness level runs almost imperceptibly for the user. Furthermore, the extreme variations of the outdoor lighting should also not cause an imbalance of the lighting control. P and D controllers are not so common for lighting control systems. Only integral (I) action control is in practice sufficient to fulfil the requirements of the user.

Finally, the luminaires can work according to occupancy schedules. Using timers, it is possible to select pre-fixed time when the lighting system work. It is useful to use this strategy in spaces where the occupancy pattern is accurately predictable so in very specific part of the day, e.g. classrooms, common spaces and outdoor lightings.
It can be applied using a device called time switches or time clocks. The programming can be do via personal computer interface to run through daily, weekly, monthly or even annual cycles.

Comparing with the other strategies, the advantage is the cost more affordable. The controller can be “stand alone” or integrated in lighting panels of the control system.
In case of time schedule programming or motion detectors a multilevel switching can be applied. It makes sure the users or not exposed to complete darkness suddenly dimming the lamps step by step. In case of an override, the time switch should automatically return to scheduled mode after a certain time (National Electrical Manufacturers Association, 2006). Ribinstein and Karayel (Ribinstein and Karayel, 1984) reported savings in office building applications between 10% and 40%.

Scheduling systems are commonly used in combination with other control systems like occupancy sensors and photocells as well. These systems are able to use more than

one the explained strategies. These systems can be used in different cases according to improve the performance using the strategies adequate for the situation.
Furthermore, ul Haq affirmed that in order to ensure maximum amount of savings without compromising user satisfaction, researchers have experimented with combinations of multiple types of control schemes in one system (ul Haq et al., 2014).

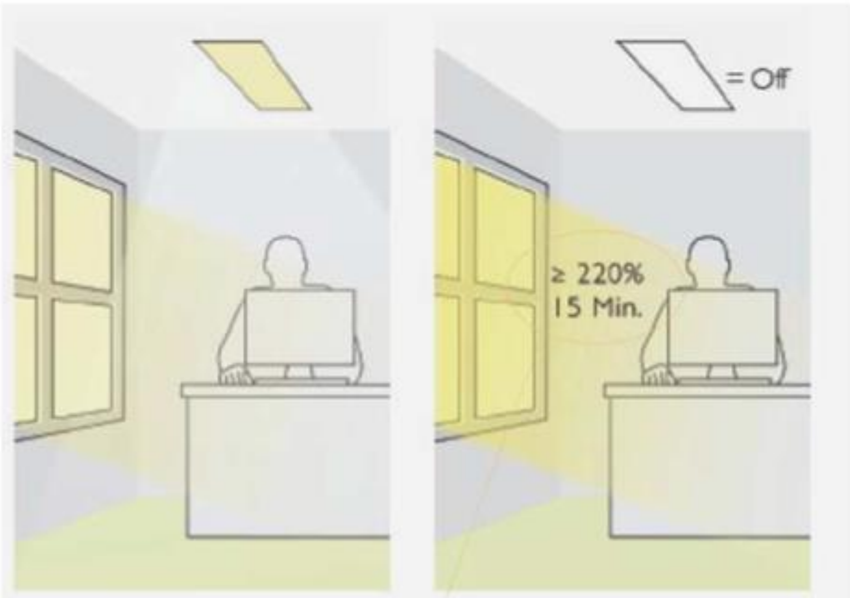

Figure 41. Conceptual scheme of the combination of motion detector with a photosensor (source: PHILIPS)

Obviously in order to select the more adequate strategies, it is necessary to analyse the costs of the system and of the installation, to consider the pattern of daylight availability in the space, the occupancy behaviour (task of the space, frequency of entrance and exit, time of occupancy, etc.). Lindsey JL studied that dimming of electric lamps show no negative effect on lamp life (Lindsey, 1997). Indeed, despite the high initial cost compared to scheduling or occupancy-based controls, daylight-linked lighting controls can still be economically feasible due to high energy savings potential. But, in some case could be more convenient to select and on-off strategy. There are several advantages and disadvantages of using switching or dimming system. ul Haq summarised them in following table suggesting that it is necessary to take into account them and to study before implementation and tuning of the control scheme.

Factors	Switching	Dimming
Suitable daylight condition	Contribution of daylight is significant, and daylight is consistent throughout days hours	Contribution of daylight is variable throughout the day
Suitable occupant activity	Occupant behaviour is not stationary, in circulation areas or common	Occupants performing critical task in particular areas of the space, like offices

Factors	Switching	Dimming
	spaces. Task performed is not critical. Example – hallways	
Advantages	• High savings in suitable areas • Low initial cost compared to dimmable systems • Relatively easy installation	• High savings in variable daylight • Gradual change between light levels, this less obtrusive to occupants • Greater accuracy in control
Disadvantages	• Less accuracy in control • Prominent change in lighting state causes less user acceptance	• Higher initial cost • Requires precise tuning for optimum performance

Table 7. Comparison between daylight-linked and dimming controls (ul Haq et al., 2014)

2.5 Application and Performances evaluation (literature)

Many other works present results and conclusions from filed studies of daylighting performance. In the same work, ul Haq et al. did also a very interesting review of achievable energy savings using daylight linked control system and occupancy-based control analysing different studies that use data measurement. In Table 8 the comparison is reported.

Warren et al. studied the performance of a system installed in an office in San Francisco. They carried out one of the first study that shows that a high frequency dimming system may result less energy and cost savings than an on/off switching in very well daylit spaces when the daylight intensities far exceed the design illuminance (Warren et al., 1986). Knight (Knight, 1999) tested two versions of the PIR/photocell control system and compared the results with estimates of the performance of “switchstart” intelligent system and ‘standard’ high frequency fluorescent luminaires. Savings of around 10% has been achieved with the original ‘intelligent’ control system installed achieved electrical. Furthermore, energy savings averaging around 80%. Authors affirmed that these fittings need proper commissioning to return their full potential savings.

Douglas et al. quantified the impact of photosensor spectral response on its illuminance values, selecting five commercial photosensors and measuring their spectral response and the spectral transmittance of 16 commercial types of glazing (Doulos et al., 2008). Empirical data obtained via field measurements have been used sometimes to develop theoretical models to predict energy savings for different control schemes.

As well Richman (Richman et al., 1995) used data field to calculate savings in lighting systems. Their study included 141 sample spaces using different time delay settings to observe its effect on savings. Depending on the time delay which varied between 5 and 20 min, the research reported savings ranging from 50% to 3% respectively for private offices, and for restrooms, 86–73%.

Room Type	**Control method**	**Research method**	**Savings [%]**	**Reference**
Office	Dimming	Pilot project	20	Chung et al., 2001
	Dimming	Field study	20	Galasiu et al., 2007
	Dimming	Experimental	30	Görgülü and Ekren, 2013
	Dimming	Pilot project	25	Guillemin and Morel, 2001
	Dimming	Pilot project		Hughes and Dhannu, 2008
	Dimming	Pilot project	27	Jennings et al., 2000
	Dimming	Pilot project	9-27	Ribinstein and Karayel, 1984
	Dimming	Experimental	31	Onaygil and Güler, 2003
	Dimming	Experimental	23.4-6.,3	Cheung et al., 2010
Classroom	Switching	Experimental	19.8-65.5	
	Switching +Dimming	Experimental	49.2-70.4	
Indoor open space/atrium	Switching	Pilot project	11-17	Atif and Galasiu, 2003
	Dimming		46	
Savings from occupancy-based controls				
Room type	Research method	Time delay [minutes]	Savings [%]	References
Offices	Field study	20-2	3-84	Richman et al., 1996
	Retrofit project	15-7	10-19	Floyd et al., 1996
	Field study	20-5	28-38	VonNeida et al., 2001
	Experimental	20-15	20-26	Jeggins et al., 2000
	Field study	-	35	Galasiu et al., 2007
	Pilot project	-	35	Hughes et al., 2008
Educational	Retrofit action	10	11	Floyd et al., 1996
	Field study	20-5	52-58	VonNeida et al. 2001
	Field study	20-5	47-60	VonNeida et al. 2001
Infrequently occupied spaces	Field study	20-2	46-78	Richman et al., 1996
	Field study	20-5	17-50	VonNeida et al. 2001

Table 8. Review on the performance of the lighting control system (ul Haq et al., 2014)

Regarding the field measurements, it has been performed, a study on energy saving from using the daylight responsive lighting control system in a test office in Istanbul, Turkey (Onaygıl and Güler, 2003). Authors monitored in particular the illuminance level from daylight and artificial light, and the power input to the lamps with daylight responsive lighting control for 174 days. This study has been carried out within a project developed by the Electrical Engineering Department of Istanbul Technical University. The aim was to find out how much energy can be saved by using a daylight responsive lighting control system in comparison with a conventional lighting system by evaluating the collected data during one-year. Authors classified data monthly, seasonal and annual and weather conditions as clear, mixed or overcast. Results show that energy saving obtained by daylight responsive lighting control systems shows differences according to the months and seasons. They found that the achieved energy savings depend on the seasons or weather conditions. The potential energy saving was 35%, 33% and 16% for clear days, mixed days and overcast days, respectively.

Lee and Selkowitz (Lee and Selkowitz, 2006) took for 6 months measures to study the influence of the daylight on the lighting energy performance in a building in New York. The aim of this study is to know if the proposed daylight related artificial lighting control strategy works well in real application and, so, if two different systems could work in real application and how much energy it could save. The building was separated into two zones, one faces south and another one faces west, respectively. In each zone automatic shade control was applied and the two different daylight control systems were applied: in the west- facing zone used the dimmable ballasts with an open-loop proportional control system and the south facing one used the digital addressable lighting interface (DALI) ballasts with a closed- loop integral reset control system. The average saving was 20–23% and 52–59% for west and south facing areas, respectively, subject to the different lighting schedules.

Atif and Galasiu (Atif and Galasiu, 2003) presented a study based on the field-measured energy performance of two common types of daylight-linked lighting control systems, continuous dimming and automatic on/off installed in two existing large atrium spaces located in Canada. Results showed that the continuous dimming lighting control system provides 46% annual savings in electrical lighting consumption, while the automatic on/off saves between 11and 17% in lighting energy. These savings account for 68% of the lighting energy consumed during main occupancy for the continuous dimming system, and 31.5% for the automatic on/off. It must be underlined that authors found some operation irregularities such as a reduced dimming linearity and an incorrect adjustment of the phases of the dimming control system, as well as the inadequate location of the photocell controlling the automatic on/off lighting system, the improper maintenance of the skylight during winter and the oversizing of the lighting system reduced the energy efficiency of the lighting control systems by 30–65%.

Yun et al. (Yun et al., 2012) carried out a study based on a measurement campaign analyses in four case study offices in a University in the Republic of Korea. The measured energy saving from daylight using dimming control for the studied offices could be up to 43%, and up to 50% if there is a change in occupant pattern.

However, Li et al. (Li et al., 2010) examined the visual and energy performances for a school building using energy-efficient lighting installations and high frequency dimming controls using fluorescent lamps associated with electronic ballasts. They computed an energy consumption of 1.04 kW h leading to a 28% reduction in energy expenditure for electric lighting in the workshop. A further lighting energy saving of 770 kWh/year could be resulted when the high frequency lighting control dimmed down the illuminance to the recommended value. Authors demonstrated that dimming systems could be not more advantageous than switching ones and that the required task illuminance affects system energy performances as well.

Roisin et al. (Roisin et al., 2008) study the energy savings in a single office room equipped by lighting control systems. They simulated the daylight by the software DAYSIM and calculated the daylight and artificial light performance. The algorithm has been used to simulate a closed-loop daylight dimming system based on the simulated daylight data and measured lighting system data. It includes in the calculation the light that is the sum of the daylight, of the artificial light associated with that luminaire, and of the other luminaires. In their study different control systems have been considered:

- IDDS: Individual Daylight Dimming System. The lamp light flux is controlled according to the daylight availability. The sensors (one per luminaire working in close-loop) are fixed on the luminaires and measure the reflected illuminance of the plane located under them (this product is known as ELS- ETAP Lighting System).
- MDS: Movement Detection Switching. This system, based on an infrared occupancy sensor, switches the light on and off, according to movement detection. The length of the delay can be chosen in order to limit the number of switch on and switch off cycles.
- MDD: Movement Detection Dimming. This system, as the MDS, is based on an infrared occupancy sensor, but dims the light to a chosen flux in case of absence. This flux can be chosen by a set of dip switches located on the sensor. In our case, we choose the minimum output flux (3% of the nominal flux) to maximize the gains.

In following figures, the annual lighting consumption are shown for three different cities (Athens, Stockholm and Brussels).

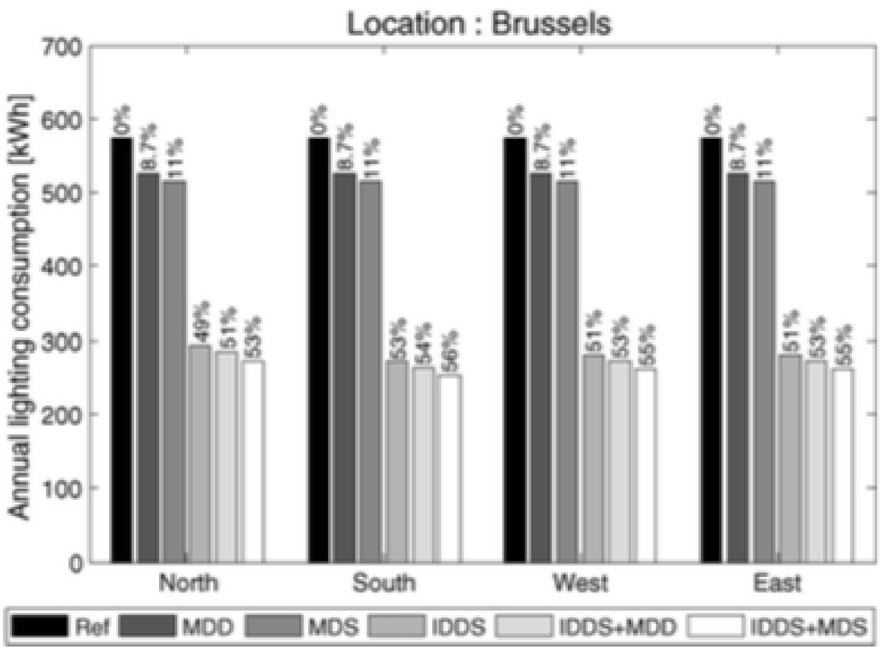

Figure 42. Annual lighting consumption and gains for Bruxelles

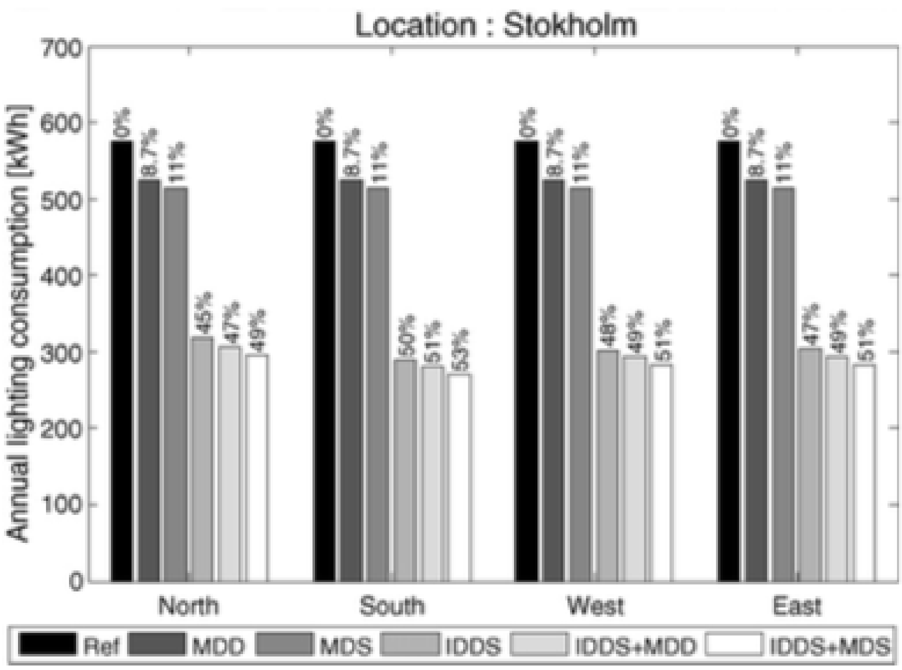

Figure 43. Annual lighting consumption and gains for Stockholm.

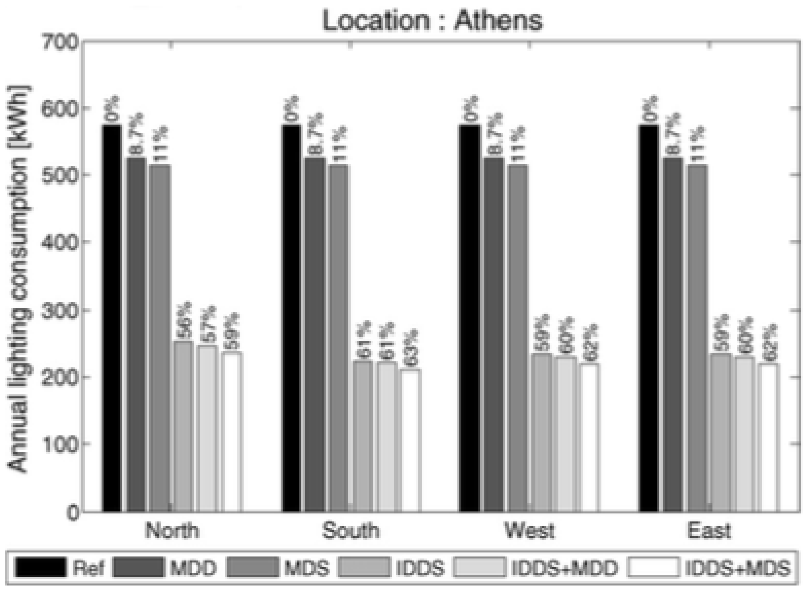

Figure 44. Annual lighting consumption and gains for Athens

In order to find the adequate dimming rate and, therefore, to achieve the required task illuminance it was necessary to perform an iterative process. Consequently, the dimming rate could be converted into the fraction of power output so that the induced annual lighting energy saving from daylight could be achieved. The study includes the application of the described method for three locations in Europe and four main orientations for the individual daylight dimming control. The best energy saving scenario was found in south-orientated Athens, which was 61% and the worst case was found in north-orientated Stockholm, which is 45%, an additional energy saving of 1–4% could be gained if the presence control is also applied.

In (Li et al., 2006), same authors presented field measurements of electric lighting load, indoor illuminance levels and daylight availability for a fully air-conditioned open plan office using a photoelectric dimming system. They found that energy savings in electric lighting were over 30% using the high frequency dimming controls. When indoor daylight availability decreases, high frequency dimming controls provide greater energy savings at a low illuminance set point.

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3. Cost optimisation of the best retrofit actions for lighting system based on daylight availability indices on two cases study

As already said, the application of control systems can be expensive. The selection of the wrong technologies and the definition of a not accurate design strategy can make this option not cost effective. In this section a method able to select the best retrofit action for lighting system, selectively analysing the daylight conditions and applying the cost-optimal methodology is presented. Several scenarios have been developed for the implementation of retrofit actions in two existing educational buildings located in Italy. With the aim to improve both energy efficient and visual comfort conditions, the retrofit scenarios include lighting solutions with different combinations of technologies. They include the replacement of lamps with more efficient lighting sources and the application of lighting control.

The method is based on the use of the index DA as a parameter to distinguish the actions among the rooms. Each choice is then analysed using financial indices aiming to select the best performing. It has been published by the author in (Bonomolo et al., 2017). As well in this case, the selected case studies are educational buildings. Anyway, main case study of this thesis (DEIM) cannot represent a good example for the application of this method, given that it is a single space. Moreover, the educational sector represents one of the most intensive parts of energy consumption in public buildings. In Italy most of the existing stock was built before 1980 and most of the buildings are obsolete. Thus, the retrofit of them can be relevant because of the poor energy performance of the stock, as well as for its high social value (Zinzi et al., 2016).

On the other hand, many studies demonstrated that retrofit actions can be very expensive and, if not well designed, their actual performances, both in terms of comfort and energy, could be lower than the expected ones (Beccali et al., 2107). An accurate predictive analysis of different possibilities of intervention and strategies is necessary to achieve good energy and comfort performances.

Kesten Erhart et al. (Kersten et al., 2016) presented a study developed within an initiative, financed by the Innovation and Quality Fund of Baden-Württemberg (Germany), that supports the development of universities as living laboratories to demonstrate and implement sustainability (Ministry of Higher Education, Research and the Arts, 2014). In particular, they investigated efficient ventilation and lighting solutions for the retrofitting of campus buildings, with a particular emphasis on a lecture hall.

Retrofit actions for lighting system can be a good strategy to achieve significant energy savings. Indeed, also in this field, in many countries about 75% of the lighting installations are considered to be out of date (older than 25 years). With the aim of improving the lighting refurbishment process in non-residential buildings, in order to unleash energy saving potentials while at the same time improving lighting quality, a big team of experts is working on SHC Task 50. The main activities are developing a sound overview of the lighting retrofit market, planning trigger discussion, initiate revision and enhancement of local and national regulations, certifications and loan programs, increasing robustness of daylight and electric lighting retrofit approaches technically, ecologically and economically, increase understanding of lighting retrofit processes by providing adequate tools for different stakeholders, demonstrating state-of-the-art lighting retrofits and developing as a joint activity an electronic interactive source book including design inspirations, design advice, decision tools and design tools. Many studies have been carried out based on method developed within this task.

Dubois et al. (Dubois et al., 2016) presented some results from a large monitoring campaign performed in 22 buildings around the world as part of International Energy Agency (IEA) Task 50 "Advanced lighting solutions for retrofitting buildings", addressing in particular the work of Subtask D, which aims to demonstrate sound lighting retrofit solutions in a selection of representative, typical Case Studies. A method to select the best retrofit action in terms of energy savings achievable and not too long payback time, is the cost-optimal methodology. It is a useful tool to address the evaluations of financial, energy and environmental issues. Through the balance between energy consumption and costs, it is possible to choose the best performing solutions, exploiting many variables and selecting different best configurations.

Baglivo et al. presented the results of the application of a methodology to identify cost-optimal levels in new residential buildings located in a warm climate (Baglivo et al., 2015). Chen et al. (Chen et al., 2016) proposed a cost-benefit evaluation method for building intelligent systems, using life cycle net present value (NPV) of all the costs and benefits, including tangible and intangible, as an index to evaluate the performance of the building intelligent systems. Some research focused on the economic analysis for retrofit of lighting system.

Yang and Nam (Yang and Nam, 2010) did an economic analysis of the daylight-linked automatic on/off lighting control system installed for the purpose of energy savings in office buildings.

Beccali et al. (Beccali et al., 2015) demonstrated the importance to analyse different scenarios in order to select the best ones.

3.1. Case studies

In order to apply the proposed method, two different case studies have been considered. Both of them are educational buildings and located in south of Italy.

The first one is the Liceo Classico "Antonio Calamo". It is located in Ostuni (40°43'34"N, 17°34'20"E), 17.572901) in Apulia, in a suburb zone. The building has been built in 1960 and has three floors. It is used for about 10 hours during the working days and, occasionally during holydays. It is characterized by a "T" shape plan and it has a terrace. The floor height is about 3,85 m. The windows are equipped by double-glazing. The existing indoor lighting system is composed mainly by fluorescent lighting sources characterized by different power, luminous flux and shape.

The second school, “Istituto Pertini-Fermi”, is located in Taranto (40°27’13"N, 17°15’37"E). It was built in 1950 and it has a covered area of 1900 m^2. For both cases, the outdoor lighting systems, consisting in metal halide lamps in the first school and sodium vapour and metal halide lamps for the second ones, have not been considered in this study. In Figure 45 some pictures of the schools’ objects of this study.

Both the schools have not other buildings present in the external surroundings area.

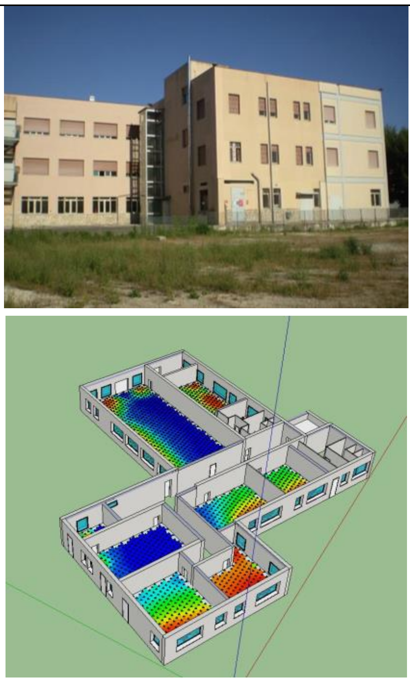	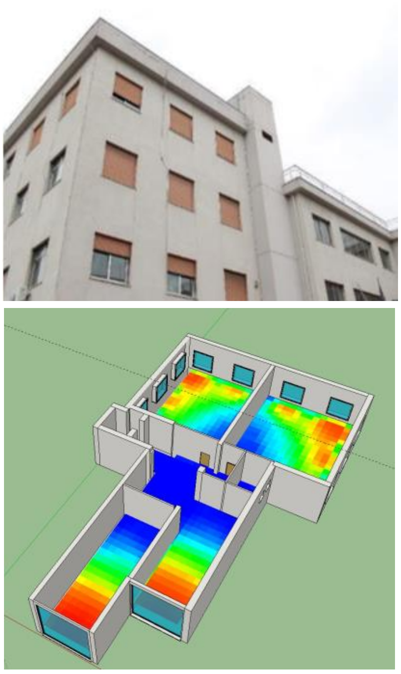
Liceo Classico “Antonio Calamo”	“Istituto Pertini-Fermi”

Figure 45. Some pictures of the schools and of the models

3.2. Methodology

In order to select the best retrofit action, paying attention both to the energy efficiency and visual comfort conditions, a visual comfort analysis has been performed, analysing the illuminance values achieved with the existing system. In particular, for selecting proper lighting the task illuminance values suggested by the Standard EN 12464-1 “Light and lighting-Lighting of workplaces" (EN 12464-1:2011) have been considered. For selecting different scenarios, the daylight contribution for each space of the schools has been taken into account. Daylight analysis has been carried out using the simulation software Daysim (Reinhart, 2010) that is able to calculate the Daylight Autonomy (Reinhart et al., 2006). In each room, it has been calculated for a grid of points at a height of 0.85 m. Given that in this step of study, the possibility to divide in different control groups the luminaires have not been taken into account, the minimum value of daylight autonomy has been considered as whole value for each space.

For all the models the following optical characteristics of materials have been considered:

- inner coating of plaster: reflectance 0.80%, rugosity 0.01%, specularity 0.0%;
- floor material: reflectance 0.20%, rugosity 0.03%, specularity 0.02%;
- task plane material: reflectance 0.60%, rugosity 0.02%, specularity 0.05%;
- windows double glazing: transmittance 78%.

Energy plus weather data files have been used for considering climatic conditions of the two locations. Simulations have been carried out considering an average of 9 daily hours of occupancy. For each school 8 different scenarios (combination of retrofit actions in selected rooms) have been proposed and analysed (table 8). The scenarios have been selected with a criterion based on Daylight Autonomy calculated for each room.

Two kinds of retrofit actions have been considered: the replacement of the existing lighting sources (L.R.) and the installation of ON-OFF automated lighting control systems (C.S.I.). The first scenario (0) considers the replacement of the existing fluorescent lamps (18W, 36W e 58W) with LED fixtures (10W, 16W e 24W) in every room of the schools. This action is the main retrofit intervention included in previous studies made for these schools by local authorities which have commissioned to external professionals a global lighting design (Unione delle Province). For the scenario 1 only the replacement of the luminaires has been analysed, but only in the rooms where the minimum value of DA is <30% and where high values of illuminance are required for the task (e.g. laboratories). Given that the schools are used for the most part during the daytime, in these spaces the luminaires would be turned on for a larger number of hours. Thus, the energy saving would be higher, replacing the existing luminaires with the more efficient ones. The scenario 2, in addition to the retrofit action considered in scenario 1, includes the replacement of the existing lighting sources and the installation of a control lighting system in the spaces where a minimum value >20% of DA has been calculated. Scenarios 3, 4, 5, 6 and 7 include the same retrofit actions of scenario 2, but selecting for the installation of the automated system only the spaces where a minimum value of DA is >30%, for scenario 3, >40%, for scenario 4, >50%, for scenario 5, >60%, for scenario 6, >70%, for scenario 7.

Scenario	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
L.R.	All rooms	<30%	<30%	<30%	<30%	<30%	<30%	<30%
C.S.I.	\	\	>20%	>30%	>40%	>50%	>60%	>70%
Legend: L.R.: Lamp and fixture replacement; C.S.I.: Control system installation								

Table 8. The analysed scenarios and the selection criteria based on DA minimum value

3.3. Cost optimal analysis

3.3.1. Case 1: Liceo Classico "Antonio Calamo"

Once defined the measures for each scenario, the cost-optimal analysis has been carried out. Table 9 points out the calculated costs, the energy consumption ante and post, the energy savings and economic indices of investment, i.e. the Net Present Value (NPV) and the Total Return Swap (TRS).

Table 9. Financial analysis of Case 1

Scenario	0	1	2	3	4	5	6	7
Total cost [euro]	32358	14590	37829	36768	26692	20712	18590	16785
Yearly consumption of the lighting system - Ante intervention [kWh/y]	18183	8823	18636	18183	13949	11454	10547	9731
Yearly consumption of the lighting system –Post intervention [kWh/y]	8390	4230	8446	8174	6010	4925	4606	4397
Savings attributed to the intervention [%]	53.9	52.1	54.7	55.0	56.9	57.0	56.3	54.8
Savings after the intervention [kWh/y]	9793	4593	10190	10008	79390	6529	5941	5333
Unit cost of the energy [euro/kWh]	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Annual Savings [euro/y]	1763	827	1834	1801	1429	1175	1069	960
Period of intervention [y]	25	25	25	25	25	25	25	25
NPV [y]	4474	3085	466	859	3310	4095	4052	3618
Total Return Swap (TRS) [y]	17.9	16.9	20.2	20.0	18.2	17.1	16.8	16.8
Total Return (TR) [y]	22	20	25	25	22	21	20	20

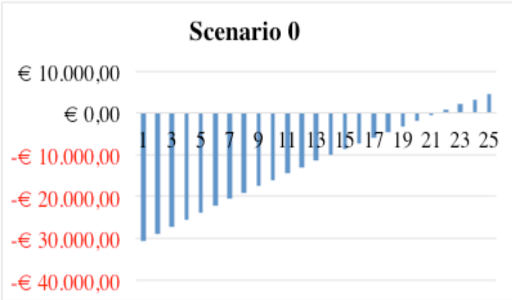

Figure 46. Scenario 0 of Case 1

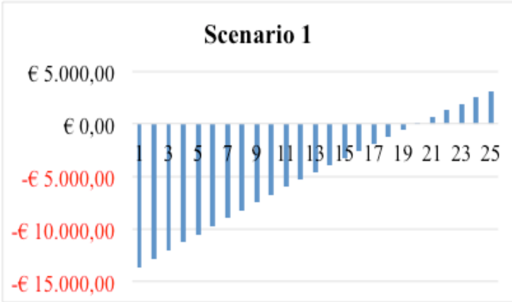

Figure 47. Scenario 1 of Case 1

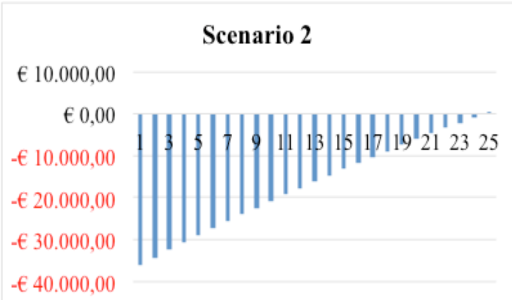

Figure 48. Scenario 2 of Case 1

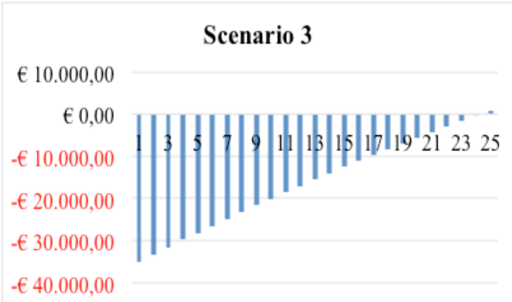

Figure 49. Scenario 3 of Case 1

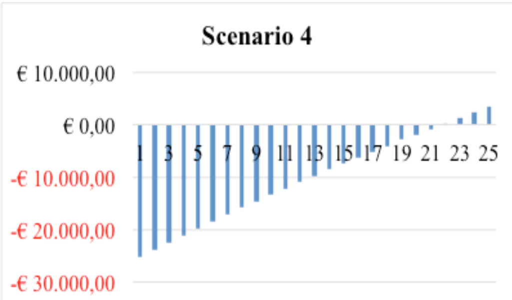

Figure 50. Scenario 4 of Case 1

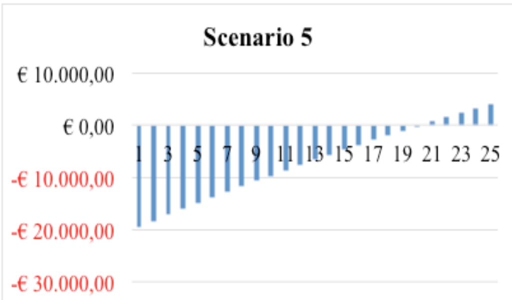

Figure 51. Scenario 5 of Case 1

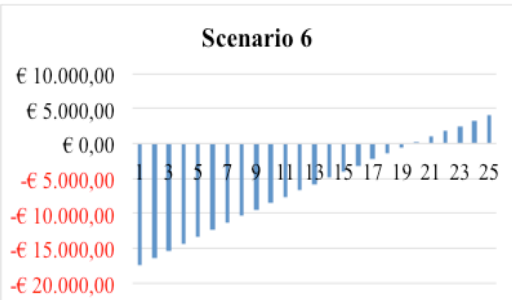

Figure 52. Scenario 6 of Case 1

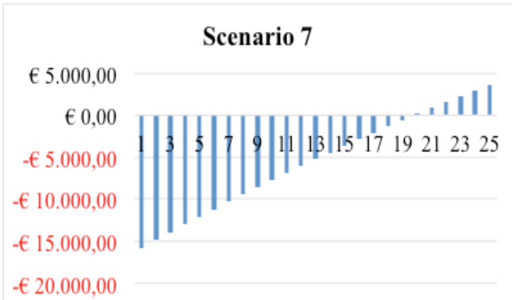

Figure 53. Scenario 7 of Case 1

The selection of the best action may be done basing on the NPV for up to 25 years cash flows and on the payback time. In particular, the results outline a TR for the scenario 107 equal to 20; 25; 25; 22; 21; 20 e 20 years, involving the amortization of the total cost within the considered time.

Figure 46-53 show the NPV trend for each scenario, highlighting the inversion of the trend after the 20th year for the scenarios 1, 6 and 7 after the 21nd year for the scenario 5; after the 22nd year for the scenario 4 and after the 25nd year for the scenario 2 and 3.

3.3.2. Case 2: Istituto Pertini-Fermi

As the previous case, the financial parameters have been reported in Table 10 for each scenario.

Scenario	0	1	2	3	4	5	6	7
Total cost [euro]	92072	38078	98826.3	85660	83604	78139	67436	47869
Yearly consumption of the lighting system - Ante intervention [kWh/y]	43777	18648	40763	35552	35008	33042	29232	22458
Yearly consumption of the lighting system –Post intervention [kWh/y]	20076	8907	18081	14799	14349	13385	11819	9707
Savings attributed to the intervention [%]	54.1	52.2	55.6	58.4	59.0	59.5	59.6	56.8
Savings after the intervention [kWh/y]	23701.4	9740.6	22682.5	20753	20659	19657	17412	12751
Unit cost of the energy [euro/kWh]	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Annual Savings [euro/y]	4266.3	1753.3	4082.8	3736	3719	3538	3134	2295
Period of intervention [y]	25	25	25	25	25	25	25	25
NPV [y]	-3997	-1438	-14506	-8447	-6738	-4963	-2532	-140
Total Return Swap (TRS) [y]	21.4	21.3	24	22.7	22.3	21.9	21.27	20.5
Total Return (TR) [y]	–	–	–	–	–	–	–	–

Table 10. Financial analysis of Case 2

Figure 54. Scenario 0 of Case 2

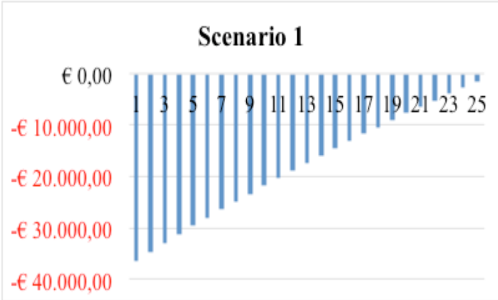

Figure 55. Scenario 1 of Case 2

Figure 56. Scenario 2 of Case 2

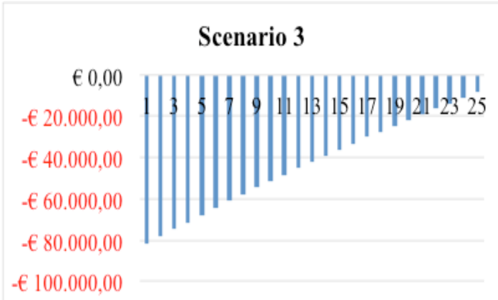

Figure 57. Scenario 3 of Case 2

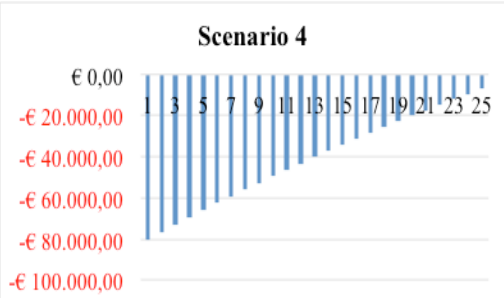

Figure 58. Scenario 4 of Case 2

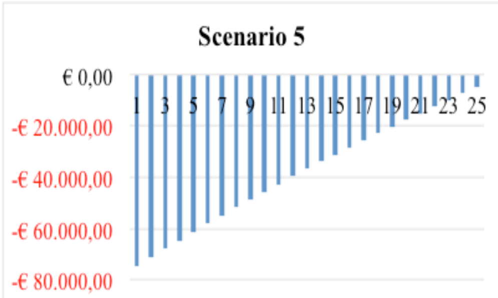

Figure 59. Scenario 5 of Case 2

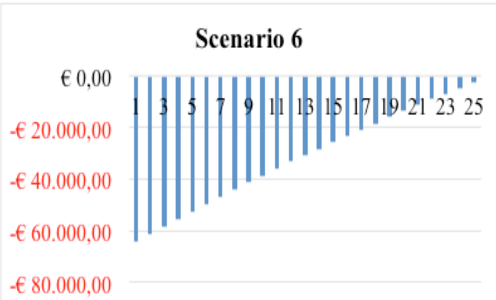

Figure 60. Scenario 6 of Case 2

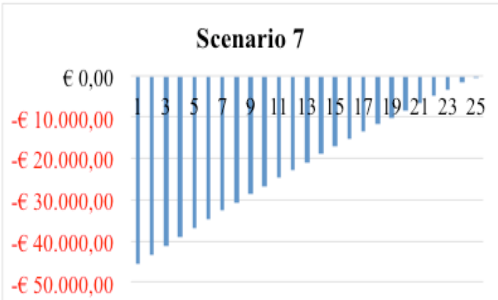

Figure 61. Scenario 7 of Case 2

For each scenario, the TR values are higher than the considered time (25 years), leading to the consideration that the proposed measures are not convenient from an economic point of view, Figures 54-61.

3.4. Discussion

Graphs in figure 62 show the comparison between energy savings and the comparison of the cost calculated for each scenario for the two schools.

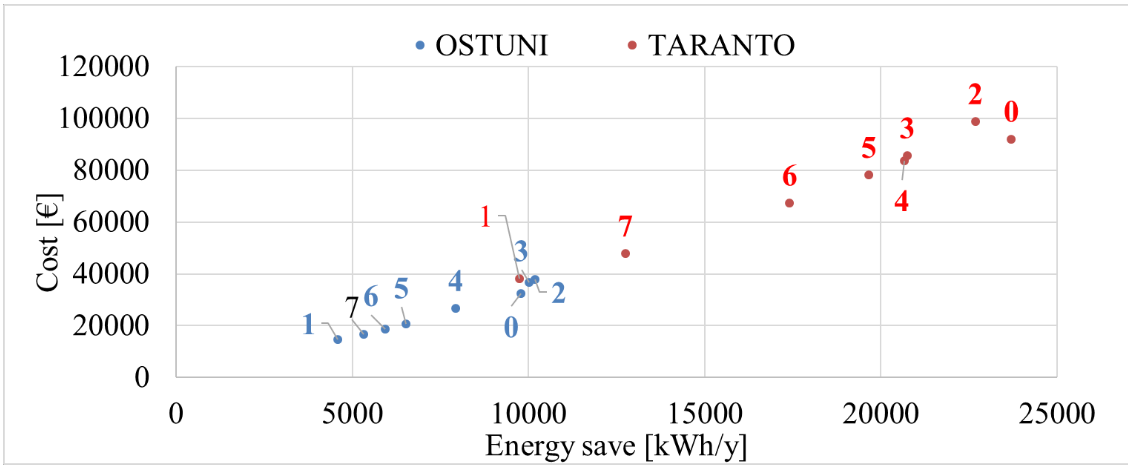

Figure 62. Comparison between energy savings and costs calculated for each scenario

Looking at the analysis carried out for the school "Pertini-Fermi", if we analyse also another set of scenarios having as a threshold value for lamp substitution DA< 10%, it is possible to plot the NPV and the DA threshold curves (figure 63).
It can be noted that the right selection of rooms leads to optimize these financial indices (maximum NPV). Moreover, a too wide or a too restricted implementation of retrofit actions penalizes the economic performance.
This example is useful to highlight how the DA can be utilized as a factor for performing cost optimal analyses.

Unfortunately, in the second school the financial analysis has highlighted very poor results in terms of economics while the trend of NPV is almost the same.

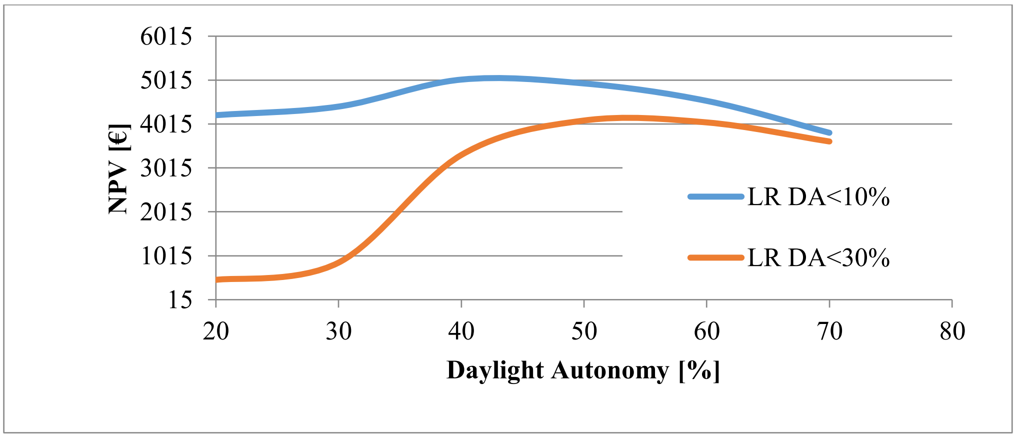

Figure 63. NPV vs Daylight Autonomy values used to build retrofit scenarios

3.5. Final remarks

Retrofitting of lighting systems can be a sustainable action for buildings. Anyway, it can be very expensive and a detailed preliminary analysis of the costs it is necessary to achieve high performances not only in terms of comfort and energy but also from the economic point of view.

This chapter presents a method that allows selecting the best retrofit action for lighting system, analysing the daylight contribution for different scenarios proposed for two existing educational buildings located in Italy. These have been selected as cases studies and analysed. Using the simulation software Daysim, daylight conditions for both schools have been simulated and the results have been studied in order to choose among the possible retrofit actions for lighting system. In particular, for each space of the schools the Daylight Autonomy index has been calculated. Based on this daylight index values, four different scenarios have been proposed and for each one an economic analysis have been carried out. The scenario 0, the replacement of the luminaires has been analysed for all rooms of the schools, without taking into account the DA minimum values. The scenario 1 considers the replacement of the existing fluorescent lamps with LED only in rooms where the minimum value of DA is <30%. The meaning is to avoid massive replacing of lamps and focus the intervention only in areas were artificial lighting has the major probability to be utilized. The scenario 2, in addition to the retrofit action considered in scenario 1, includes the replacement of the existing lighting sources and the installation of a control lighting system in the spaces where a minimum value of DA >20% has been calculated. Scenarios 3, 4, 5, 6 and 7 include the same retrofit actions of scenario 2, but selecting for the installation of the automated system the spaces where the minimum value of DA is >20%, >30%, >40%, >50%, >60% and >70% respectively. As well in this case the rationale is to consider only the rooms were the best energy performances could be expected. All scenarios have been calculated considering a period of intervention of 25 years.

Regarding the school “Liceo Classico Antonio Calamo”, the highest total intervention cost is related to the scenario 2, because the considered “range” of the DA (>30%) for the selecting the application area of the C.S.I. action is larger. Consequently, also the yearly consumption and the savings after the intervention are the highest. Moreover, looking at the payback times, Scenarios 0 and 4 are the less convenient, being the calculated TR of 25.00 years. Furthermore, looking at the TRS, results show that scenario 6 is the far more cost-effective, even if the application of scenarios 1 and 7 that have the same TR.

In the second case, the analysis shows that, in general, these kinds of retrofit actions may not be convenient.

The difference of scale of the buildings areas, causes the impropriety of using the same selection strategy for the two schools.

DA or other lighting index will be considered as measurable variables to look for a cost optimal analysis of several scenarios.

It is interesting to note that where the retrofit action has a good potential in terms of energy saving, the DA can be utilized as a factor for the optimization of the economic performances related to different grades of implementation.

In a further work, the application of further different strategies will be analysed and compared. Furthermore, cost-optimal analysis for other retrofit actions for lighting system (e.g. dimming control system) will be calculated and included in the proposed scenarios study.

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4. Lighting Analysis at Existing University Campus Buildings to Improve Sustainability and Energy performance. A case study at the University of Applied Sciences of Stuttgart

In order to increase the performance of a control system and, more in general, to carry out a proper design of a light system it is necessary to do a deep analysis of the space. To this aim, a specific monitoring campaign can be planned in order to take data regarding the luminous ambient, the daylight distribution and the actual use of the room. First of all, as already seen in chapter 1, these data can be used to estimate expected energy consumption applying one of the available methods.

Moreover, they can be used to study the distribution of the daylight in order to know where it could be convenient to place luminaires and photosensors and better understand how they can control artificial light accordingly. Finally, they can be used to evaluate the visual comfort condition of the room. In addition, a record of the actual occupation of a room (which can be non-consistent with the scheduled or expected one), can help to tune the control strategy and to avoid not useful lighting and associated consumption.

This chapter describes some analyses of daylight and of its relationship with the actual occupancy, which has been performed for a case study.

The work has been carried out by the author during her period of studies and researches at the Stuttgart Technology University of Applied Sciences – Hochschule für Technik of Stuttgart together with the university team.

In that period, a measurement campaign of 174 days has been conducted. The investigated space was actually occupied and its lighting system was controlled by a DLCs. It means that this case study gave the possibility to test a different end-use from the case study presented in section 5, main object of this thesis.

The analyses aimed first of all to check the actual performance of the existing automated system equipped with on-off and occupancy controls and to understand how the system could work better.

Furthermore, the large number of the sensors used to measure the illuminance values have provided useful support to study the distribution of the light and the relationship between the illuminance values measured on the workplane and the illuminance values measured on the ceiling.

The study also aimed to analyse the installed lighting system in order to develop a more effective method for designing the lighting system for the Stuttgart University of Applied sciences in energetic, ergonomic and sustainable terms by implementing the system with other strategies (e.g. dimming strategies related to occupancy patterns).

4.1. The building and its context

The monitored test room is a lecture hall in one of the buildings (Building 3) of the University campus. It is located in Stuttgart (latitude: 48.78, longitude: 9.17). The location of building 3 and the site plan of the campus are shown in Figure 64. The duration of sunshine varies between 1300 and 2000 hours per year, while annual global irradiation varies between 780 and 1240 kWh/m^2. During winter, Stuttgart's daylight can range from 8.5 to 9 hours per day. In summer the average daylight period is almost 16 hours per day. The annual mean temperature for Stuttgart is 10.9°C.

Figure 64. Bird's eye view of the University of Applied Sciences, Stuttgart

The test room's floor area is 212.7 m^2 and it is characterized by a depth of 11.5 m a width of 19.1 m and a height of 3.77 m. The main façade (the only one with windows) is oriented to northeast.

Figure 65 shows the floor plan of building 3 and the selected lecture hall (R224). The window-to-wall-ratio of the lecture hall facade is 40%. The room surface reflectance values are: $\rho_{ceiling}$ = 80%, ρ_{walls} =80%, ρ_{floor} = 30%, $\rho_{furniture}$ = 50%. The windows have two layers of clear glass with a total visible transmittance (Vt) of 72%.
As shown in the plan (Figure 66), the building is looking over a court and it is on the second floor. For that reason and being northeast oriented it receives direct daylight only for a few hours in the morning and only in a part of the room (Figure 65). Furthermore, in the classroom there are eight rows of desks (0.60x0.80x0.80 m).

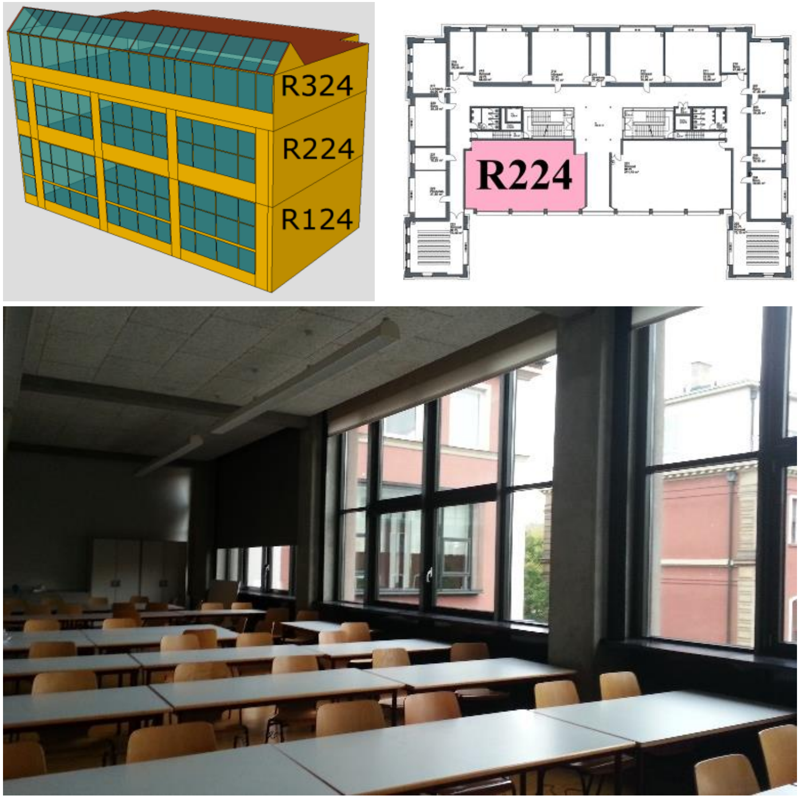


Figure 65. Top-left: 3D-Model of the selected lecture halls; Top-right: Second floor plan of Building 3 and the selected lecture hall 224; Down: picture of the classroom

The installed T8 lamps have different colour temperatures that range between 4000 K to 6000 K. Each luminary consists of one fluorescent tube and one ballast with standard diffuser. Type of the lighting is direct lighting. Totally 15 luminaires are present. Each lamp has 58 W powers and total lighting load is 1065 W including the power absorbed by the conventional ballasts.

40 ceiling luminaires, equipped with fluorescent lamps and in groups of three, are installed in the classroom.

As Figure 66 shows, the luminaires are distributed in 4 rows (except the 4 luminaires on the main desk) parallel to the windows. Furthermore, the existing luminaires are distributed in three different electrical circuits (Figure 66): F41 (18 luminaires), F42 (13 luminaires) e F43 (9 luminaires). Two lighting and motion detectors control the lamps actions. When the illuminance value is less than 500 lux, the luminaires should be switched on.

The switching contact closes if the illuminance level is lower than the threshold level (500 lux) and if the presence of a person is detected. It is open when the illuminance level is adequate and/or no presence is detected. The switch off delay time is 7.5 min.

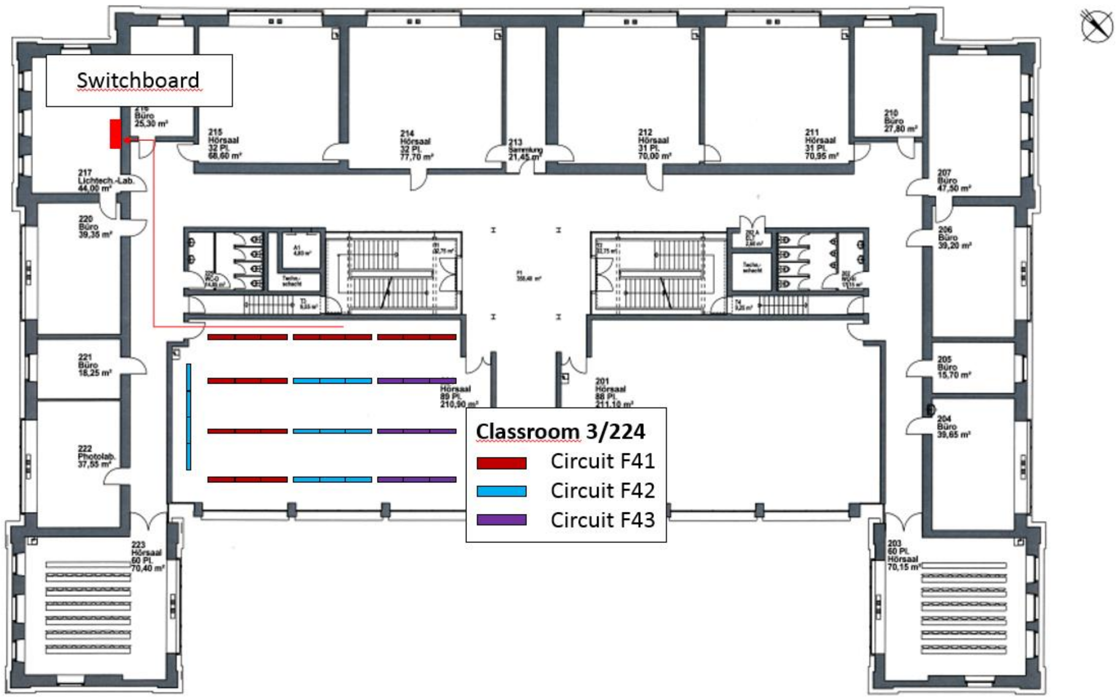


Figure 66. Plan of the building with the luminaires location divided into circuits

4.2. Measurement campaign

The monitoring campaign has been six months long. An automatically equipped data monitoring system manufactured by National Instruments CompactRIO (Crio) has been used for data recording. Several room parameters have been identified and monitored such as the temperature, the illuminance level, the energy consumption (electricity) of luminaries, the occupancy detection (presence detection), CO_2 concentration. Two sensors have been assigned for presence and illuminance level threshold, three split core transducers have been assigned monitoring the electricity consumption, one for CO_2 concentration and one for temperature. The electricity consumption of the artificial lighting has been measured continuously with a time step of 10 seconds. The global horizontal illuminance (measured by a sensor placed on the roof) as well as illuminance level at the working plane and on the ceiling, has been also measured on two grids with 16 measurement points each as well as the occupancy (presence of people).

The ten ECO-IR 360A presence/ daylight sensors have been integrated into the monitoring system. The detection range of the sensor is 7 x 7m as seated position and 10 X 10 m in walking position. Because of that, 2 sensors have been mounted on the ceiling of the lecture room.

For measuring AC currents (lighting energy consumption) split core transducers have been used, manufactured by LEM (AT 10 B10). The circuit cable is placed in the middle to the magnetic rings (transducers) and generate the voltage potential. The lecture room has 3 lighting circuits (F41, F42 and F43. All of them have been connected to the measurement set up.

In particular, the computer software LabWIEV (Labview, 2017) has been used to control the data logger. The program converted the monitored voltages into standard units using calibration constants assigned for the sensors.

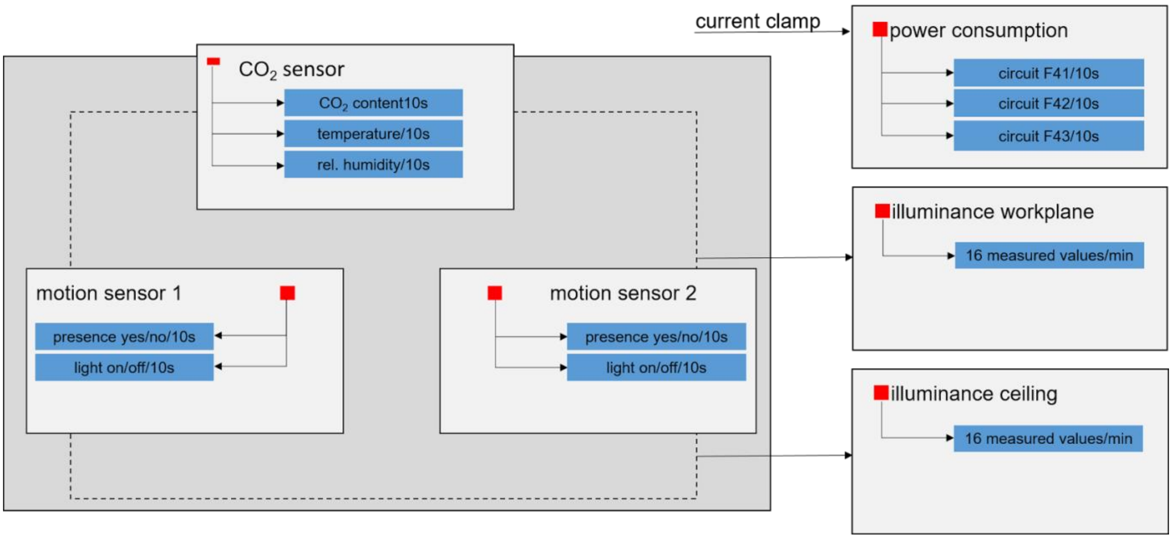


Figure 67. Field measurement concept: Data input and timesteps

Input Data	Date	Timestep
horizontal illuminance	19th April - 26th May	15 min
vertical illuminance	19th April - 26th May	15 min
illuminance ceiling	19th April - 26th May	15 min
illuminance workplane	20th, 25th, 26th, 27th, 29th April, 4th, 11th, 21th, 22th, 25th, 26th May	1 min / 15 min
electric power	19th January - 23th May	10 sec
CO_2 level	19th January - 23th May	10 sec
relative humidity	19th January - 23th May	10 sec
temperature	19th January - 23th May	10 sec
artificial light on/off	18th April - 23th May	10 sec
presence yes/no	18th April - 23th May	10 sec

Table 11. Measured parameters with dates and timesteps

The HOBO Pendant Temperature/Light Data loggers have been used for the illuminance measurements in 16 points on the ceiling and 16 points on the working level. Two sensors have been assigned for the monitoring outdoor horizontal and vertical illuminance (façade). The photometric sensors measure from 0 to 320,000 lux. Each has 64K bytes self-memory and up to 28000 measurements can be saved.
Concept scheme of the monitoring set up is shown in Figure 67.

4.3. Data Analysis

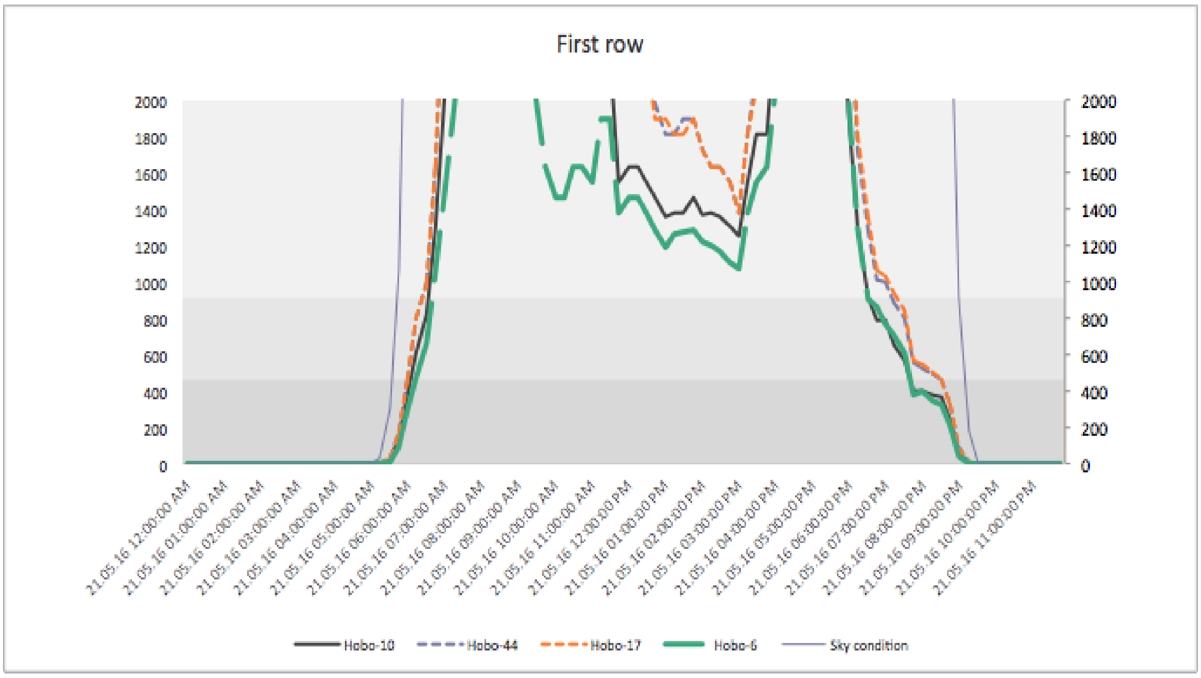
All the data have been utilised for several analyses. The illuminance measured values due to daylight have been used to study the lighting distribution in the space, to study the direct and indirect contribution and to study the relation between the illuminance values measured on the desk and on the ceiling. Since the classroom is actually utilized, in order to carry out this analysis two days of measures have been taken during holidays with a time step of 15 minutes. To have a horizontal and vertical illuminances fast preview, a shading analysis has been done and presented in 4.3.2. using simulated data from 1st January to 31th August. Collected measures (from 19th January - 23th May with a time step of 5 minutes) of absorbed power have been compared with meteorological data.

Using data measured during the same period, but with a time step of 15 minutes, other analyses have been carried out and presented in this chapter. Indeed, it has been possible to compare the signals elaborated by the commercial sensors installed to control the lighting with the data measured by HOBO. The illuminance values, the status of the luminaires and the presence in the classroom have been compared and analysed in order to study the actual behaviour of the existing control system.

4.3.1. Comparison between illuminance values measured on the desk and illuminance values measured on the ceiling

As already said, for two days (21st and 22nd of May) the illuminance values from daylight have been measured. In order to know the sky condition for each moment of the day, and also the illuminance values on the roof (horizontal) and on the middle façade have been measured.
The illuminance values on the middle of the façade are important to know the real condition of lighting in the classroom. Sometimes, in fact, while the value measured on the roof (horizontally) indicates that the sky was clear, the value measured in the façade (vertically) indicates that there is not direct illuminance in the classroom.

In Figure 68 the comparisons between the values measured on two rows of the tables, the values on the roof and on the façade, are shown. On the background of the graph there are three different graduation of grey to distinguish better in which sky condition the measurement has been carried out.



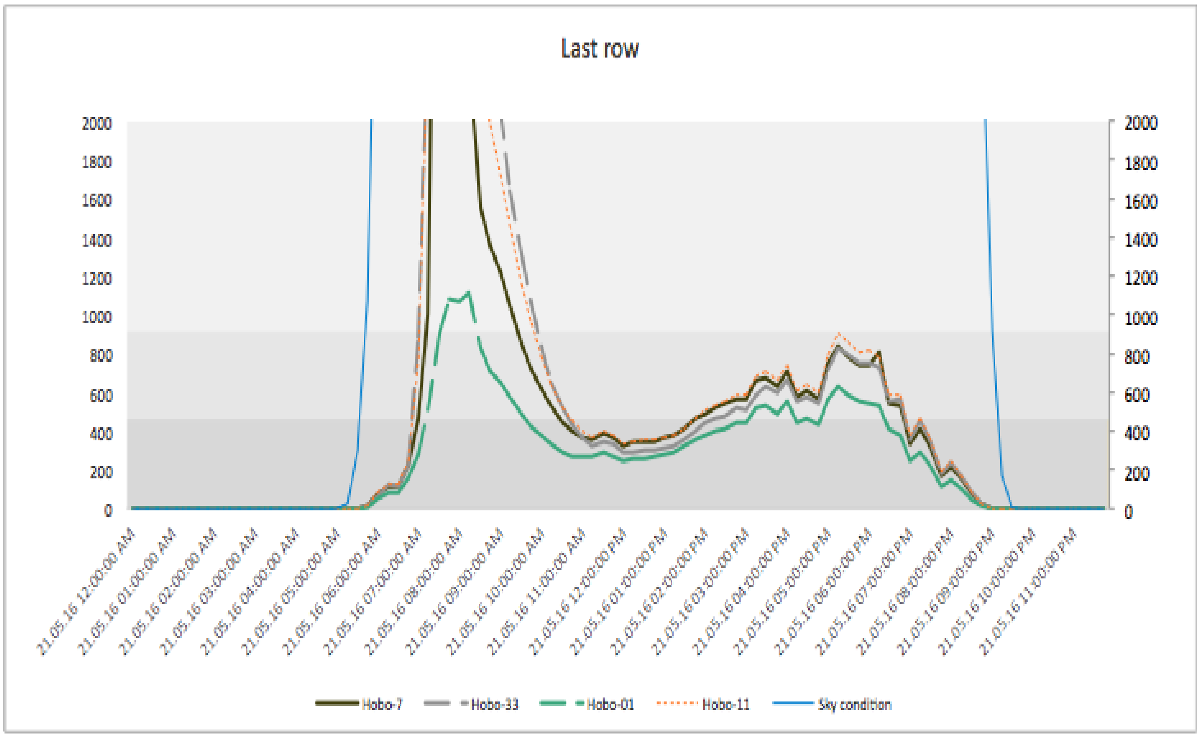


Figure. 68 Distribution of the illuminance of the first and the last row of desk

Door	1	7	11	33
Table	2	8	12	40
	3	9	15	39
	6	10	17	14
	Window	Window	Window	Window

Table 12. Numbering and scheme of the position of the hobos on the desks (blue lines)

Door	37	36	29	21
Table	42	34	28	20
	43	31	26	19
	45	39	25	18
	Window	Window	Window	Window

Table 13. Numbering and scheme of the position of the hobos on the ceiling (orange lines)

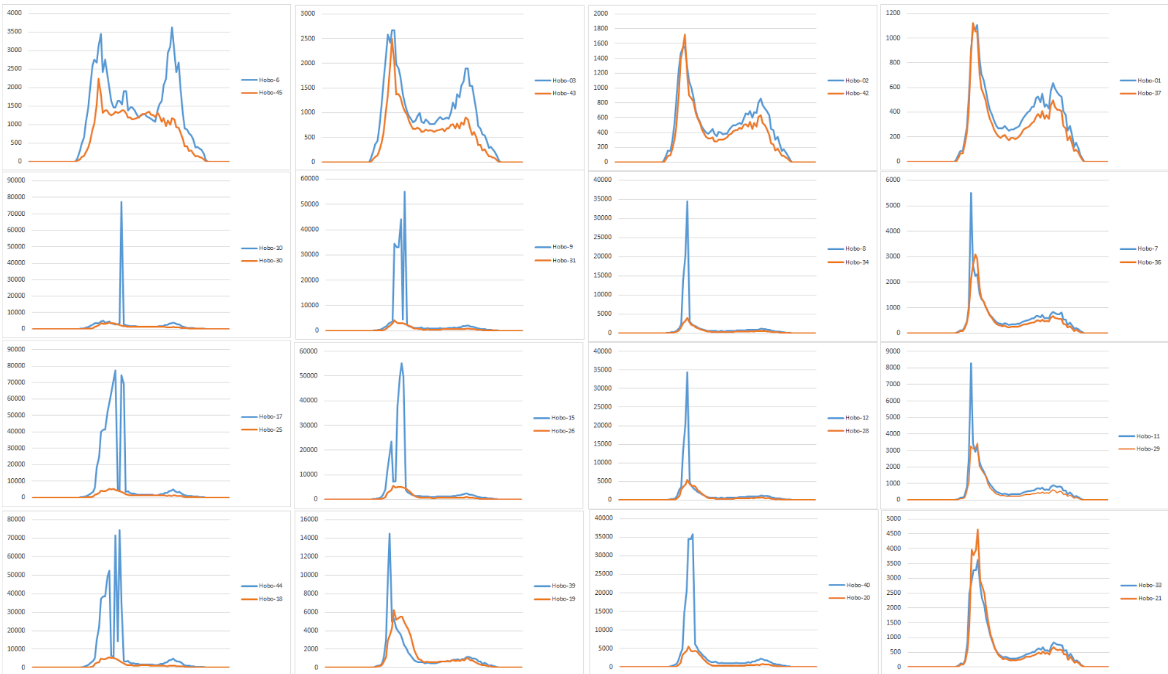


Figure. 69 Comparison between the illuminance values measured by the hobos on the desk (blue lines) and on the corresponding points on the ceiling (orange lines)

Figure 69 shows the distribution of the daylight illuminance during one days and the Tables 12 and 13 shows the distribution of the Hobo on the desks and on the ceiling. It must be noted that the values on the desk (where the illuminance values should be achieved) and on the ceiling (where the sensors are installed) are different mainly on the desks closer to the windows. Only indirect lighting is on the first row of desks (hobo 1, 2, 3 and 6) and in the top left corner of the room. For this reason, the values are lower, but on the desks and on the ceiling, are more homogeneous.

In general, where and when direct sunlight is present the difference between desk and ceiling measures is high while in case of indirect light this gap is remarkably reduced.

It is worth noting that this kind of analysis is useful to reduce the error related to the position of the photosensors which are utilised to directly control the ON-OFF or dimming of the luminaries.

4.3.2. Shading analysis

Results, obtained by illuminance measurement, were compared to the ones obtained by a shading analysis, which has been developed with the software SketchUp (SketchUp, 2017). Therefore building 3 was modelled with its surrounding buildings.

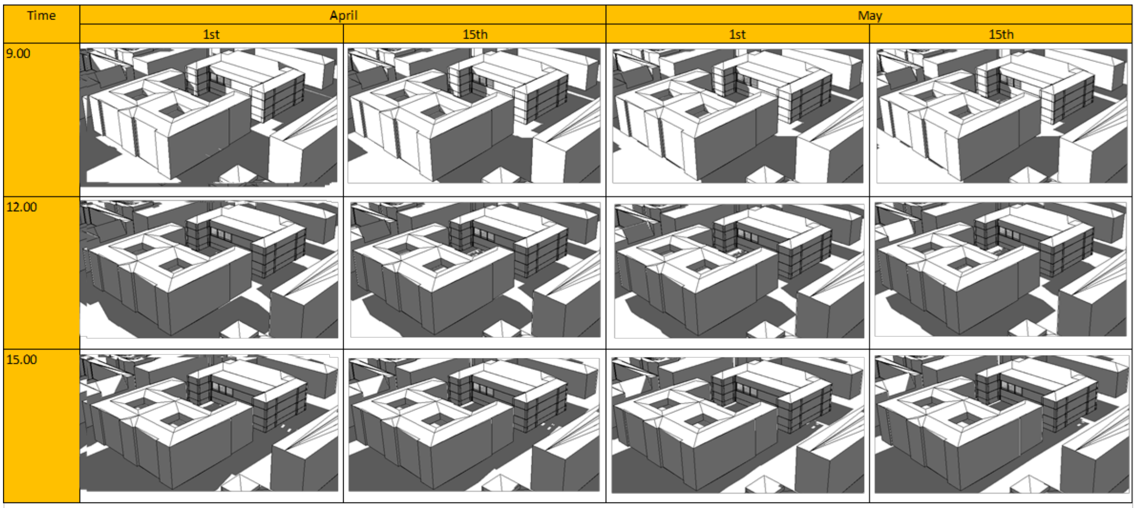
To get an overview of the solar altitude and the resulting shading of building 3, the calculation was made for each month at 1st and 15th at 9:00, 12:00 and 15:00. It becomes clear, that the lecture hall 3/224 received direct sunlight in the morning. At 12:00 as well as in the afternoon there was no direct sunlight at the facade of this room.

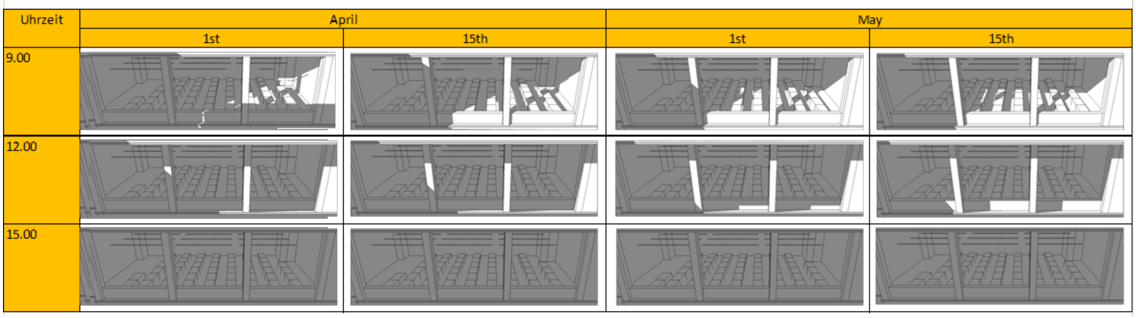
In order to verify the measurements, they were compared with the calculated shading of the lecture hall under the criteria of direct sunlight and vertical illuminance. It becomes obvious that the shading of the facade affects the vertical illuminance.

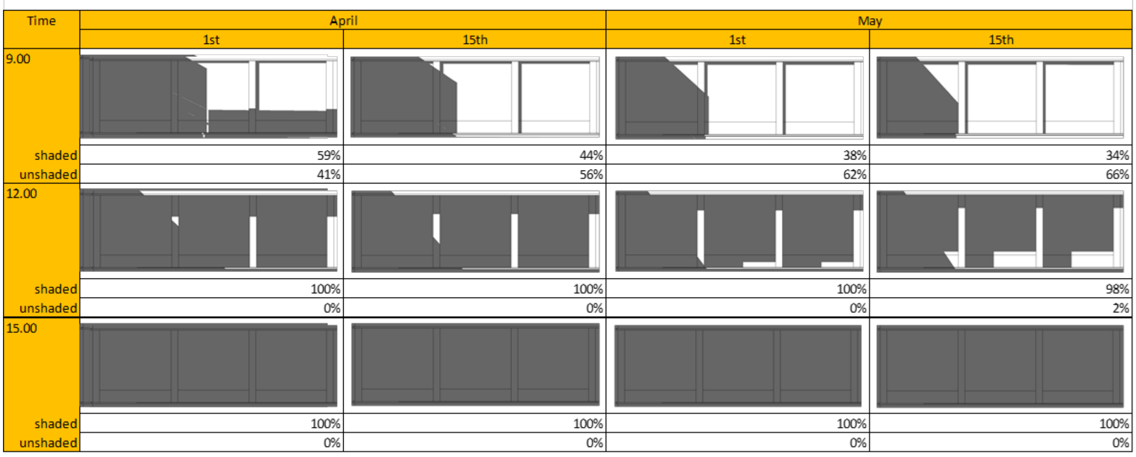
In Figure 70 an example of 27th April and 21st May is shown. On those days at 9:00 there is a low vertical illuminance, although the facade receives direct sunlight. As the facade is shaded at the measurement point there is no contradiction.

Comparing the illuminance in the lecture-hall the results of measurements are matching the simulations of shadows because the same illuminance distribution can be found. High illuminance values are near the windows in the back of the room.

With the increasing depth of the room the illuminance with high component of sunlight is minimised.

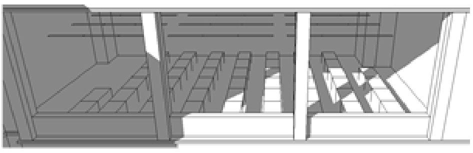
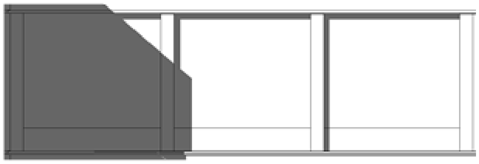




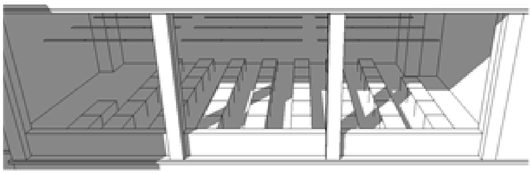
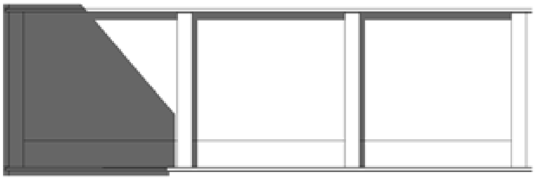


Time		April 1st	April 15th	May 1st	May 15th
9.00	shaded	59%	44%	38%	34%
	unshaded	41%	56%	62%	66%
12.00	shaded	100%	100%	100%	98%
	unshaded	0%	0%	0%	2%
15.00	shaded	100%	100%	100%	100%
	unshaded	0%	0%	0%	0%

Figure 70. SketchUp shading analysis for April and May

Time	27th April	
	Sketchup	Field Measurement
9.00		see field measurement grid below
		$E_{vertical}$= 33.067 lx
shaded	54%	
unshaded	46%	

Tür	517	786	1.313	1.464
Tafel	710	1.378	2.239	2.583
	1.550	2.325	26.178	4.995
	2.670	3.100	33.067	26.178
	Fenster	Fenster	Fenster	Fenster

21st May	
Sketchup	Field Measurement
	see field measurement grid below
	$E_{vertical}$= 12.756 lx
49%	
51%	

Tür	657	1.227	1.722	2.067
Tafel	1.001	2.067	3.100	6.200
	1.895	44.089	49.600	3.617
	2.756	4.306	52.356	49.600
	Fenster	Fenster	Fenster	Fenster

Figure 71. Comparison of SketchUp and field measurement on 27th April and 21st May

This kind of analysis could be useful in a preliminary stage to have a picture of daylighting distribution and availability during the day and the year as well as the relative weight of its direct and indirect components in several points of the room.

4.3.3. Check of the installed commercial photosensor

Moreover, a comparison of HOBO's and commercial photosensors measurements has been performed. To validate the data of the HOBO's and the photosensors, both have been compared from 19th April to 23th May in 15 min timesteps.
For this comparison the measures taken using two sensors and the status of their nearest hobo on the ceiling have been used. As the sensors used to control the luminaires can work according to an illuminance <500 lx or >500 lx, this threshold has been selected as reference point for the comparison of the lux meters. In total 3268 values have been

analysed, 2053 values matched for the first sensors and 2073 for the second. This means conformity of 63% and a difference for 37%.

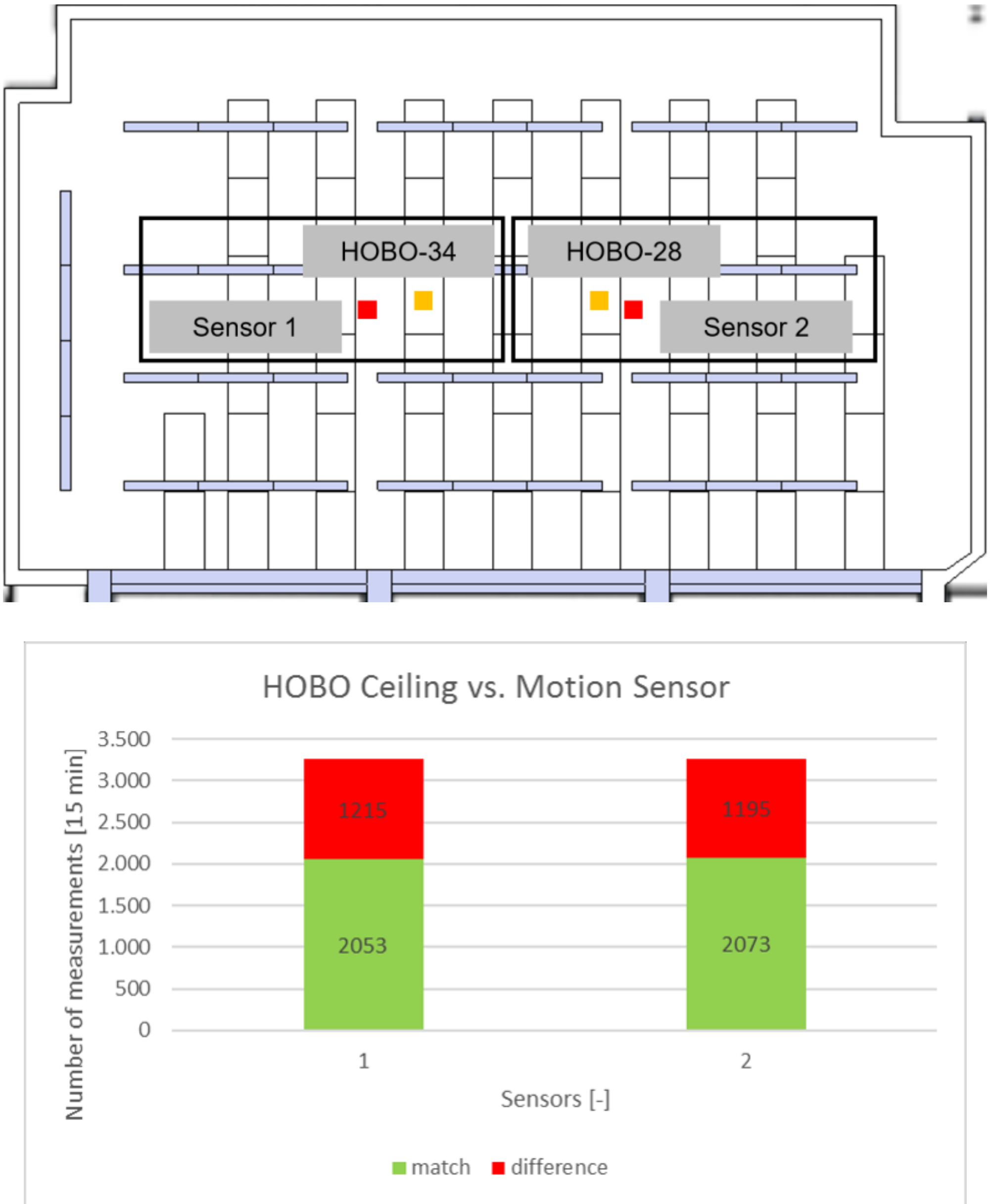


Figure. 72 Compared HOBO’s and sensors and result

As we can see in Figure 73, the light was switched on also when the illuminance values were more than 500 lux. Only the data measured by the Hobo 28 (on the ceiling) are shown in the graph because the values on the desk have been measured only during short period.

Moreover, as shown in Figure 69, the illuminance on the desk is most of the time higher than the illuminance on the ceiling. Therefore, it is very meaningful that the values have been already high on the ceiling.

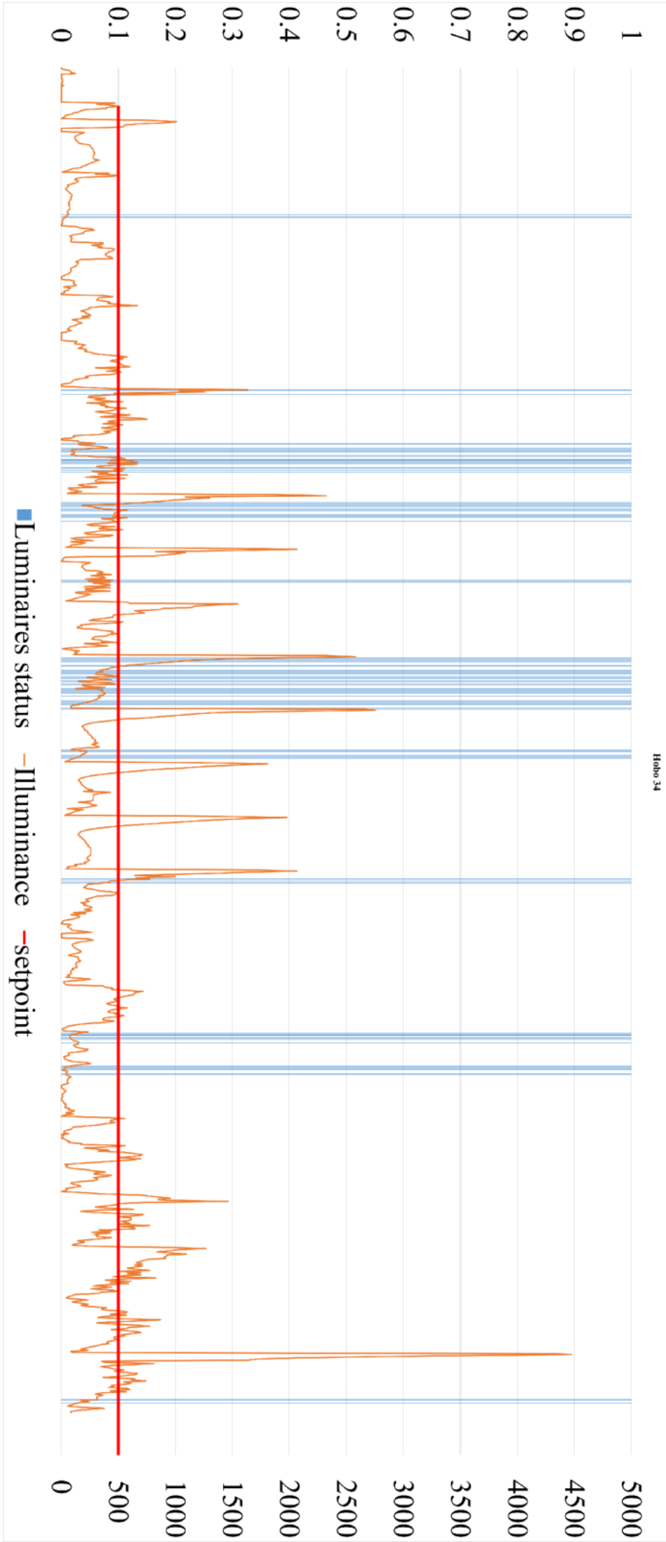


Figure 73. Plotted data of illuminance values measured on the desk, setpoint value and the frequency of the luminaire switching on

As an example, during a short period of measurements, in Figure 74 the values on the desk and the values on the ceiling are compared with the luminaires status and with the setpoint that should be achieved.

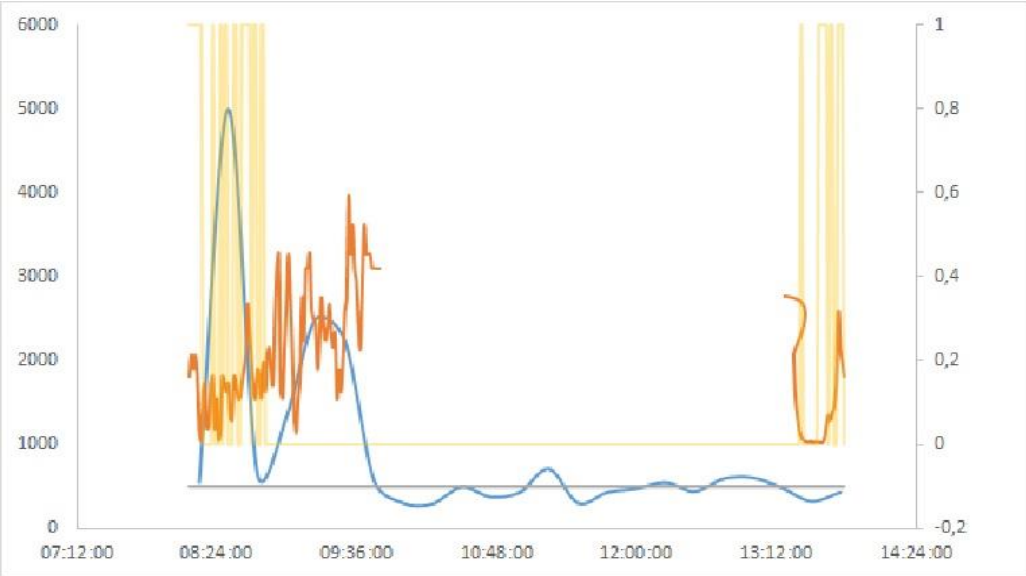


Figure 74. Values on the desk and the values on the ceiling compared with the luminaires status for a short period

Moreover, the performance of the control lighting system has been studied comparing the illuminance values measured on the desk, the illuminance values measured on the ceiling and the data from the lighting sensor of the Syrio system.

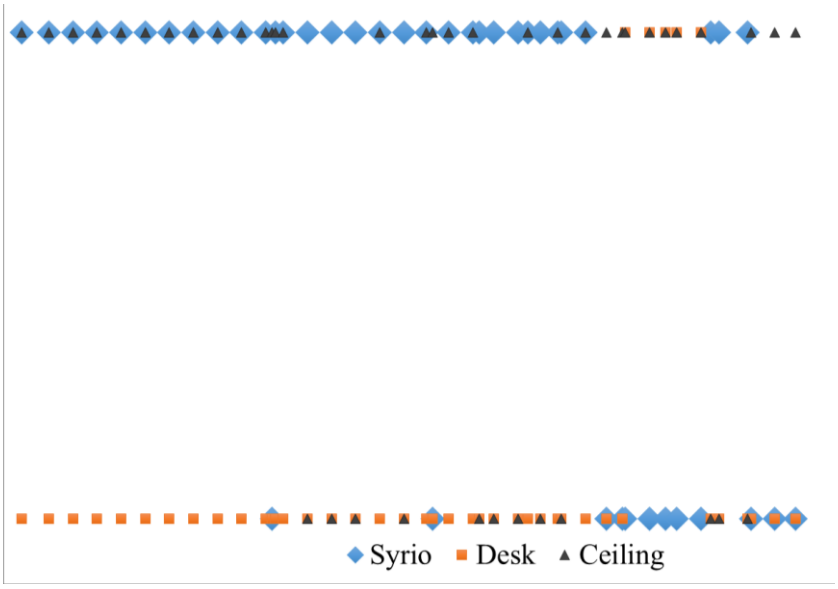


Figure 75. Plotted data of the luminaires status and the illuminance status measured on the desk and on the ceiling

The row on the top indicates the time when luminaires should be turned on. The bottom row indicates the time when the luminaires should be turned off. The rhombus position on the top indicates that the lighting detector of the Syrio system measured less than 500 lux and the luminaires should be switched on. The triangles position on the top means that, according to the illuminance values measured by the Hobo placed on the ceiling, the luminaires should be switched on. The squares position on the top means that, according to the illuminance values measured by the Hobo placed on the desk, the luminaires should be switched on. Figures show that the Syrio system worked, for the most part of the time, according to the illuminance values measured on the ceiling.

4.3.4. Relationship between energy consumption and meteorological data

During the measurement campaign energy consumption of the existing system has been collected. Ideally, the electric consumption for lighting system can be related with the weather condition and in particular with the sky condition. For this reason, a consumption analysis related to meteorological data has been carried out.
First of all, looking at Figure 76, it is possible to see the frequency distribution of the sky condition days during the measurement period.
In particular, according to the illuminance measured on the roof, it was possible to know the percentage of the time, during 5 weeks of measurement, for each sky condition. The night time is not included in these percentage.

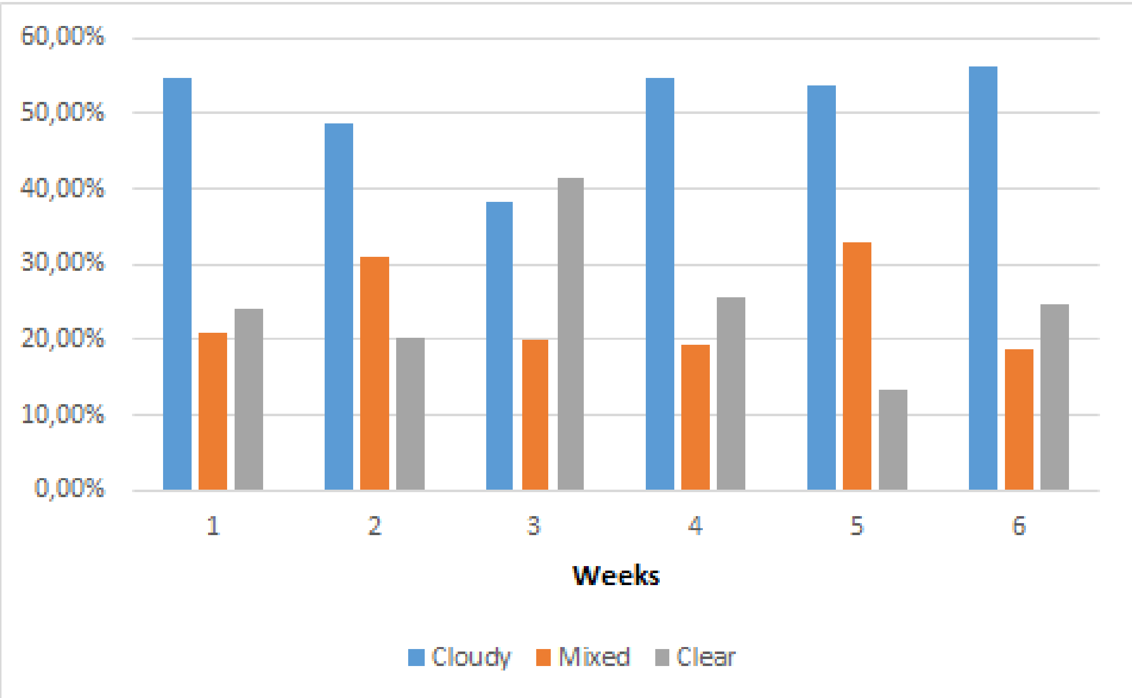


Figure 76. Sky condition distribution during 5 weeks of measurement

The weather conditions are considered by classifying the days as clear, mixed or overcast. The weather conditions are considered in this study by classifying the days according to the CIE Spatial Distribution of Daylight (CIE Standard) illumination levels. Energy saving obtained by daylight responsive lighting control systems shows differences according to the months and seasons.

As previously told, the lighting system has been adjusted for maintaining a constant illumination level of 500 lux on the working desk according an on-off strategy. When the daylight level at the work desk exceeds 500 lux, the artificial lighting is switched off automatically. Furthermore, the values measured by sensor on the working desk have been checked continuously to see, if the horizontal illumination level drops below the limit of 500 lux.

The current, voltage, active power, reactive power and power factor of the automatically controlled system, which adjusts the amount of the artificial light according to the available daylight, has been measured and stored every 10 seconds since January 2016 till August 2016. Figure 77 shows a clear relationship between sky conditions and electricity consumption.

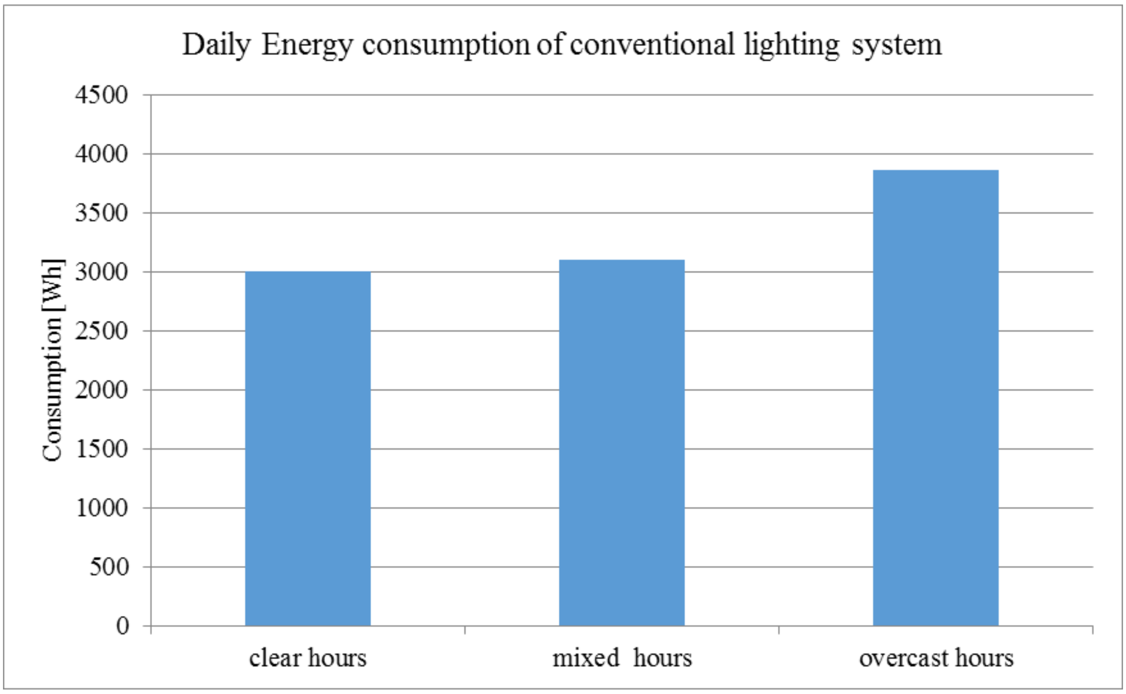


Figure 77. Annual average hourly energy consumption for various types of days during the monitoring time (Wh)

As far as data regarding sky conditions are not commonly available, some meteorological data can be easily known and collected without the use of photosensor and other measurement instruments. Hence an analysis of other parameters such as the temperature, the rainfall and the hours of sun has been carried out. In Figure 78 it is possible to see some of these figures. During the year 2016 the month of December has been the coldest of the year with minimum temperature of 2° C. While the hottest has been July with maximum temperature of 20° C. December has been the month less rainy (6 l/m^2); while June has been the rainier month (101 l/m^2). Finally, the number of hours of sun was higher during July (256 h) and lower during February (52 h).

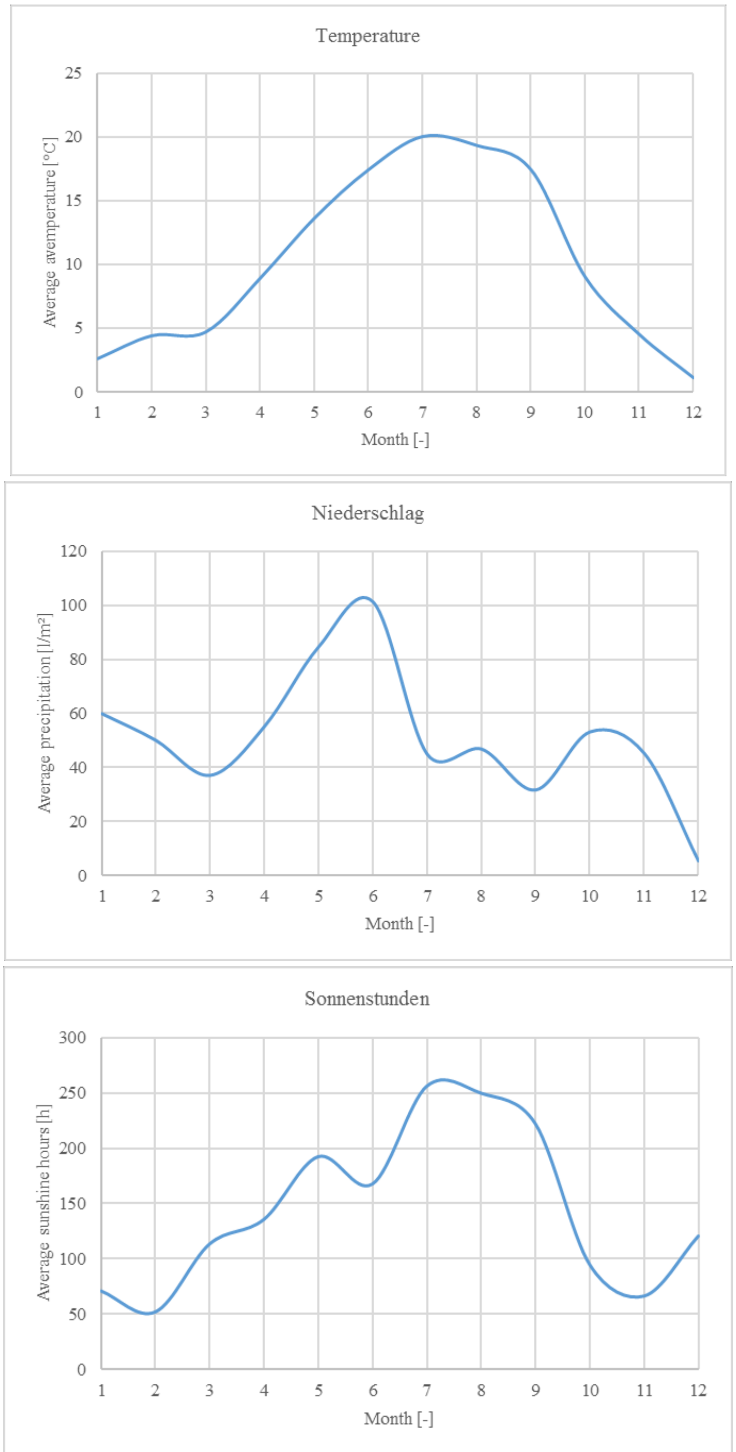


Figure 78. Temperature, rainfall and hours of sun during 2016

Figure 79 shows the energy consumption of lighting system during the months. The average of the yearly consumption is 17.8 kWh/m^2 and, in particular 31.1 kWh/m^2 for February, 27.9 kWh/m^2 for June and 39.9 kWh/m^2 for November. Indeed, as already observed in Figure 79, this period has been characterized by a low number of hours of sun. During the period from March to May the energy consumption ranges between 5.9 and 19.8 kWh/m^2. During the period between June and July the room is in general occupied for the exams session. Very low consumption has been recorded during May, August and December because of the holydays.

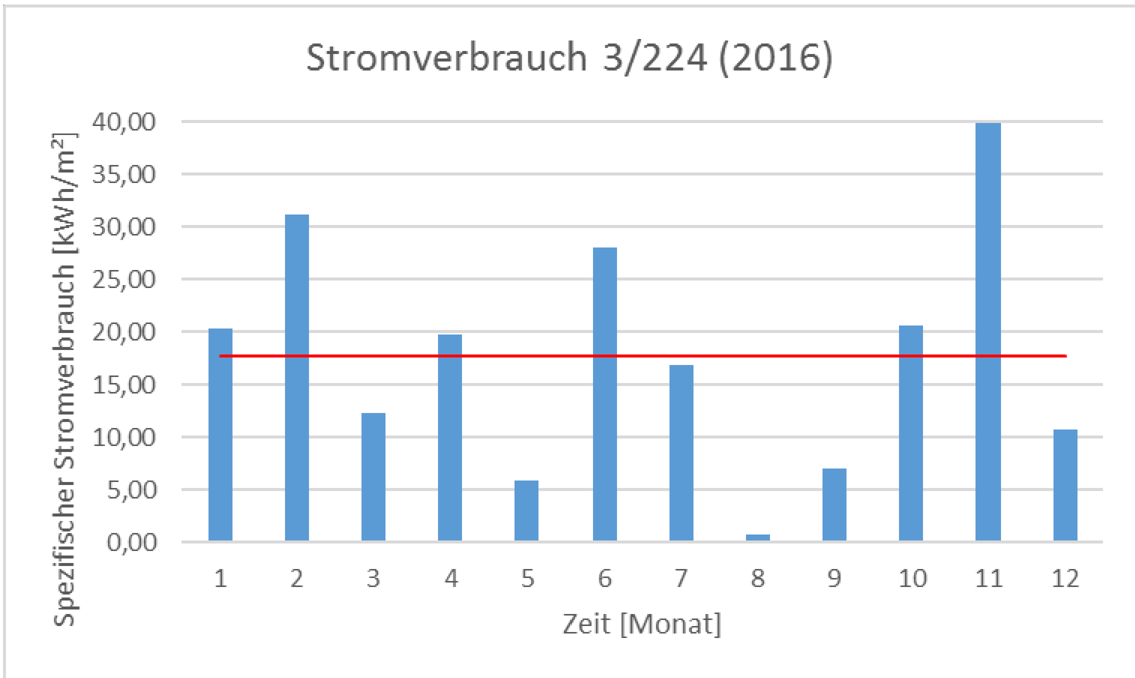


Figure 79. Yearly electrical consumption for lighting system

As a result of these analysis it can be observed that a good relationship exists between electricity consumption and sunshine hours (inverse) and rainfalls (direct) when particular occupation patters did not occur.

4.3.5. Assessment of the existing control system performances and of the potential additional saving related to new control strategies

In order to know the assess the current performance and the energy savings achievable by implementing a more advanced lighting control system, the frequency of several use cases has been analysed during 4 months, in the current state (without advanced lighting control) and with a possible further design. In a first step, three general cases (do not taking into account the illuminance values measured by the sensors) have been studied. The first case indicates the times when nobody was in the classroom, but the luminaires were switched on. Probably this is due to the fact that lighting system control installed has a ''delay time'' of 10 minutes before to switch off the lamps also if there was no one here anymore. Fortunately, this is the rarer case. More common is the second case. This is the most efficient case because someone was inside and the luminaires were switched off. The third and most common case is the case when someone was inside and the luminaires were switched on. The following graph shows the percentages of the times for each case.

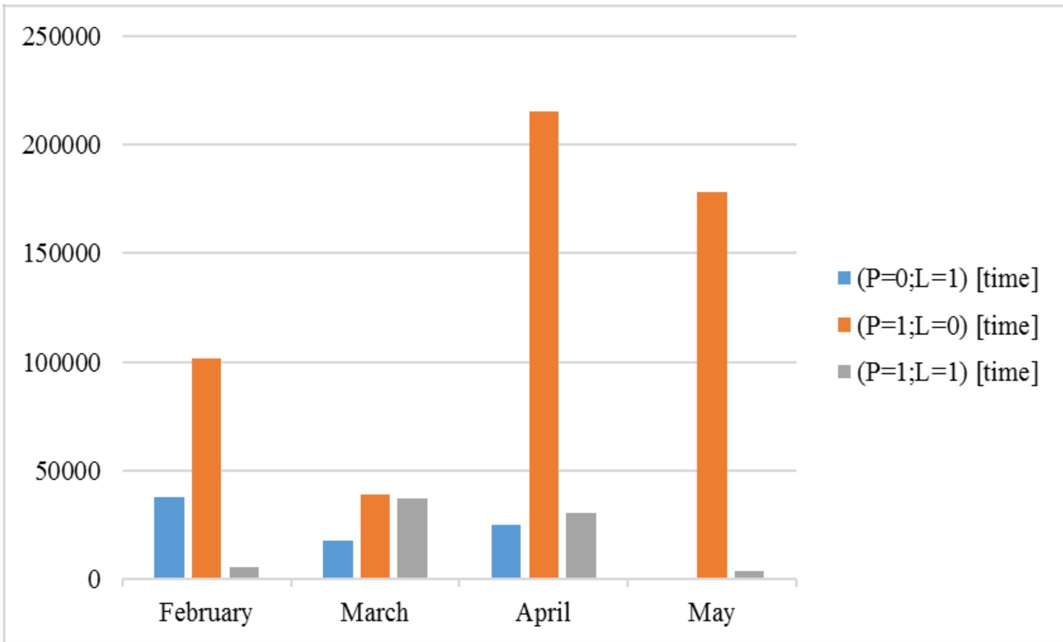


Figure 80. Scenarios occurrence

In a second step, 7 use cases have been analysed. Contrary to the cases analysed in the first step, they take into account also the illuminance values measured by the two hobo installed on the ceiling close to the installed commercial photosensors.

Scenario	**P**	**L**	**E (on the ceiling)**
1	1	0	>500
2	1	0	<500
3	1	1	>500
4	1	1	<500
5	0	1	>500
6	0	1	<500
7	0	0	>500 or <500

Table 14. Scenarios criteria

The cases are summarized in the Table 14 considering ''P=1'' if someone was in the classroom, ''P=0'' if nobody was in the classroom, ''L=1'' if lamps were switched on, ''L=0'' if lamps were switched off.

The Figure 81 shows the percentages of the times that each scenario happened in the 4 months excluding Scenario 7. The most common case is the scenario 2. It indicates that the lamps were switched off, the illuminance on the ceiling was less than 500 lux and someone was inside. Luckily, the scenario 4 never happened.

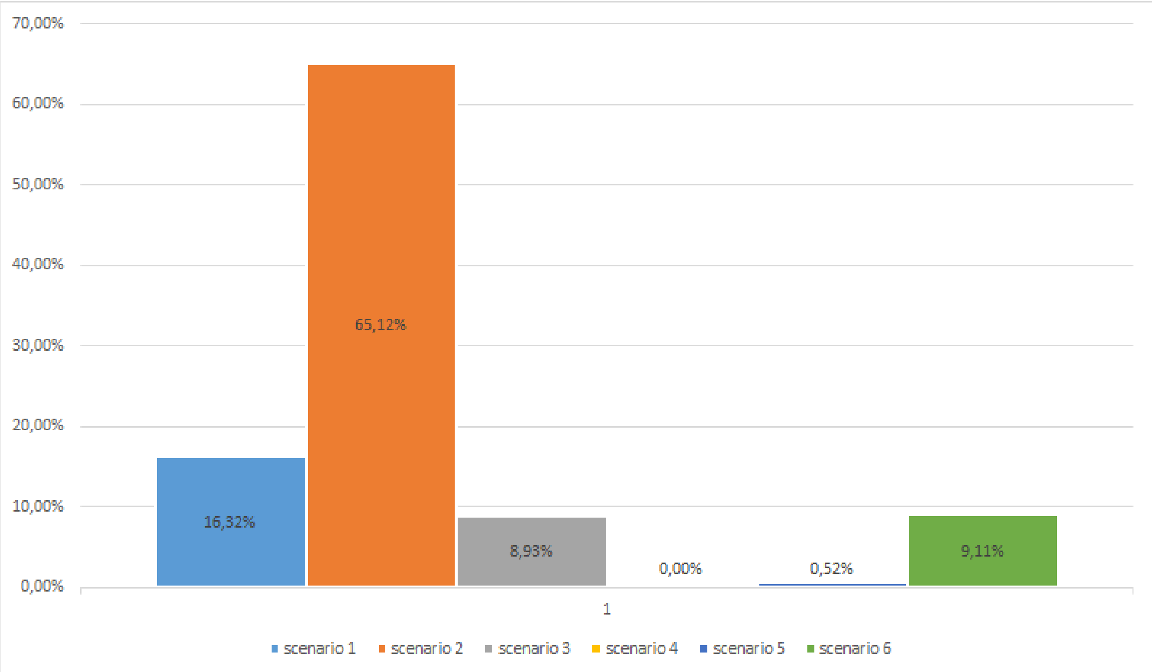


Figure 81. Percentage of scenarios occurrence

4.3.6. Energy saving prediction methods

4.3.6.1. Ideal energy saving using illuminance and occupancy measured data

The potential energy saving, for an ideal system that would work according the illuminance values measured on the desk, has been calculated. At the same time, multiplying the total installed power times, the hours when the luminaires should be turned on, according to the ceiling illuminance values, it has been calculated that the energy consumption that would be about 16.7 kWh.
This result has been compared with the value calculated according to the desk values (ca. 2.6 kWh). Therefore, the potential energy savings would be of 14.1 kWh.

The graph in Figure 82 shows 4 different conditions when the luminaires have been (ideal condition) or could be (ideal condition):

- "Scenario A" indicates the ideal case when the time when the luminaires could be switched on because the hobo, placed on the ceiling, measured E<500;
- "Scenario B" indicates the number of the times when someone was inside and the luminaires were switched on (P=1; L=1);
- "Scenario C" indicates the number of the time when nobody was in the classroom and the luminaires were switched off (P=0; L=0);
- "Scenario D" indicates every time the luminaires were switched on, both when someone was in the classroom and when nobody was in the classroom (P=0; P=1; L=1).

The number of the times of the 4 cases have been based on the scheduled occupancy hours of the classroom. The scheduled time is different from the real occupancy hours' time. As well for this reason, the Scenario C case is present. Comparing the Scenarios A and B with the Scenario D is possible to understand which is the real "status" condition and situation of the luminaires and which is the potential energy saving achievable, taking into account the illuminance condition and the presence (Scenario A) or only the presence (Scenario B).

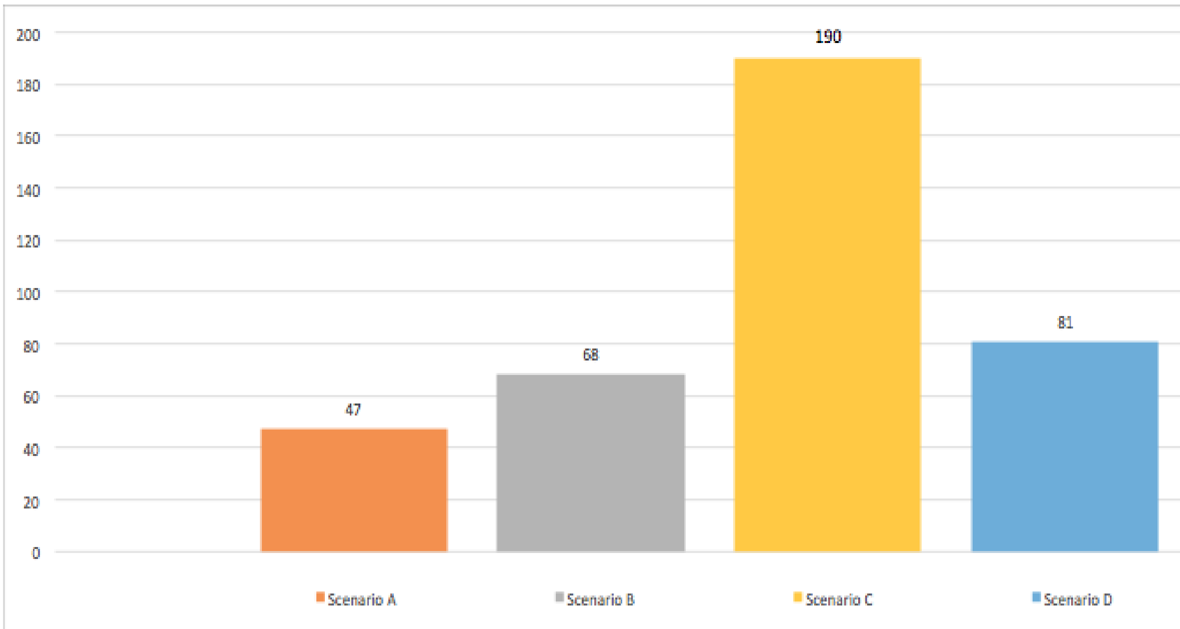


Figure 82. Percentage of scenarios occurrence

4.3.6.2. Energy savings assessment using simulation software

Being the measurement of the daylight factor (DF) not sufficiently representative of the daylight performance of a space, climate-based daylight modelling has been used to analyse the lecture rooms. In order to conduct climate-based daylight modelling, standardized meteorological files have been used for specific geographical locations.

As previously mentioned in chapter 1, simulations software has been can be used in several studies to preview daylight contribution and, more in detail, to preview energy consumption for lighting. For the presented case, a model of the room has been built to perform lighting simulation. Three computer simulation tools have been used to model the daylight performance and the energy consumption achievable using a dimmer system. In particular, 3D geometries, including the rooms' surroundings, have been built using Ecotect Analysis 2011 (Ecotect Analysis, 2011).

Numeric simulation results have been also visualized via the same tool. Radiance 3P7 for MS Windows® has been used for daylight analysis. Climate based annual lighting analysis have been performed via Daysim 3.1 for MS Windows® (Reinhart, 2011).

Additionally, an energy analysis of the existing lighting system and of suitable renovation suggestions has been carried out by DIALux (Dialux, 2017).

Because the daylight savings time lasts from April 1st to October 31s, the total annual hours of occupancy considered for this analysis at the work place are 2,000 hours.

In a defined baseline scenario, the electric lighting system had an installed lighting power density of 11 W/m^2 and it was manually controlled with an on/off switch. Electric lighting was activated 1,798 hours per year. The occupants perform the tasks that require a minimum illuminance level of 500 lux. The lecture hall had no dynamic shading system installed.

The daylight autonomies for all core work plane sensors lie between 41% and 82%. Daylight illuminances in the range of 100 and 2000 lux are considered either desirable or at least tolerable. Furthermore, the useful daylight illuminance between 100 and 2000 lux is generally not causing a visual discomfort. According to this approach, the Useful Daylight Indices (UDI) for the evaluated zone have been calculated using ECOTECT. They are: UDI < 100 lux = 22%, UDI = 100-2,000 lux = 21%, UDI > 2,000 lux = 57%.

The predicted annual electric lighting energy use in the investigated lighting zone was 19.6 kWh/m^2. Assuming a lighting zone correspondent to all the lectures rooms similar to the investigated one, its size is of 210.9 m^2 corresponds to a total annual lighting energy use of 4,153.3 kWh.

A simplified calculation of the electricity consumption by the adoption of a dimming control has been done using the Continuous daylight autonomy (cDA), already presented in chapter 1. The luminous flux needed to achieve the task illuminance value has been calculated as the difference between the illuminance level of 500 lux and the illuminance value calculating from the cDA. Then, the percentage of power and of luminous flux have been calculated. The results show that the needed annual electrical consumption for lighting to achieve the illuminance level of 500 lux is 1,010 kWh and the annual specific electric lighting energy use is 4.8 kWh/m^2. The calculations have been done based on the lighting density power. The luminaire locations, types and the physical properties of the lamps have been not taken into account.

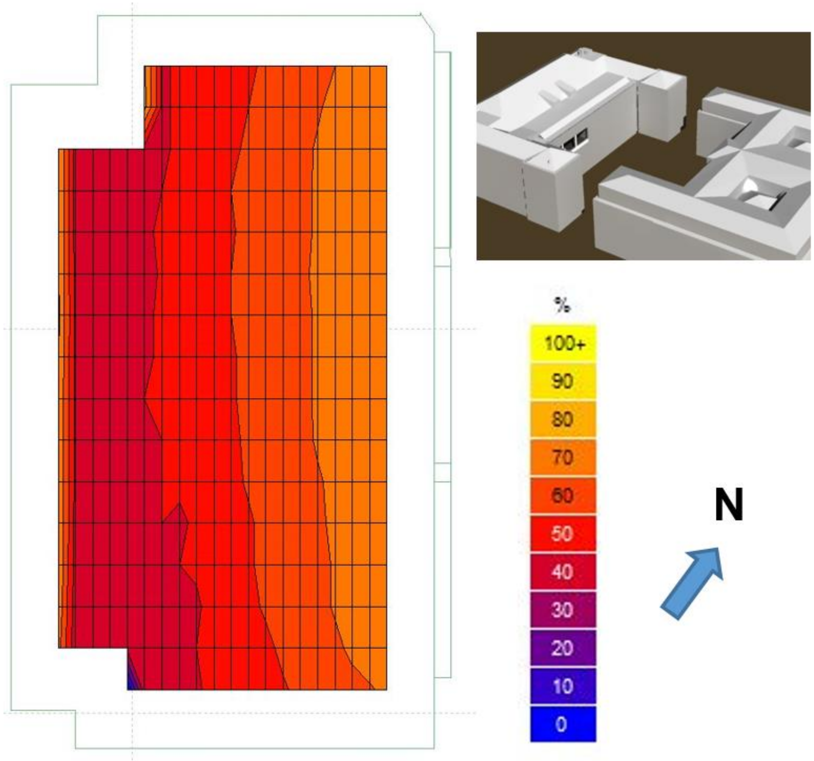


Figure 83. The continuous daylight autonomy distribution in the lecture hall assuming existing occupancy schedule and a 500lux target illuminance

Considering the same number of occupancy hours, the electrical consumption savings achievable by installing a lighting control system have been calculated also through the lighting simulations by DIALUX. In particular, in order to calculate energy consumption, sixteen different representative lighting scenarios have been chosen: 4 hours (9:00, 12:00, 15:00 and 17:00) of 4 representative days during a year (21st March, 21st June, 21st September and 21st December).

The simulation performed at 9:00 has been considered representative for a time slot between 8:30 and 10:30, the simulation at 12.00 between 10:30 and 13:30 and at 17:00 for a slot time between 16:30 and 19:30. Furthermore, the simulations carried out setting the time at 21st March have been considered representative for the period from February to April, the simulation carried out setting the time at 21st June have been considered representative for the period from May to July, the simulation carried out setting the time at 21st September have been considered representative for the period from August to October and the simulation carried out set the time at 21st December have been considered representative for the period from November to January. In order to calculate the energy consumption achieved with a dimmable lighting system, the luminaires have been divided in four control groups.

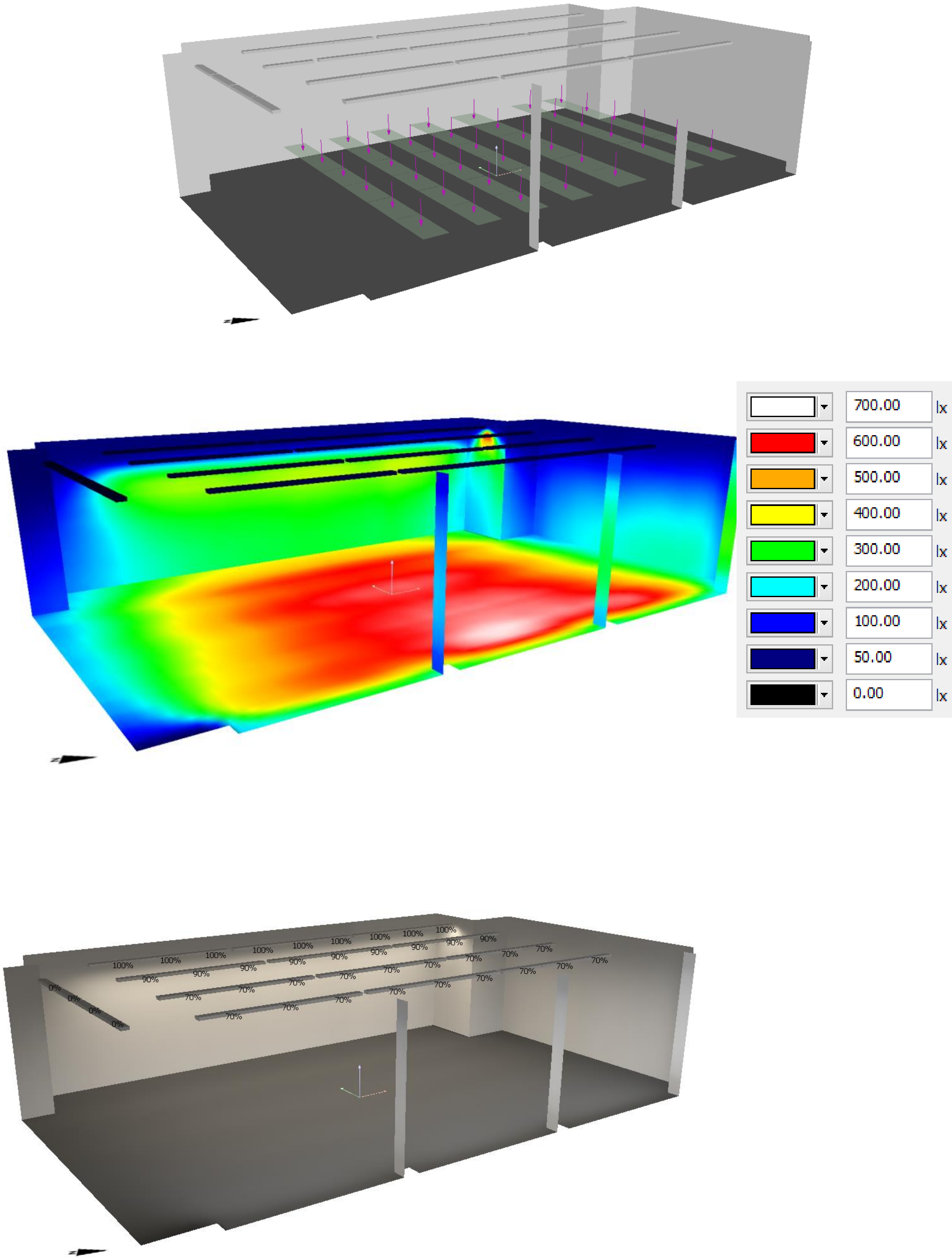


Figure 84. Pictures of the DIALUX simulation model at 21st March at 9:00

Based on the daylight contribution, for each control group the percentage of artificial light needed to achieve a minimum task illuminance of 500 lx has been calculated. Then, according to this percentage of luminous flux, the percentage of absorbed power and the energy consumption. On the contrary, the energy consumption achieved with a lighting system controlled manually has been calculated multiplied the occupancy hours times the 100% of absorbed power.

The calculated energy consumption achievable with a manual lighting system is 3,690 kWh and 17.5 kWh/m^{2}a. While, the calculated energy consumption achievable with a lighting control system (lighting sensor and dimming lamps) is 2,220 kWh and the total annual lighting energy use is 10.6 kWh/m^{2}a.

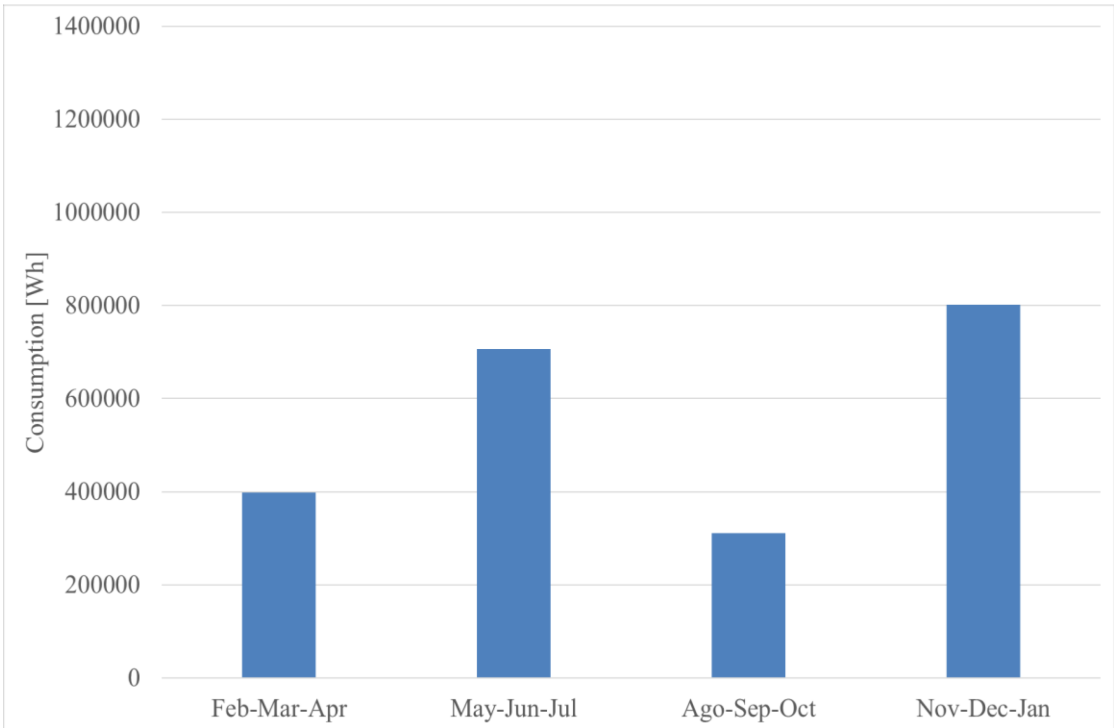


Figure 85. Consumption calculated for a dimmer system using methodology based on DIALUX simulation

In Figure 86 the consumption calculated for a system controlled with dimmer and controlled manually using methodology based on DIALUX simulation have been reported. It is possible to see that in the occupancy hours influence widely the scale of the consumption in the four different periods. For this reason, it is not possible to see how the amount of daylight can influence the consumption.

Anyway, in the first case the consumption is low because the dimmed luminous and, therefore, the dimmed absorbed power.

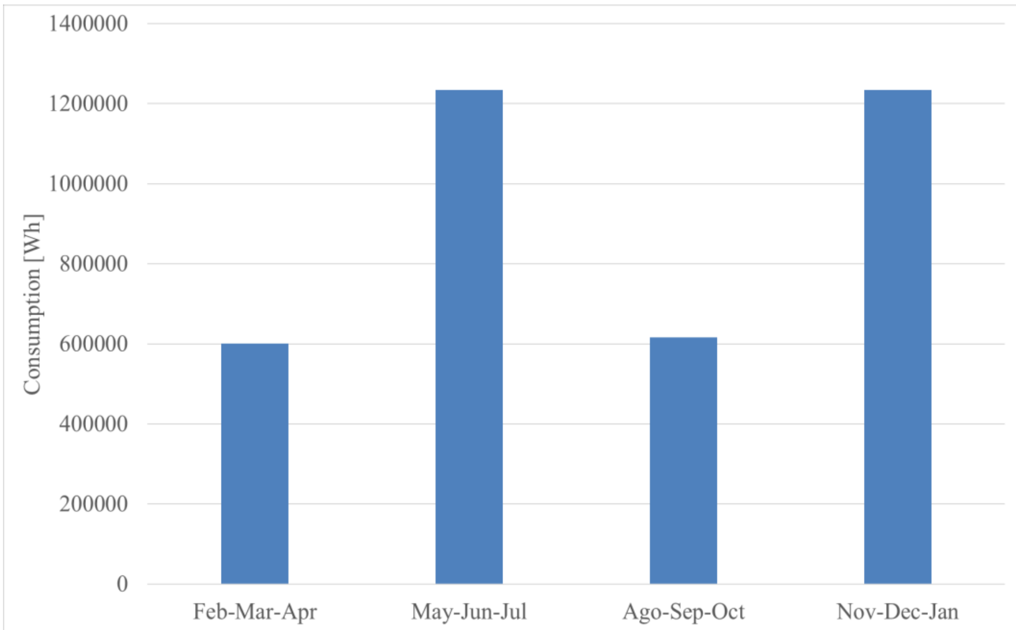


Figure 86. Consumption calculated for a system controlled manually using methodology based on DIALUX simulation

The DIALUX method predicts higher but supposedly more "realistic" lighting energy savings than the cDA method because it considers the construction, application and photometric characteristics of the lighting system. The calculated primary energy savings of the electric lighting system is around 2,640 kWh_{PE}/a. It can be concluded that approximately 40% of the energy consumption can be reduced by proposed lighting system which involved precision selection of lamps and luminaires, without sacrificing required illuminance levels in the interiors.

4.4. New lighting system and control system

Based on the presented analysis, a new lighting system, implemented with a control system, has been designed in order to generally increase the energy efficiency and the fulfilment of visual tasks. The new lighting system provided for LED luminaires produced by OSRAM and SITECO.

The new system provided a control based on the integration of artificial and natural lighting. Furthermore, it would be able to change the colour temperature of the lamps and it provided the plan of different scenarios.

The control system has been implemented with a DALI Gateway and new luminaires selected performing lighting simulation in order to achieve an illuminance of 500 lx values on the workplane.

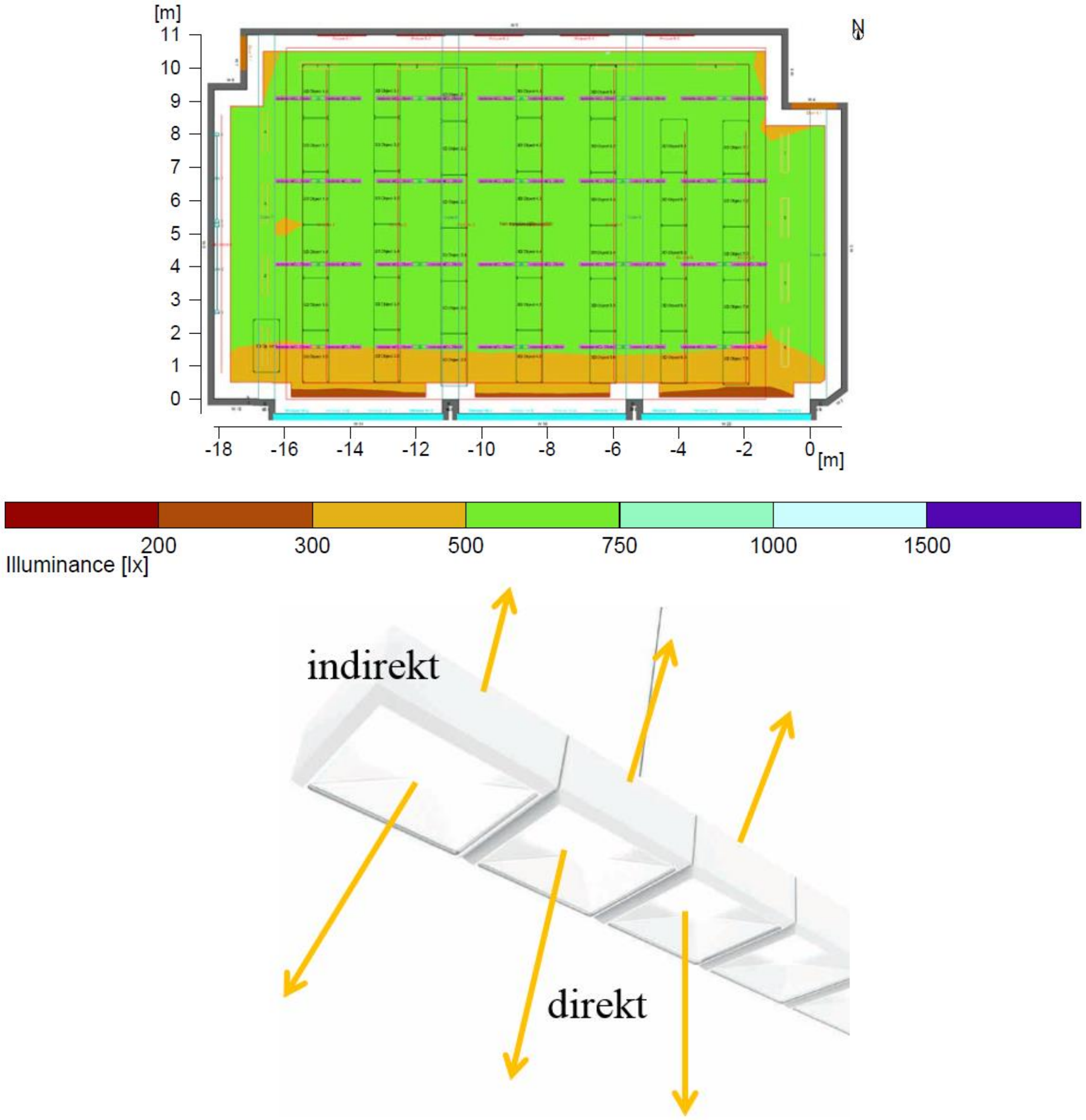


Figure 87. False colour rendering and the selected new luminaires

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5. A Laboratory Setup for the Evaluation of the Effects of BACS and TBM Systems on Lighting at DEIM

In section 6, 7, 8 and 9 different analyses have been applied using data of other cases study. They were all educational building. In this section the main case study object of this thesis is described. It is an existing laboratory where an experimental setup has been installed in order to test two lighting control systems and to simulate other two different end-use: an office space and a residential one (Beccali et al., 2015).

5.1. Laboratory description

The laboratory is located at the *Dipartimento Energia, Ingegneria dell'Informazione e Modelli Matematici (DEIM)* of the University of Palermo. It is located at latitude 38.104060° and longitude 13.34612°. According to the Decree DPR 412/93 classification, Palermo is considered in climatic zone B with about 2500 sunhours per year.

The basement of the building façade is covered with grey stone bricks, while the rest with yellow plaster (ρ=0.40). The building has four floors and the laboratory is on the 3rd floor that has an area smaller than the other floors. In fact, the room shares three borders with a terrace and one border with another room. The laboratory area is 106 m^2 and the height is 4.40 m not considering the false ceiling, and 3.40 m considering the false ceiling. All the indoor walls are white painted (ρ=0.8), while the floor is covered with marble tiles (ρ=0.6) and the false ceiling surface is composed by light grey painted modules in aluminium covered by white paint (ρ=0.8).

In the laboratory some furniture are present: a wood desk (ρ=0.3), a grey plastic desk, a grey metal bookcase (ρ=0.6), and a grey metal closets (ρ=0.6). This has glass doors that can cause specular reflection.

Along the wall located at southeast there are four windows that are 2.40 m wide and 2.60 m high. Externally, the windows have a ceramic frame. The glass has a light transmission factor of 0.78. While, along other walls there are not windows. During the measurement the existing blinds were completely open. This façade is partially covered by a shelter, equipped with a Photovoltaic/Thermal collector connected with both a HVAC system (a solar thermally driven advanced DEC system) and the electric grid through a storage/management system. The view immediately out this façade is a green roof (albedo average value= 0.25). This fact is very important for the distribution of the light in the room because the vegetation grows or can change the colour, and therefore the albedo, during the time. Due to the latitude of the laboratory the presence of the snow is extremely rare.

Figure 88. Some pictures of the laboratory in Palermo

5.2. Lighting system

In the laboratory, the following lighting luminaires are installed:

- four suspended luminaires equipped by LED (each one with a power of 54W);
- four mono optic indoor LED spotlights (15 W).

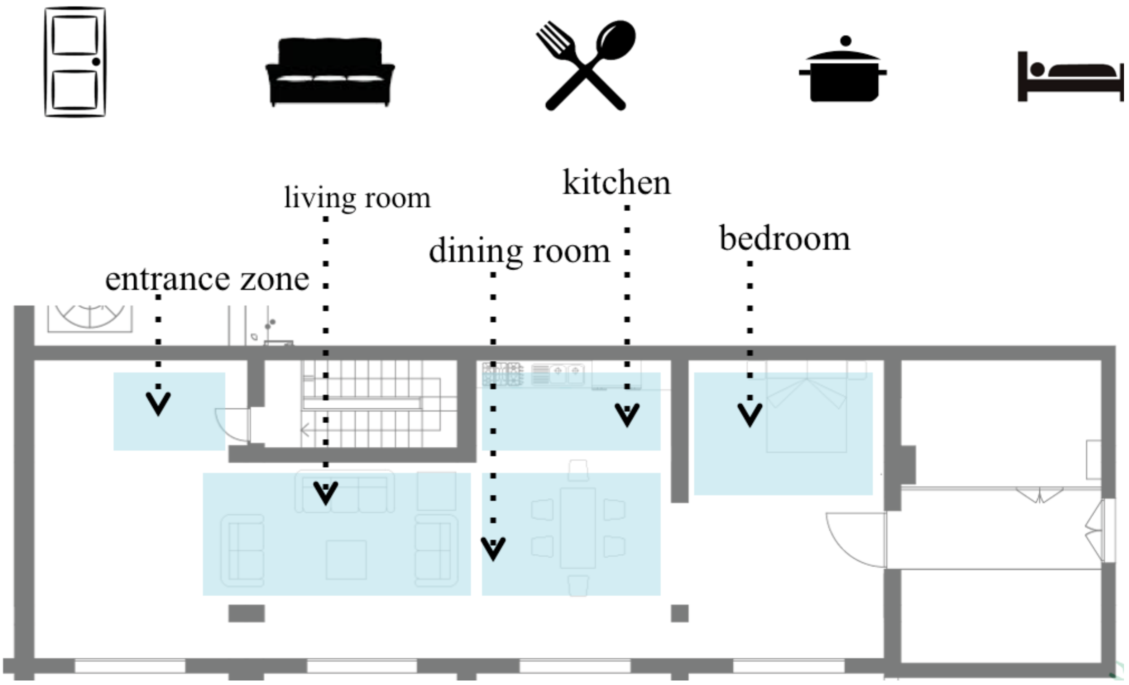
The first luminaries are characterized by a power supply unit with DALI interface and are equipped with micro-lens optics in a polycarbonate cover. The initial luminous flux declared by the manufacturer is 3600 lm and the initial LED luminaire efficacy 92 lm/W. Regarding the mono optic LED, the initial luminous flux was 700 lm and the luminaire efficacy was 50 lm/W. Both luminaires have a colour temperature of 3000 K and a colour rendering index of ≥80. The lighting power density is 1.86 W/m^2 for the whole area and 2.9 W/m^2 for the area of the zone considered in this work (where the three dimmable suspended luminaires are installed). The luminaires have been selected in order to achieve for each zone the illuminance values, suggested by the Italian UNI 10380 standard (UNI 10380), for the residential case, and by the EN 12464 (EN 12464) standard, for the office case. To do this, laboratory has been ideally divided in several zones according to the assumed end use.
For the office case the laboratory has been zoned in:

- a manager room;
- two work stations;
- an entrance.

For the residential case the laboratory has been zoned in:

- a bedroom;
- a living room;
- a dining room;
- an entrance.

Preliminary calculations have been performed using the lighting simulation software DIALUX (Dialux, 2017) (see Figure 89) in order to design the lighting system.



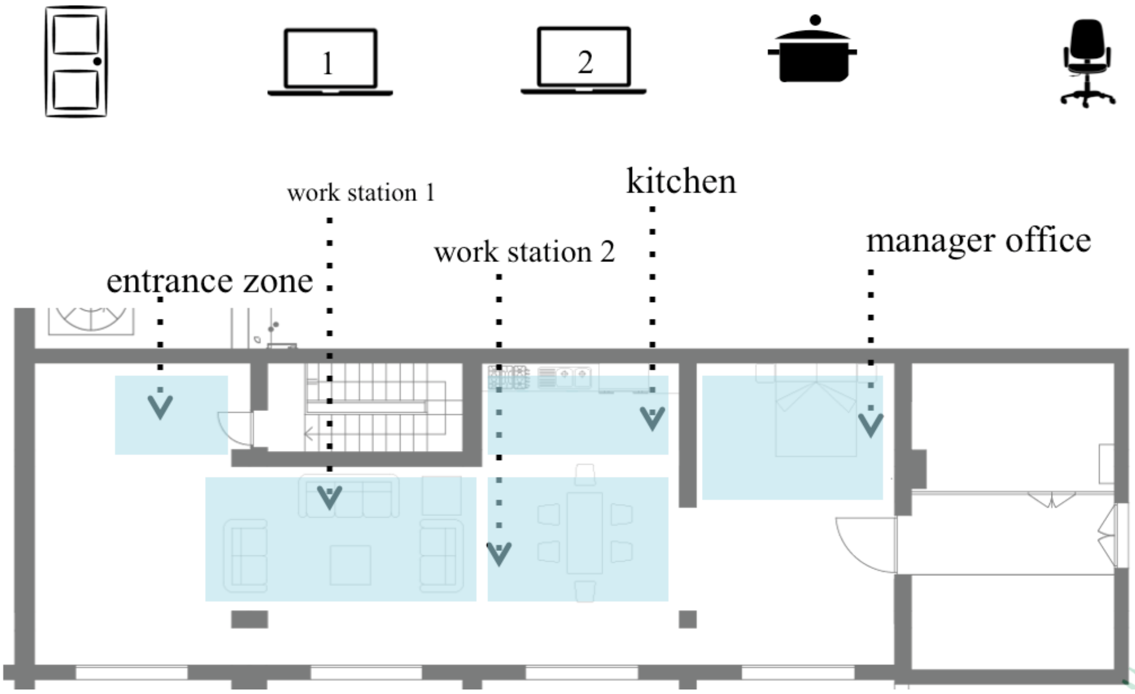


Figure 89. Zones for the two end-uses

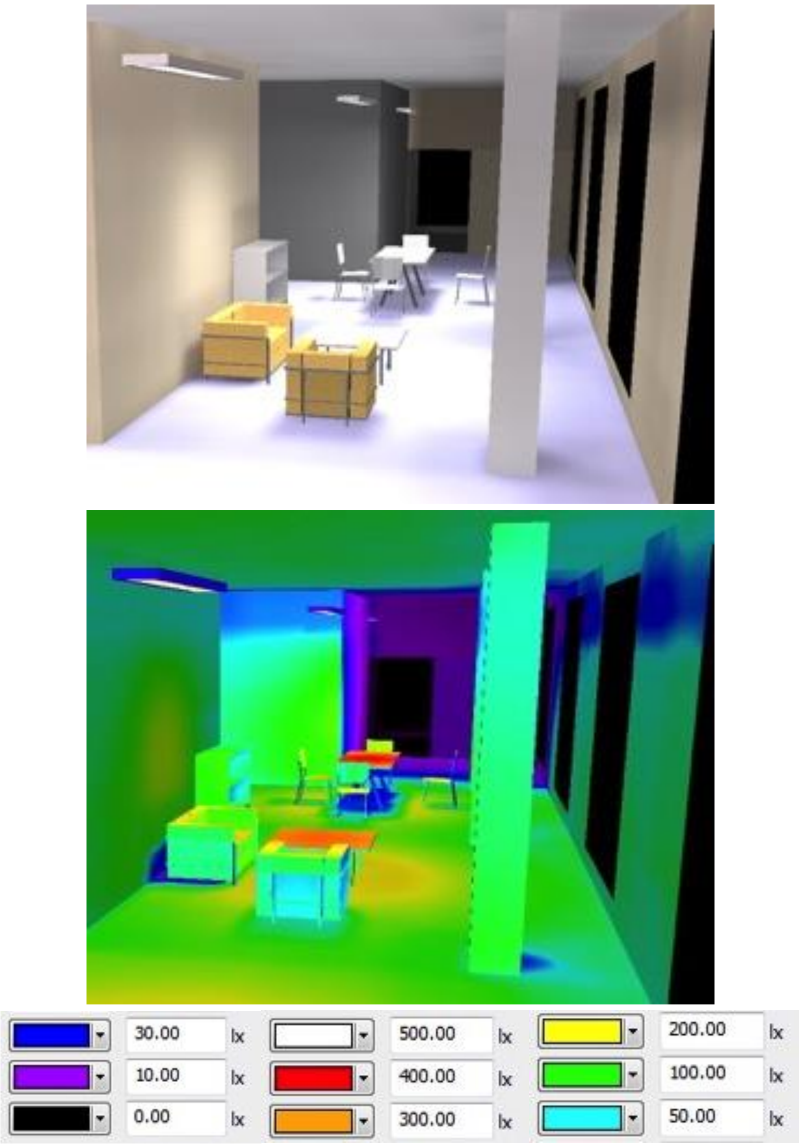


Figure 90. Real and false colour rendering of lighting simulation

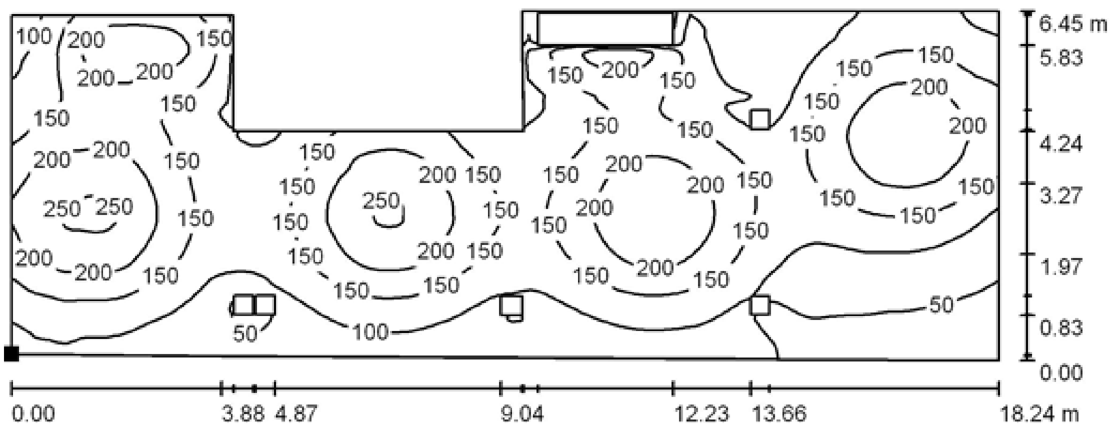


Figure 91. Isolines of artificial lighting on the floor

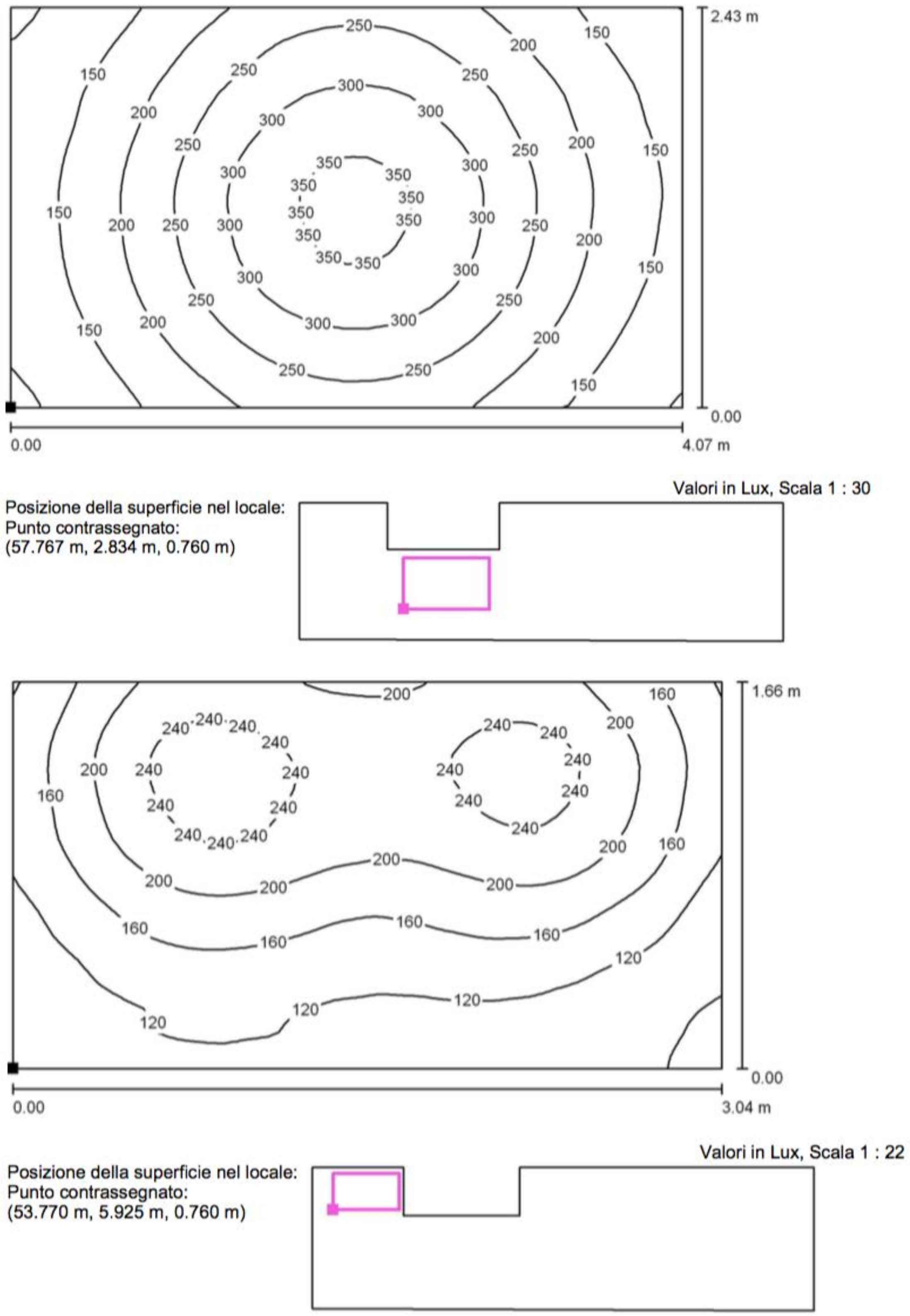


Figure 92. Isolines of artificial lighting in living zone Isolines of artificial lighting in living zone and in the entrance zone

Mono optic luminaires | Suspended luminaires

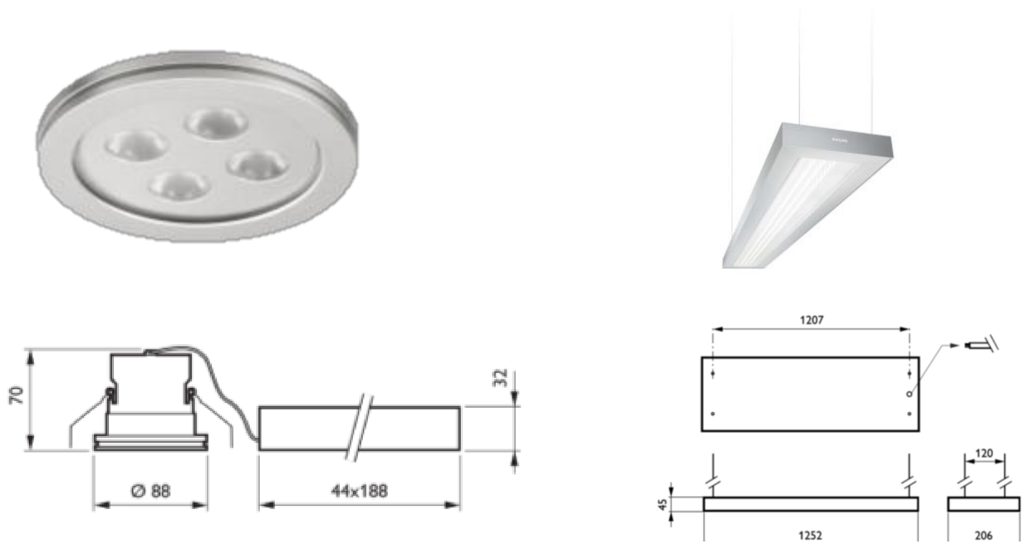


Figure 93. Installed luminaires

In particular, they are distributed as following:

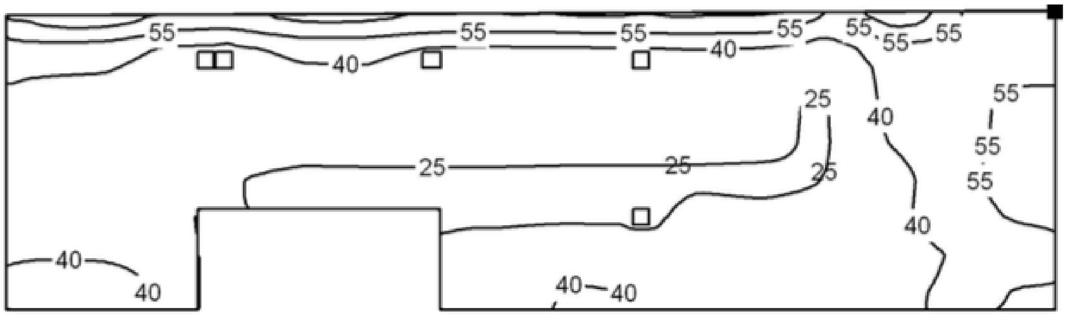
- n. 2 mono optic spotlight, installed on the ceiling, in the "entrance zone";
- n.3 suspended luminaires in the "living/dining" or in “work station” area;
- n. 2 mono optic indoor spotlight, installed on the ceiling, in the "kitchen";
- n. 1 suspended luminaire in the "bedroom".

Zone	E (lux)	Colour gradation	Glare classification
Passageway	50-100-150	W	A
Reading zone	200-300-500	W	A
Writing zone	300-500-750	W	A
Dining zone	100-150-200	W	A
Kitchen	200-300-500	W	A
Bathroom: General lighting Mirror (vertical surface)	 50-100-150 200-300-500	W	 B B
Bedroom: General lighting Closet (vertical surface) Bedroom	 50-100-150 200-300-500 200-300-500	W	B B B

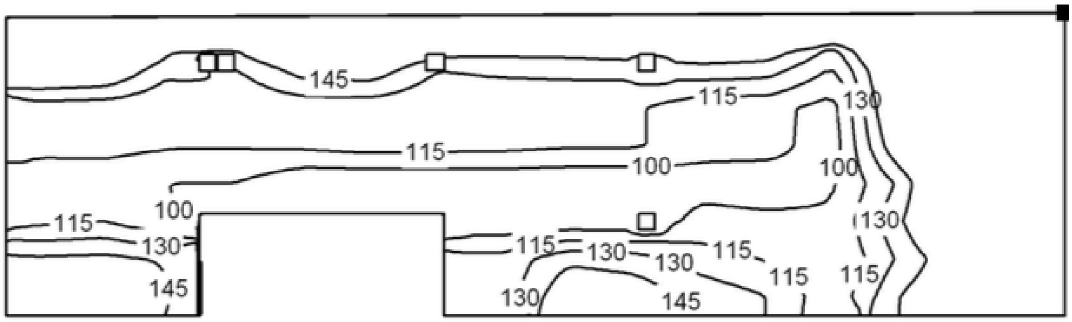
Table 15. Illuminance values suggested by EN 12464 standard for each task zones

In order to place the photosensor, other simulation, but only with daylight contribution, have been carried out for 4 days of the years (21st March, 21st June, 23th September and 23th December) at 9:00, at 11:00, at 13:00, at 15:00, at 17:00 and at 19:00.

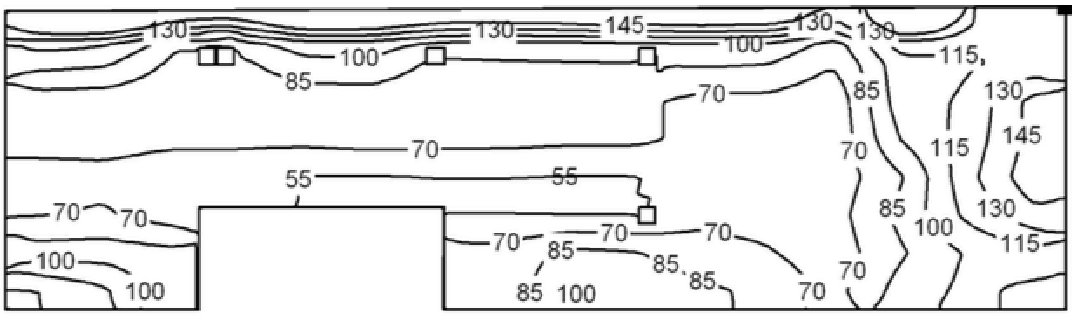
Obviously, in March and in December the illuminance values in the simulation after the 17:00 is close to 0 lx. In following figures, some isolines of these simulations are shown.



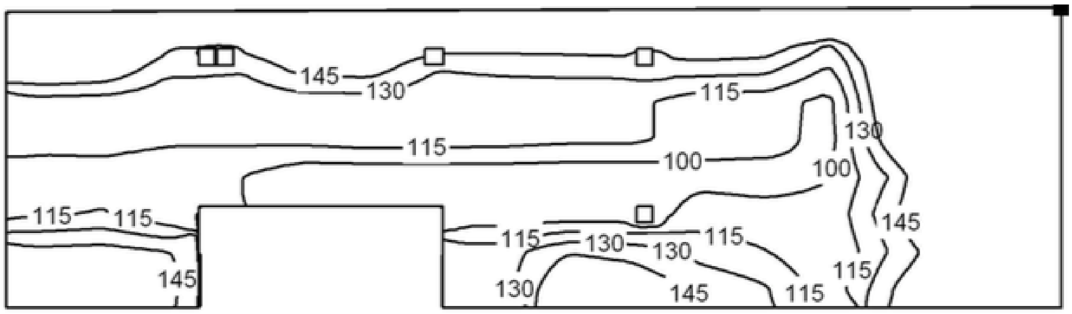
23rd December, 9:00



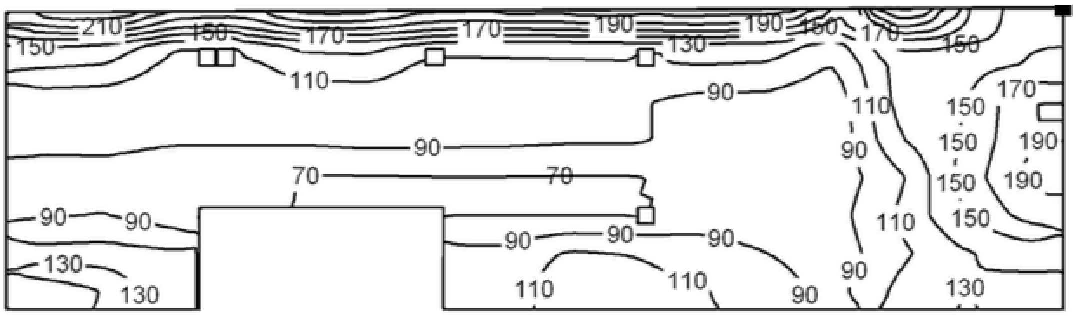
23rd December, 11:00



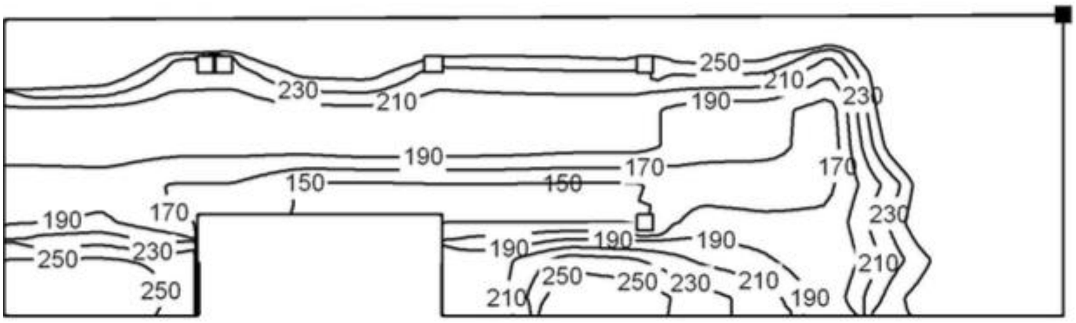
23rd December, 13:00



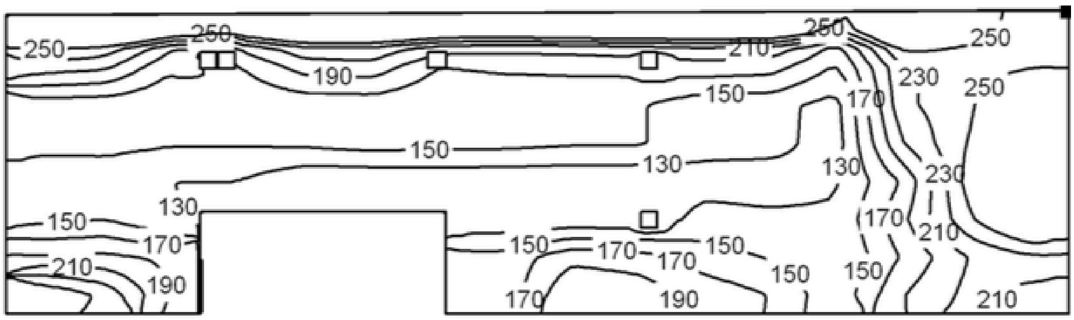
23 rd December, 15:00



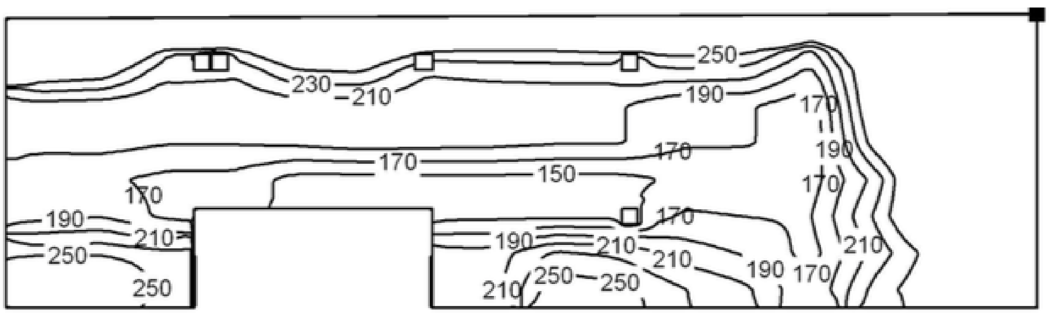
21st March, 9:00



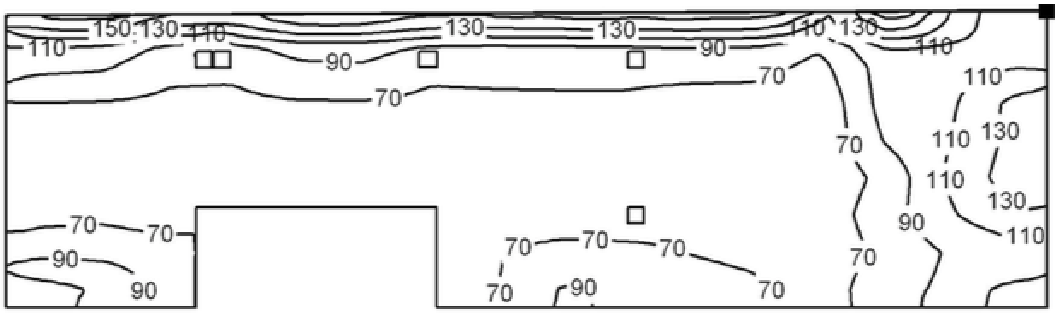
21st March, 11:00



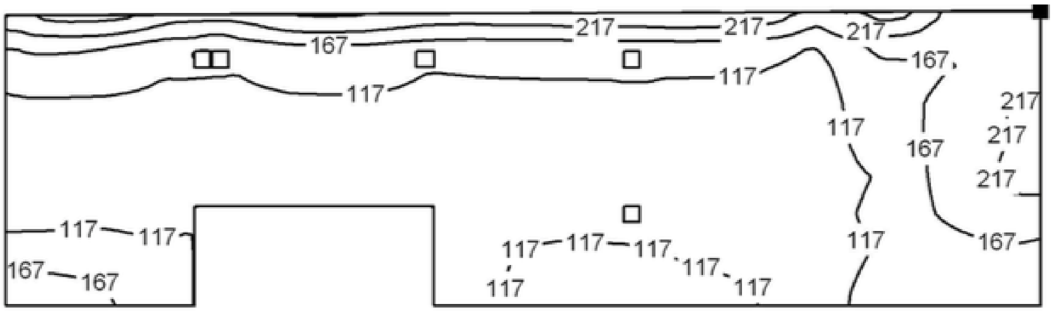
21st March, 13:00



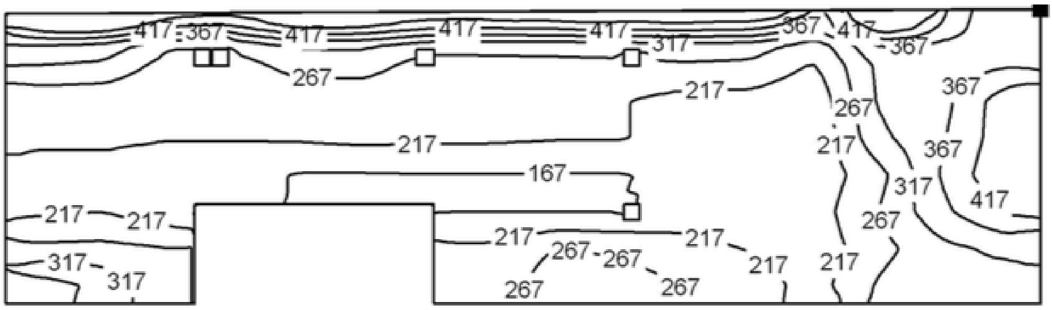
21st March, 15:00



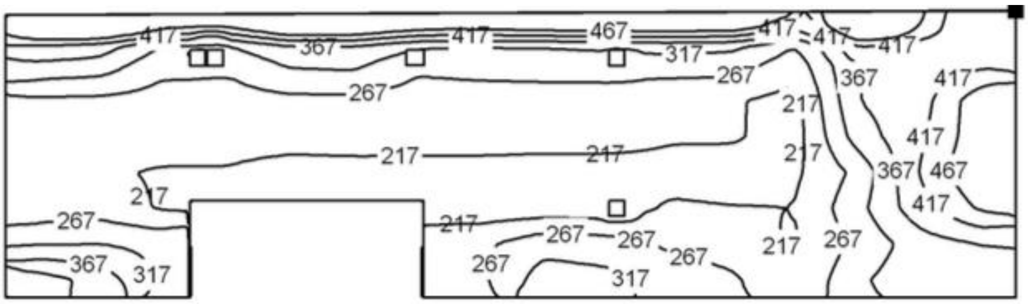
21st March, 17:00



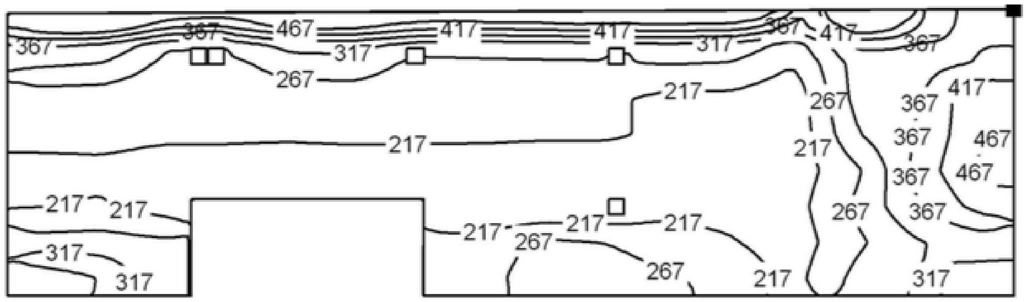
21st June, 9:00



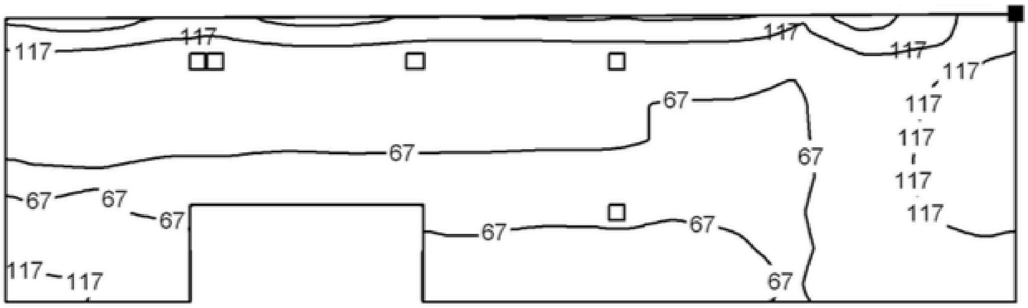
21st June, 11:00



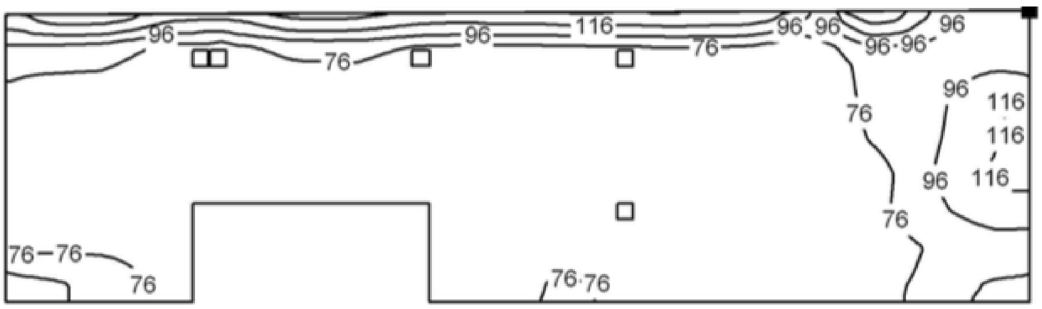
21st June, 13:00



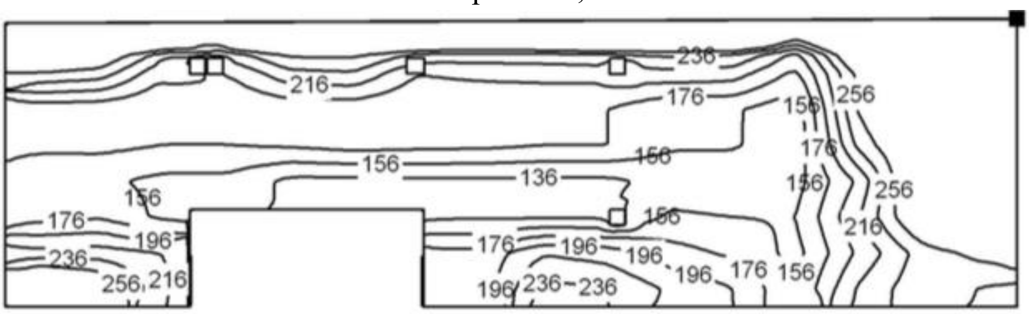
21st June, 15:00



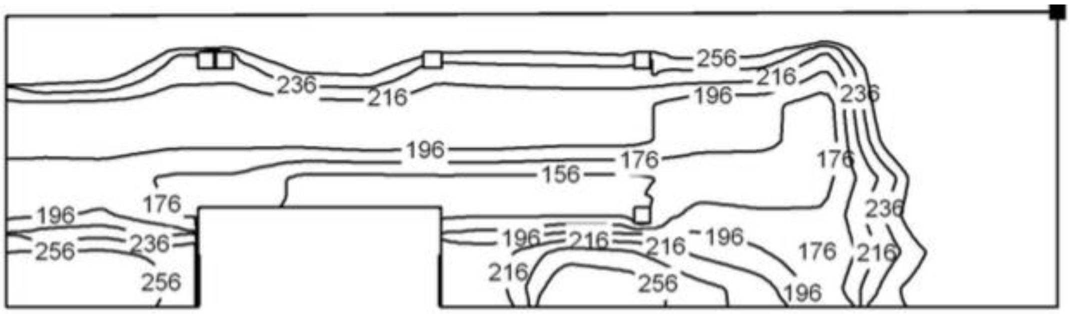
21st June, 19:00



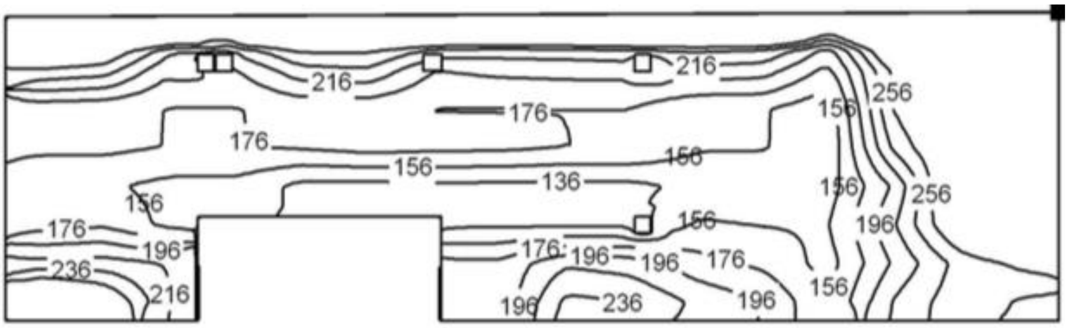
23rd September, 9:00



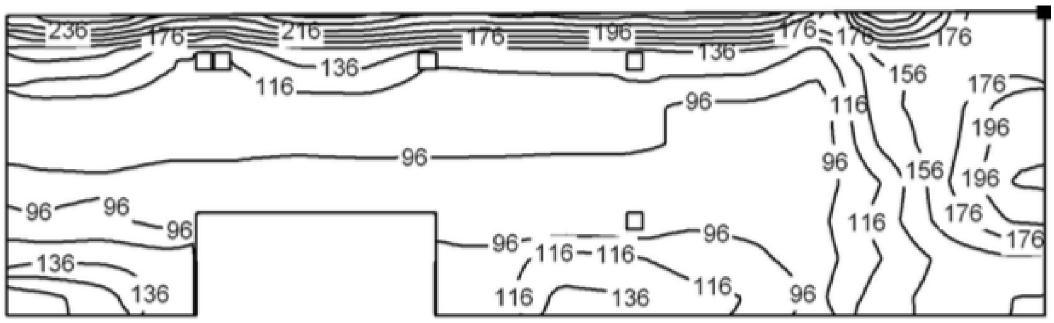
23rd September, 11:00



23rd September, 13:00



23rd September, 15:00



23rd September, 17:00

Figure 94. Isolines of daylight distribution on the ceiling performed by Dialux

5.3. Daylight Linked Control system

In order to test the DLC systems, only the four suspended luminaires equipped by LED (each one with a power of 54 W) have been connected to the control system. Two different daylight linked control systems, produced by two manufactures have been tested. The first one has been installed and tested, in a first period. It's photosensors has been placed on the ceiling at about m 1.60 away from the window, characterized by an angle view of 180° longitudinally and 360° horizontally. As in most lighting control systems, its positioning was not really optimized with a precise method but simply following the manufacturer's suggestions. This DLC is designed for being easily usable by anyone, also by not skilled personnel; indeed, its interface is very user-friendly. It is composed by a closed loop photosensor, a scenario programmer, a touch dimmer, 3 manual actuators and 4 basic controls (common switches).

The system is a commercial product manufactured by BTICINO and it is settable using the proprietary software MyHome Suite which can manage several BAC functions, including lighting control. Figure 95 shows the plan of the Solarlab with the identification of the zone where the lighting task has been analysed, and the distribution of the luminaires and the position of the control system devices.

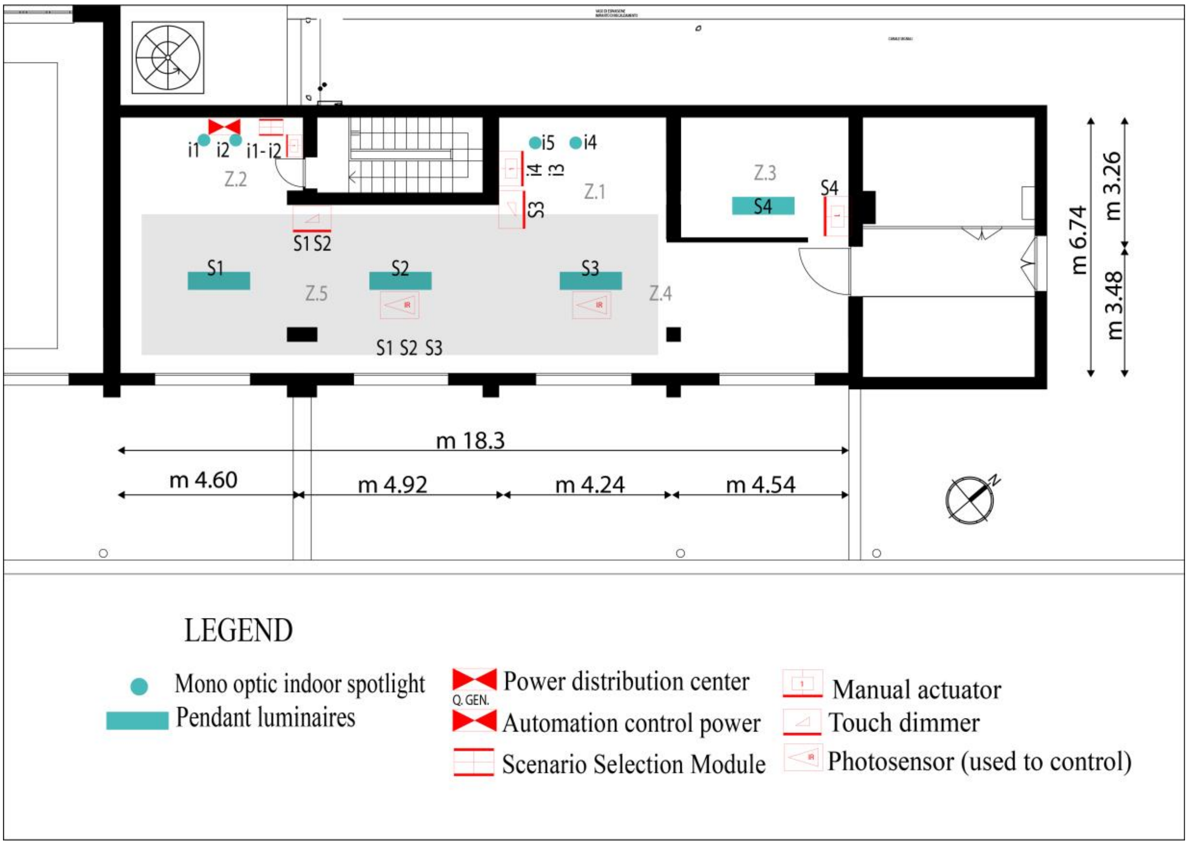


Figure 95. Laboratory plan and section with luminaires and DLCSs devices of system Bticino

The photosensor algorithm, used to control the luminaires, was "closed loop".
A target luminance can be set on the software menu after a "rapid" calibration of the photosensor, which is made with a remote control device. After the measurement of the desired lighting level on the task area with a luxmeter, the device sends a "calibration" command to the photosensor. This procedure has been made once with only artificial light and once with only daylight (without direct solar irradiance).

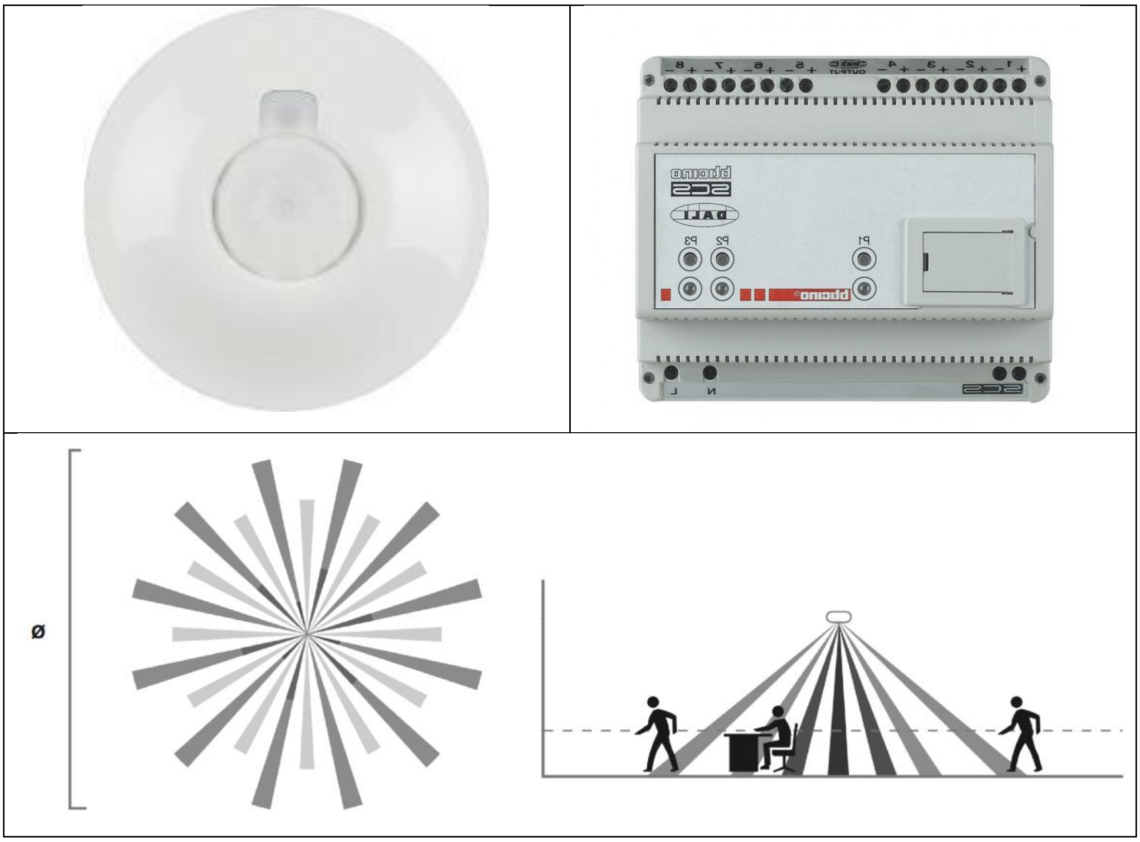


Figure 96. Control unit and photosensor Bticino with its field view

Selected functions are shown in table 16 and described in Figure 97, according to CEI Guide 205-18 scheme

Kitchen	Manual on/off control i3 e i4
Entrance	Manual on/off control i1 e i2
Bedroom	Manual on/off control S4
Living	Dimmer control S1 e S2
	Scenario control
	Manual on/off control S1 e S2
Dining	Dimming control S3
	Scenarios control
	Manual on/off control S3

Table 16. The function applied to each zone

Functions, defined by CEI Guide 205-18 for lighting control, F49A (presence detection and automatic ON/OFF) and function F48A (presence detection Auto-ON/Reduction/OFF) have been implemented. In particular function F49A has been selected for kitchen zone, entrance zone and bedroom and function F48A for dining room and living room.

In zones where artificial lighting was controlled by function F49A, the natural lighting contribution was not enough to achieve the illuminance values suggested by standard EN 12464. For this reason, during the time of occupancy of these spaces, it was necessary to have the maximum luminous flux and it was not suitable to apply dimming control function.

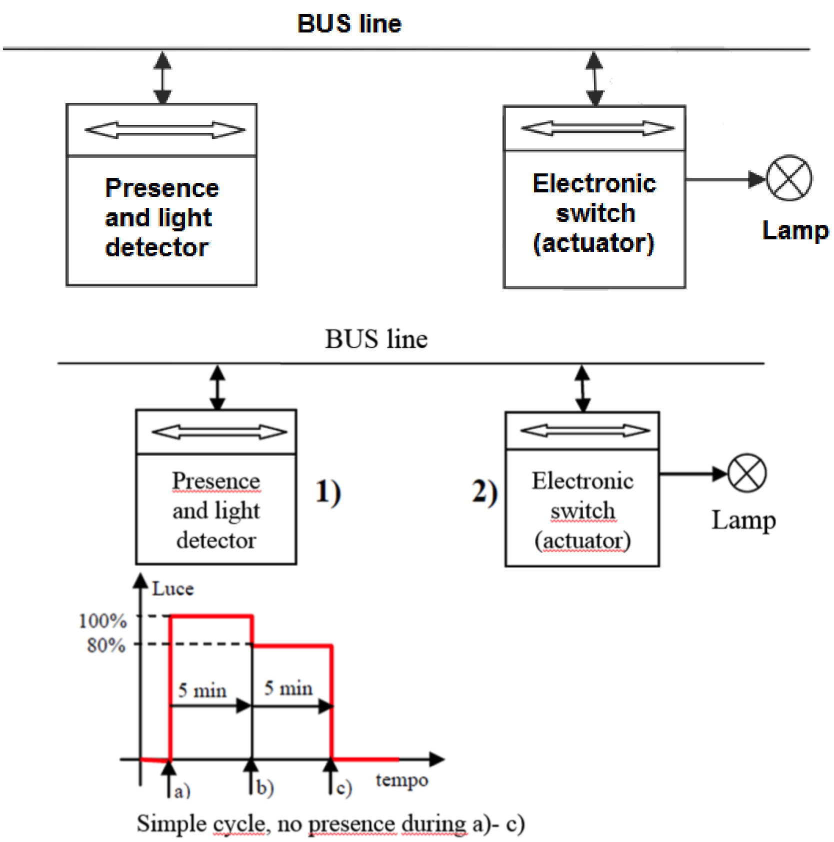


Figure 97. Scheme of functions F48A and F49A (CEI Guide 205-18)

The second tested system was produced by Zumtobel. It was composed by a DALI/DSI control unit (sensor, pir) DIMLITE produced by Zumtobel. It is able to control the luminaires either with an ON-OFF strategy or dimming (1–100 %). To do this, it was connected to a photosensor Sensor (light) ceiling mounted. It was produced by Zumtobel also.

The light sensor measures the daylight entering the room and send the command to the DIMLITE. It was mounted on ceiling according to the datasheet indications. It is equipped with a look-out open loop photosensor. This photosensor has been linked and managed by a DALI electronic control ballast able to send the signal to the luminaires. In Figure 98 the pictures of the photosensors and ballast Zumtobel are shown.

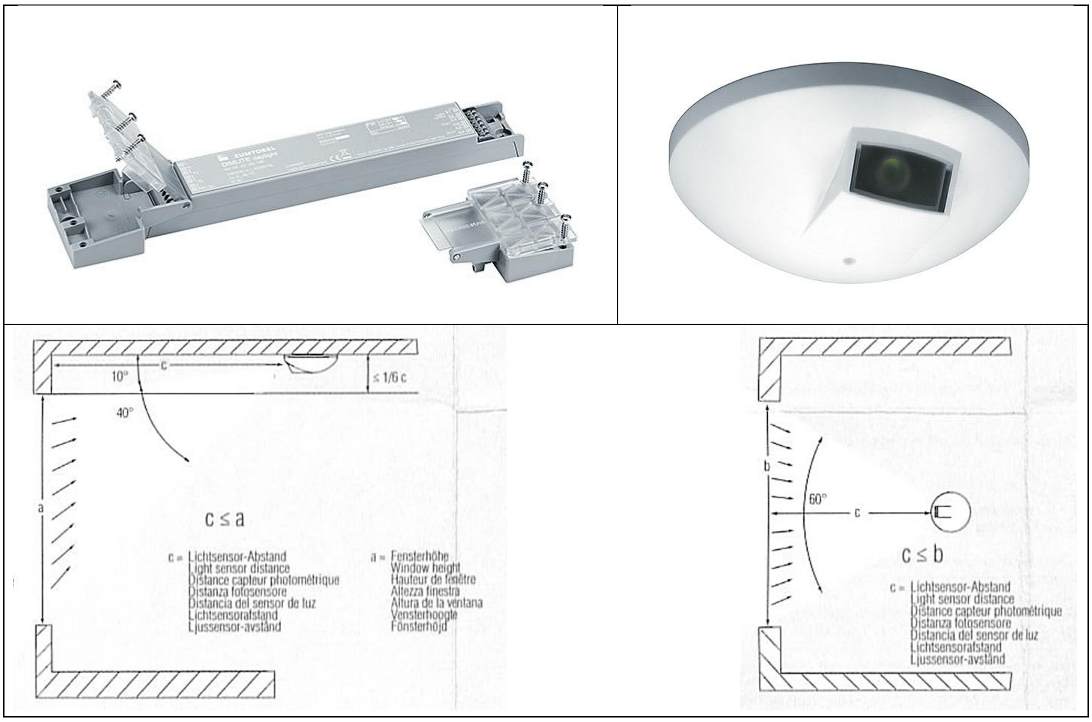


Figure 98. Control unit and photosensor Zumtobel with its field view

5.4. Measurement campaign

The measures have been taken during a 16 months long period. The aim was to evaluate actual performance of the system installed in the laboratory described below. Following measures have been collected:

- Absorbed power;
- Indoor illuminance in six different points of the laboratory;
- Current;
- Voltage.

In order to measure the distribution of illuminance values, the room has been set up with 6 photosensors Delta Ohm HD 2021T (measuring range 0.02-20 klx) placed in six different positions (two on the ceiling, two on the work plane level and 2 on the walls). For electrical measures a Power Monitoring Device (SENTRON PAC3200) for displaying all the relevant system parameters in low-voltage power distribution has been used. Figure 99 shows the instrumentation.

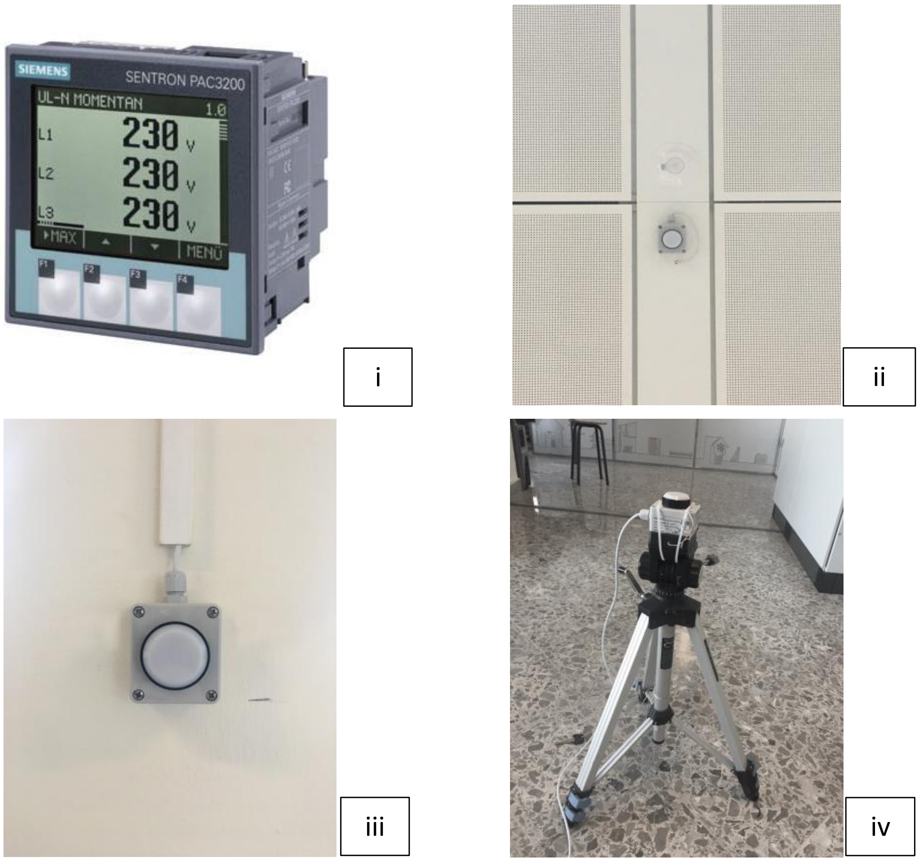


Figure 99. Picture of the Power Monitoring Device SENTRON PAC3200 (i) and of the photosensors (ii, iii, iv)

In order to perform the data analysis that will be described, it was necessary to split natural and artificial lighting contributions to indoor illuminance. To do this, in the experimental work two methods have been investigated. The first method is based on the proportionality between luminous flux and absorbed power, which is quite reliable. It was necessary to measure the absorbed power and the illuminance values due to the sum of the contributions of natural lighting and artificial lighting. The contributions of only the artificial lighting have been easily calculated by applying a W/lx factor (measured during the night time) and, consequently, the natural lighting contribution has been found to be different between the measured total illuminance and the calculated artificial lighting. In a first step of the work, this method has been used to test the indices in continuous operation schedules.

The second method is based on the short time shifted measurements of both values. The rationale of the method was that, during the test period, the lighting system can be switched off and on for a few minutes during its operation with a five-minute time-step. Figure 100 shows a scheme of the on-off actions and measurements timeline. By doing so, daylighting levels can be measured without the artificial light contribution and the latter can be calculated as the complement to the total value derived by a time interpolation between the previous and subsequent measurements. It must be noted that each illuminance value related to the artificial lighting system operation has been measured a few minutes after it was switched on. This procedure is necessary to avoid false values due to the normal hysteresis of the control system which needs some time to reach the illuminance target value on work-plane. It must be noted that the measurement campaign must be done in a short period when any users occupy the space. This method could be utilized if no consumption data are taken or in the case of systems where other electrical consumptions are measured by the same data taker.

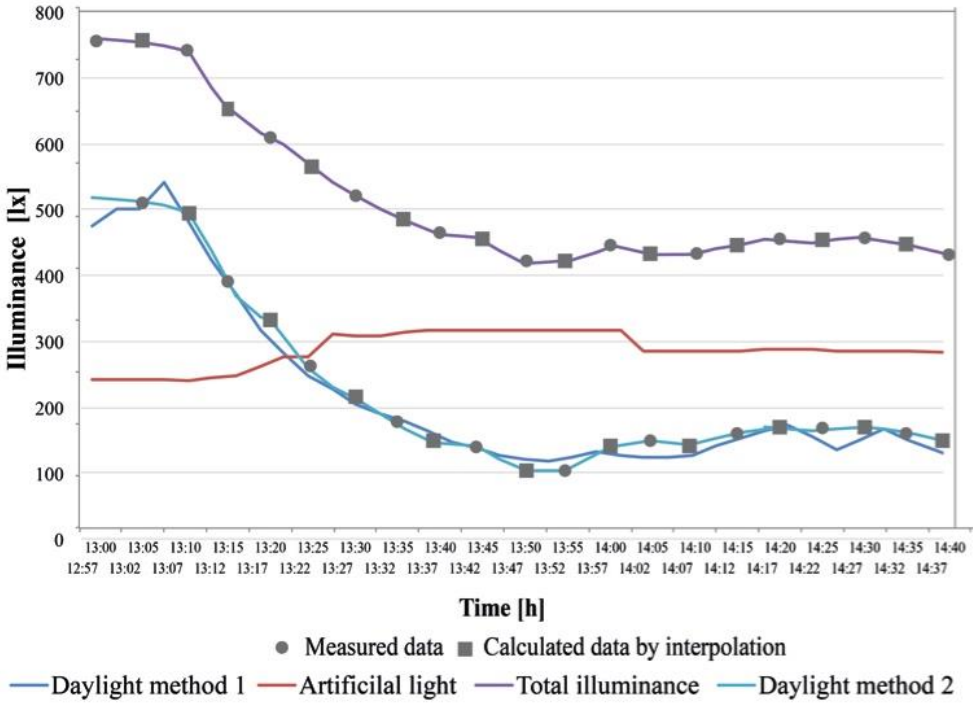


Figure 100. Example of measurement sequence and values interpolation. Comparison between measured and calculated daylight

A comparison between the results obtained with the two methods is shown in Figure 100. Experiments have been conducted in order to test the system under several operational scenarios. By the term "scenarios," we mean the different combinations of operating time schedules, of different end uses (office or residential), which also correspond to different target illuminances, and of lighting control strategies.

All the zone illuminance values have been calculated using the average of the measures taken by two pairs of photosensors (two in the ceiling and two on the work-plane) placed in the task area where a good uniformity is observed. Moreover, a set of "virtual" scenarios with ON/OFF control function has been generated by calculations. This was done by accounting the 100% of power by the luminaries when the lights were turned on by the system even if they were dimmed. Consequently, in these time steps, the luminous flux was considered to be at 100%.

Regarding the residential operating schedules, because the occupancy pattern in residential spaces is very dynamic and various, these have been defined using a specific simulation tool, SirSym-Home, developed by the DEIM of the University of Palermo within the National Research Project SIRRCE (SIRRCE project, 2010). The tool generates several occupancy schedules based on the Monte Carlo approach, considering the usage probability of the lighting system. It can be observed that also 20 days of continuous operation (ON at 6:00 am, dimming and OFF at 21:00) have been tested for office use.

The illuminance target value on task area for residential spaces has been fixed to about 250 lx at a height of a generic coffee table in the living room (0.6 m). The illuminance target value on work-plane for office operation has been defined assuming an illuminance target value on work-plane equal to 500 lx on the work-plane at a height of 0.85 m.

A total of 359 scenarios have been tested, 179 with dimmer strategies and 179 with ON-OFF strategy. For 109 day the control system has been tested for the "office" end-use and for 70 days for the residential ones. Table 17 shows all tested occupancy schedules.

Control system	Schedules	Date	End-use	Setpoint [lx]
Bticino	09:00-13:00 15:00-18:00	04/10/16	Office	500
	09:00-13:00 15:00-18:00	05/10/16		500
	09:00-13:00 15:00-18:00	06/10/16		500
	11:00-15:00 16:00-20:00	10/10/16		500
	08:00-12:00 13:00-17:00	12/10/16		500
	08:00-12:00 13:00-17:01	13/10/16		500
	07:00-11:00 12:00-16:00	17/10/16		500
	07:30-11:30	18/10/16		500
	07:30-11:30 12:30-16:30	19/10/16		500
	07:00-11:00 12:00-16:00	20/10/16		500
	07:00-11:00 12:00-16:00	21/10/16		500
	10:00-14:00 15:00-19:00	23/10/16		500
	09:00-13:00 15:00-18:00	25/10/16		500
	08:00-12:00 13:00-17:00	26/10/16		500
	09:00-13:45	27/10/16		500
	07:00-11:00 12:00-16:00	29/10/16		500

Control system	Schedules	Date	End-use	Setpoint [lx]
	07:00-11:00 12:00-16:00	31/10/16		500
	08:00-12:00 13:00-17:00	02/11/16		500
	16:00-20:00	04/11/16		500
	08:00-12:00 13:00-17:00	05/11/16		500
	09:00-13:00 15:00-18:00	07/11/16		500
	09:00-13:00 15:00-18:00	11/11/16		500
	07:00-11:00 12:00-16:00	13/11/16		500
	07:00-11:00 12:00-16:00	14/11/16		500
	09:00-13:00 15:00-18:00	15/11/16		500
	09:00-13:00 15:00-18:00	17/11/16		500
	10:30-15:30	18/11/16		500
	08:00-12:00 13:00-17:00	27/11/16		500
	08:00-12:00 13:00-17:00	28/11/16		500
	07:00-11:00 12:00-16:00	29/11/16		500
	07:00-11:00 12:00-16:00	30/11/16		500
	10:30-18:00	01/12/16		500
	08:00-12:00 13:00-17:00	02/12/16		500
	08:00-12:00 13:00-17:01	03/12/16		500
	09:00-13:00 15:00-18:00	04/12/16		500
	08:00-12:00 13:00-17:00	05/12/16		500
	09:00-13:00 15:00-18:00	06/12/16		500
	06:00-21:00	29/03/17		500
	06:00-21:00	30/03/17		500
	06:00-21:00	31/03/17		500
	06:00-21:00	01/04/17		500
	06:00-21:00	02/04/17		500
	06:00-21:00	03/04/17		500
	06:00-21:00	06/04/17		500
	06:00-21:00	07/04/17		500
	06:00-21:00	08/04/17		500

Control system	Schedules	Date	End-use	Setpoint [lx]
	06:00-21:00	10/04/17		500
	06:00-21:00	12/04/17		500
	06:00-21:00	13/04/17		500
	06:00-21:00	14/04/17		500
	06:00-21:00	15/04/17		500
	06:00-21:00	16/04/17		500
	06:00-21:00	17/04/17		500
	06:00-21:00	18/04/17		500
	06:00-21:00	19/04/17		500
	06:00-21:00	20/04/17		500
	06:00-21:00	21/04/17		500
	06:00-21:00	22/04/17		500
	06:00-21:00	23/04/17		500
Zumtobel I	09:00-13:00 15:00-18:00	31/05/17		500
	09:00-13:00 15:00-18:00	01/06/17		500
	09:00-13:00 15:00-18:00	02/06/17		500
	11:00-15:00 16:00-20:00	03/06/17		500
	08:00-12:00 13:00-17:00	04/06/17		500
	08:00-12:00 13:00-17:01	05/06/17		500
	10:30-13:30 14:30-18:00	07/06/17		500
	07:00-11:00 12:00-16:00	06/06/17		500
	07:00-11:00 12:00-16:00	08/06/17		500
	07:30-11:30 12:30-16:30	09/06/17		500
	07:00-11:00 12:00-16:00	10/06/17		500
	07:00-11:00 12:00-16:00	11/06/17		500
	10:00-14:00 15:00-19:00	15/07/17		500
	09:00-13:45	13/06/17		500
	07:00-11:00 12:00-16:00	05/07/17		500
	08:00-12:00 13:00-17:00	06/07/17		500
	08:00-12:00 13:00-17:01	12/07/17		500
	09:00-13:00 15:00-18:00	13/07/17		500

Control system	Schedules	Date	End-use	Setpoint [lx]
	07:00-11:00 12:00-16:00	17/07/17		500
	09:00-13:00 15:00-18:00	18/07/17		500
	09:00-13:00 15:00-18:00	21/07/17		500
	09:00-13:00 15:00-18:00	15/11/17		500
	09:00-13:00 15:00-18:00	16/11/17		500
	09:00-13:00 15:00-18:00	22/11/17		500
	08:00-12:00 13:00-17:00	23/11/17		500
	10:30-13:30 14:30-18:00	24/11/17		500
	07:00-11:00 12:00-16:00	25/11/17		500
	07:00-11:00 12:00-16:00	26/11/17		500
Zumtobel II	08:00-12:00 13:00-17:00	22/10/17		500
	08:00-12:00 13:00-17:01	21/10/17		500
	10:30-13:30 14:30-18:00	23/10/17		500
	07:00-11:00 12:00-16:00	24/10/17		500
	07:00-11:00 12:00-16:00	25/10/17		500
	07:30-11:30 12:30-16:30	26/10/17		500
	09:00-13:00 15:00-18:00	27/10/17		500
	10:00-14:00 15:00-19:00	28/10/17		500
	09:00-13:00 15:00-18:00	29/10/17		500
	09:00-13:00 15:00-18:01	30/10/17		500
	09:00-13:00 15:00-18:02	31/10/17		500
	11:00-15:00 16:00-20:00	01/11/17		500
	08:00-12:00 13:00-17:00	02/11/17		500
	08:00-12:00 13:00-17:01	03/11/17		500

Control system	Schedules	Date	End-use	Setpoint [lx]
	11:00-15:00 16:00-20:00	04/11/17		500
	10:30-13:30 14:30-18:00	05/11/17		500
	07:00-11:00 12:00-16:00	06/11/17		500
	07:00-11:00 12:00-16:00	07/11/17		500
	07:00-11:00 12:00-16:00	09/11/17		500
	07:00-11:00 12:00-16:00	10/11/17		500
	10:00-14:00 15:00-19:00	11/11/17		500
	09:00-13:00 15:00-18:00	12/11/17		500
Bticino	18:00-22:15	14/07/16	Residential	200
	18:00-21:45	15/07/16		200
	18:45-22:00	19/07/16		200
	17:30-22:00	20/07/16		200
	18:00-22:30	22/07/16		200
	17:45-22:30	23/07/16		200
	18:15-21:45	25/07/16		200
	18:15-21:45	26/07/16		200
	18:15-22:30	29/07/16		200
	18:15-22:30	01/08/16		200
	17:45-22:00	03/08/16		200
	17:45-22:00	04/08/16		200
	17:15-22:15	05/08/16		200
	17:15-22:15	06/08/16		200
	17:17-21:00	12/08/16		200
	17:00-23:00	13/08/16		200
	17:00-21:45	16/08/16		200
	17:00-21:00	18/08/16		200
	18:45-23:00	20/08/16		200
	18:45-23:00	21/08/16		200
Zumtobel I	18:00-22:15	06/08/17		300
	18:00-21:45	09/08/17		300
	18:45-22:00	08/08/17		300
	17:30-22:00	07/08/17		300
	18:00-22:30	10/08/17		300
	17:45-22:30	11/08/17		300
	18:15-21:45	12/08/17		300
	18:15-21:45	01/09/17		300
	18:15-22:30	18/08/17		300
	17:45-22:00	16/08/17		300
	17:45-22:00	17/08/17		300
	17:15-22:15	19/08/17		300

Control system	Schedules	Date	End-use	Setpoint [lx]
	17:15-22:15	02/09/17		300
	17:15-21:00	28/08/17		300
	17:00-21:45	29/08/17		300
	18:45-23:00	30/08/17		300
	18:45-23:00	31/08/17		300
	18:00-22:15	03/09/17		300
	18:00-21:45	04/09/17		300
	18:45-22:00	05/09/17		300
	17:30-22:00	06/09/17		300
	18:00-22:30	07/09/17		300
	17:45-22:00	13/09/17		300
	17:00-23:00	14/09/17		300
	17:00-21:45	15/09/17		300
	17:00-21:00	16/09/17		300
	18:45-23:00	17/09/17		300
Zumtobel II	18:00-22:15	18/09/17		300
	18:00-21:45	19/09/17		300
	18:45-22:00	20/09/17		300
	17:45-22:30	24/09/17		300
	18:15-21:45	25/09/17		300
	18:15-21:45	26/09/17		300
	18:15-22:30	27/09/17		300
	18:15-22:30	28/09/17		300
	17:45-22:00	29/09/17		300
	17:15-22:15	03/10/17		300
	17:15-22:15	04/10/17		300
	17:15-21:00	05/10/17		300
	17:00-23:00	06/10/17		300
	17:00-21:45	07/10/17		300
	17:00-21:00	08/10/17		300
	18:45-23:00	09/10/17		300
	18:45-23:00	10/10/17		300
	18:00-22:15	11/10/17		300
	18:00-21:45	12/10/17		300
	18:45-22:00	13/10/17		300
	17:30-22:00	14/10/17		300
	18:00-22:30	15/10/17		300
	17:45-22:30	16/10/17		300

Table 17. All the tested scenarios for each system and end-use

References

- Beccali, M., Bonomolo, M., Galatioto, A., Ippolito, M. G., & Zizzo, G. (2015, November). A laboratory setup for the evaluation of the effects of BACS and

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- UNI 10380:1994, Illuminazione di interni con luce artificiale.

6. Preview methods in standards: review and validation

The main goals of Building Automation systems installation are to achieve significant reduction of the electrical consumption and to have all the achievable, well acknowledged, benefits from the daylight (e.g. occupant comfort, health, well-being and productivity). As consequence of recent large use of the Building Automation Control Systems (BACs), new Standard bas been issued and elder ones have been updated including the topic of the automation in their text.

As said in section 1, some of them adopted methods to calculate electrical consumption. E.g. in the case of the European Standard EN 15232 that puts into evidence the importance of the presence of BACs and Technical Building Management (TBM) systems. This Standard suggests a simplified method to estimate, using some factors in tables, the impact of the BAC and TMB functions to the energy consumption in a building. The new Directive 2010/31/EU encourages the use of active control systems and intelligent metering systems for energy saving purposes whenever a building is constructed or undergoes major renovation in line with Directive 2009/72/EC. Moreover, Directive 2012/27/EU (Directive 2012/27/EU) on energy efficiency explicitly refers to automation as a way to achieve energy saving through the implementation of demand response (DR) policies, and the wide spread application of smart meters.

The European Standard EN 15193 proposes two methods to calculate the LENI (Lighting Energy Numeric Indicator). The first one is used to calculate the electrical consumption for lighting systems, the second one is used to calculate the LENI, in a faster way, by directly using the design data for the building or the space to analyse. As already mentioned, EN Standard 15232 (European Technical Standard EN 15232) deals with the effects of Building Automation Control (BAC) and Technical Building Management (TBM) systems on the final energy consumption in buildings. The standard is in-line with the EPB Directive 2010/31/EU (Directive 2010/31/EU) that recognizes the important role of automation, control and monitoring systems in energy saving actions, and encourages the use of smart control and metering systems for energy saving purposes.

Also Directive 2012/27/EU (Directive 2012/27/EU) refers to automation as a way to reduce the energy consumption also having recourse to innovative demand response (DR) strategies, and to the application of smart meters. In addition, the most recent research literature (Poel, 2007) (Klein, 2012) (Yu and Su, 2012) shows that a great potential for energy savings in buildings is in the control and interaction of air-conditioning systems, appliances and, in general, electric devices, also thanks to specific algorithms able to coordinate all the energy facilities in the building.

Aste et. al. (Aste et al., 2017) proposed a method for optimizing BAC systems performance both in terms of energy savings and of comfort and Shen et al. investigated both visual and energy performance of lighting control strategies. In recent years, many standards and their updating included more or less simplified methods to preview energy consumption achievable with automated control systems application. The standard EN 15232 provides a list of BAC and TBM functions that can affect the energy performance of buildings and introduces four different BAC efficiency classes and the simplified BAC factor method for estimating the energy savings due to the application of BAC and TBM functions.

Nevertheless, as Pellegrino et. al. underlined in their work (Pellegrino et al., 2016), sometimes the outcomes obtained from the monitored data can show some significant differences from the expected and previously estimated energy saving results.

Ippolito et al. (Ippolito et al., 2014) evaluated the impact on residential buildings of building automation control (BAC) and technical building management (TBM) systems. They investigated how the control, monitoring and automation functions considered by the European Standard EN 15232 can considerably influence the energy performance of a single-family test house and, consequently, its energy performance class.

López-González et al. (López-González et al., 2016) evaluated, according to EN 15232, the impact of BACS and TMB systems on the standardized registration of energy performance certificates of the Autonomous Community of La Rioja.

Based on the results of this study, authors expected to gain a perspective on the evolution of energy efficiency ratings in terms of both primary energy consumption and CO_2 emissions based on the implementation of BACS and TBM systems in the residential sector. The aim of this section is to analyse the method suggested by these Standards and compare the results calculated using the prediction methods and the actual ones referred to the investigated case study.

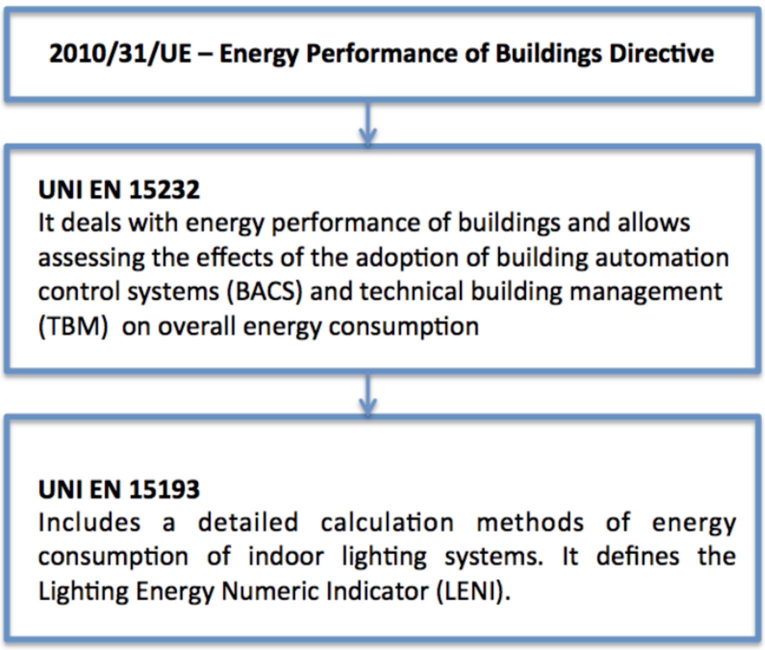

Figure 101. EN 15193 Energy performance of buildings — Module M9 — Energy requirements for lighting

6.1. The Standard 15193

The Standard EN 15193 is one of the outcome of CEN/TC 169 committee. It is part of a set of standards, which were developed to support the implementation of EPBD directives. In this standard, the LENI (Lighting Energy Numeric Indicator) was introduced as a metric to quantify the energy performance for lighting in a building, also in the perspective of providing an input for the heating and cooling load estimations for the determination of the combined total energy performance of a building.

CEN/TC 169 in general, it is responsible for standards in the field of vision, photometry and colorimetry, involving natural and man-made optical radiation over the UV, the visible and the IR regions of the spectrum, and application subjects covering all usages of light, indoors and outdoors, including environmental, energy and sustainability requirements and aesthetic and non-image forming biological aspects. Divided in subcommittees and working groups, the structure of the is divide as follows:

Working group	Title
CEN/TC 169/WG 1	Basic terms and criteria
CEN/TC 169/WG 11	Daylight
CEN/TC 169/WG 12	Joint Working Group with CEN/TC 226 - Road lighting
CEN/TC 169/WG 13	Non-visual effects of light on human beings
CEN/TC 169/WG 14	ErP Lighting Mandate Management Group
CEN/TC 169/WG 2	Lighting of work places
CEN/TC 169/WG 3	Emergency lighting in buildings
CEN/TC 169/WG 4	Sports lighting
CEN/TC 169/WG 6	Tunnel lighting
CEN/TC 169/WG 7	Photometry
CEN/TC 169/WG 8	Photobiology
CEN/TC 169/WG 9	Energy performance of buildings

Table 18. List of Subcommittees and working groups of the CEN/TC 169

Just to do an overview of some other Standards, for new and refurbished installations in the non-residential building sector the design of the lighting system should conform to the requirements in the lighting applications standards EN 12464-1 for indoor workplaces, EN 12193 for sports buildings and EN 1838 for emergency escape lighting. For residential buildings the lighting system should be designed to fulfil the needs of the rooms in the buildings or following other Guidelines, e.g. in the IESNA Lighting Handbook.
Among the last published versions of the EN 15193 there is the CEN/TR 15193-2:2017 (WI=00169067) Energy performance of buildings - Energy requirements for lighting - Part 2: Explanation and justification of EN 15193-1, Module M9.

The standard EN 15193 Energy performance of buildings — Module M9 — Energy requirements for lighting is part of a set of standards developed to support EPBD directive implementation, hereafter called "EPB standards". The aim of the application of these standards is the calculation of the energy performance and other related aspects (like system sizing) to provide the building services considered in the EPBD directive.
The Standard EN 15193 proposes three methods for evaluating the energy performance of lighting systems (Figure 102).

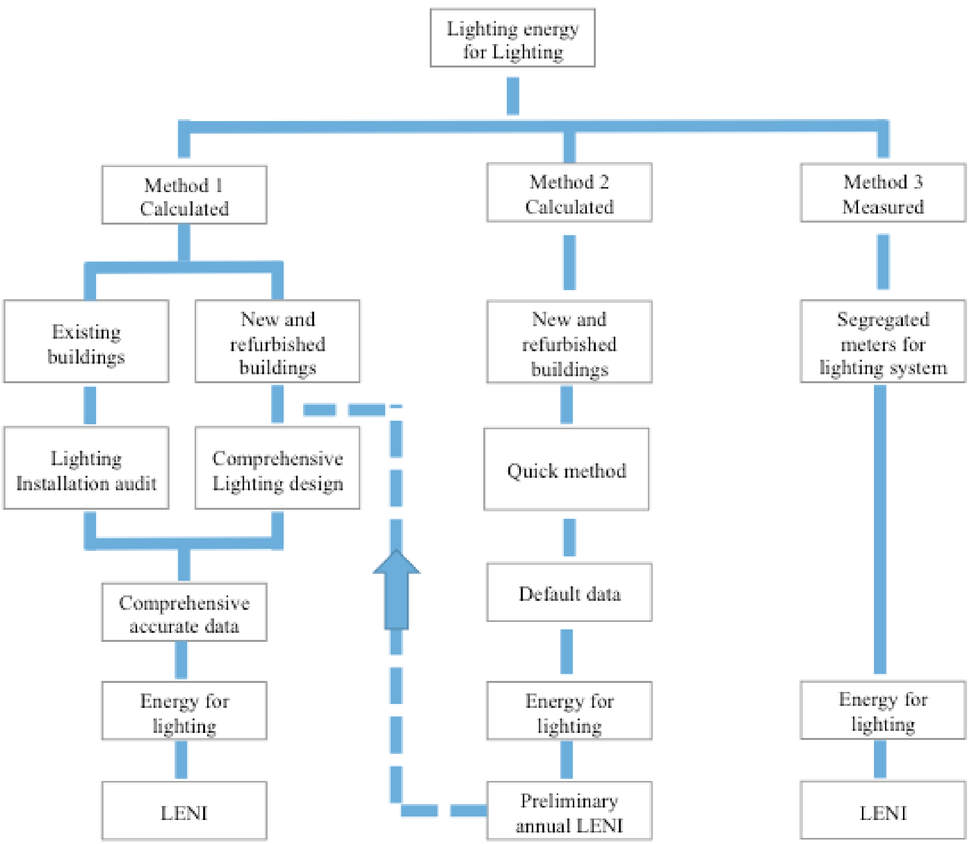

Figure 102. Flow chart of the application of the three methods

Technical Report CEN/TR 15193-2:2015 includes guidance on the requirements. Furthermore, the standard assumes that the buildings can have access to daylight to provide all or some of the illumination required in the rooms and that in addition there will be an adequate amount of electric lighting installed to provide the required illumination in the absence of daylight or with a reduced daylight contribution.

Moreover, it mainly defines the methods for estimating or measuring the amount of energy required or used for lighting in buildings. This methodology of energy estimation not only provides values for the Lighting Energy Numeric Indicator (LENI). Also, it provides input for the heating and cooling load estimations for the combined total energy performance of building indicator.

About the methods proposed by the Standard, they are:

- the comprehensive method;
- the quick calculation method;
- the direct metering method.

The comprehensive method covers the calculation of the energy requirements of lighting systems in residential and non- residential buildings where a comprehensive lighting system design has been performed. This calculation method is suitable for use during the design of new or refurbished buildings and for assessing existing buildings. The output of this method is in kilowatt hours per time step for the building. It shall be normalized for the considered time step to square meters of the useful area to give the sub-LENI value. The time step of the output can be:

- yearly;
- monthly;
- hourly;

in accordance with the time-step of the input data. Following input data about lighting system are necessary to apply the method:

- the types of luminaires, identified by a unique reference code;
- the quantities of each specific type of luminaire;
- the control technique and device types;
- the maintenance factor (MF) assumed in the design.

Following input data about room and zone of the building are necessary to apply the method:

- the types of luminaires, identified by a unique reference code;

- the quantities of each specific type of luminaire;
- the control technique and device types;
- the maintenance factor (MF) defined by the maintenance schedule.

The quick calculation method covers the calculation of the energy requirements of lighting systems for residential and non- residential buildings where a comprehensive lighting system design has not been performed. The method makes use of quick calculation and default data and the result gives budget energy values. As well in this case, the method output shall be in terms of kilowatt hours per year for the building. This yearly output value shall be normalized to square meters of the useful area to give the LENI. The time step of the output shall be yearly. This method is only suitable for use during the conceptual stage of design of new or refurbished buildings.

The last method, the direct metering one, covers the direct measurement of the energy used by lighting system in residential and non-residential buildings by segregated direct metering. This method gives the true value of energy used by the lighting system and can be used to verify the values obtained by the calculated methods. This method is suitable for use in existing buildings where the lighting circuit is sufficiently segregated to allow separate metering. This method is applicable to buildings with facilities for separate metering of the electricity used for all lighting within the building. The metering can alternatively be by a Building Management System (BMS) arrangement.

The three methods have different levels of accuracy for the installed power, occupancy estimation and daylight availability. For this reason, it is important to evaluate the advantages and disadvantages of the three methods for understanding which one is the most suitable for the case study. The first method provides the most accurate calculation procedure and it relies upon a comprehensive lighting scheme design as the main input to the energy calculation. The second one provides a quick estimation aimed for pre-design calculations and employs default values. Some default values are provided in standard annexes.

The last method provides the most accurate energy use for lighting information but can only be used after the building has been commissioned and occupied. This method can also be linked to the BMS of the building to provide continuous smart metering.

In some study this standard has been analysed. Zinzi and Mangione (Zinzi and Mangione, 2015) proposed an alternative approach to the standard, where the daylighting contribution is based on the availability of outdoor illuminance data and an explicit procedure. They tested the methods on a standard office building, whose lighting requirements are calculated for different visual tasks, observation positions and climatic zones. The study results demonstrated that there are some discrepancies among the methods and address the need of a more accurate estimation of the lighting energy service.

Tian and Su (Tian and Su, 2014) applied the comprehensive calculation method for lighting energy requirement in non-residential buildings introduced by the European

Standard EN 15193: 2007 and investigates its feasibility in China.
Furthermore, they developed a quadratic relationship needs to be used for a wider range of latitudes.

Aghemo et al. (Aghemo et al., 2016) did a comparison between the old version and the new one, analysing the differences included in the new version of the standard prEN15193-1 to calculate the LENI, especially focusing on the approach to calculate the daylight supply factor ($F_{D,S}$). In the following flowchart they compared the determination of the daylight dependency factor F_D according to the prEN 15193-1:2015 and to the EN 15193:2007.

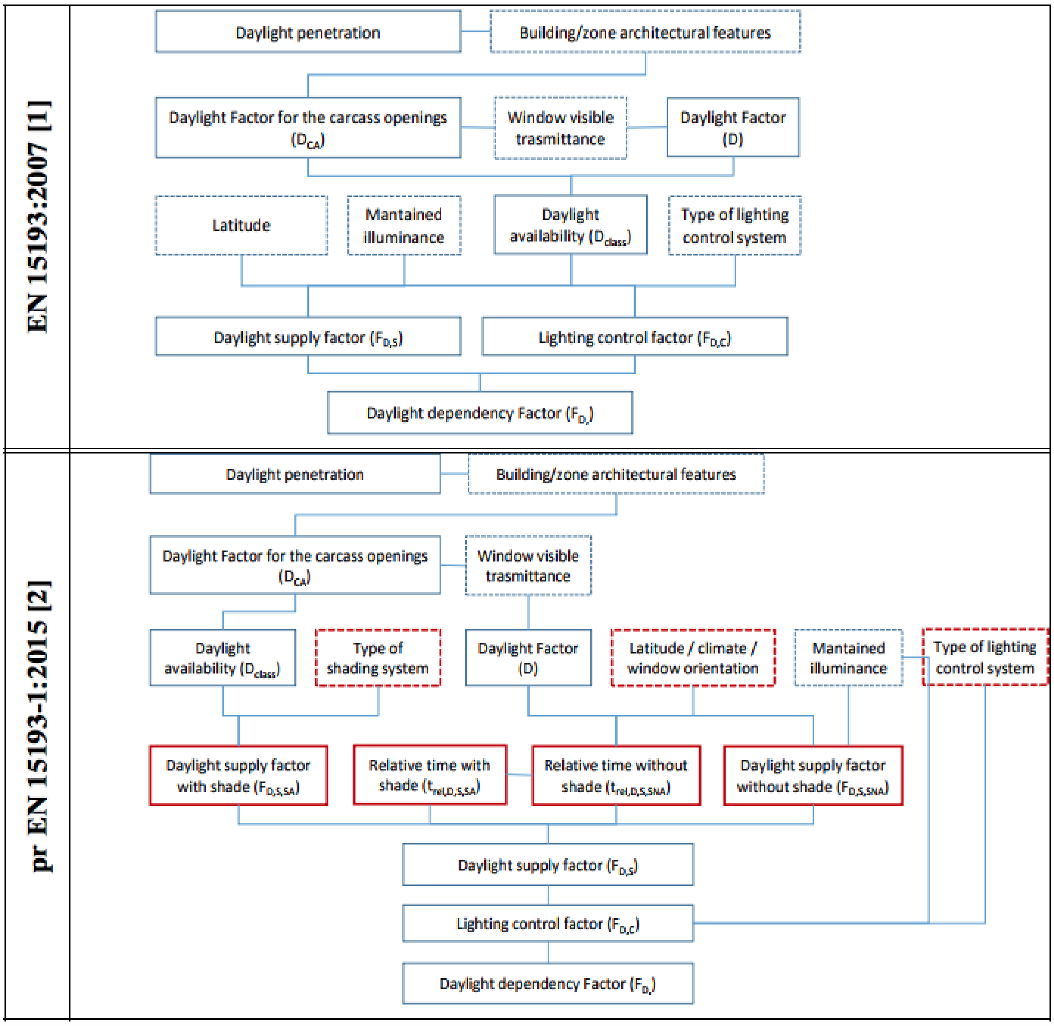

Figure 103. Flowcharts for the determination of the daylight dependency factor F_D according to the prEN 15193-1:2015 and to the EN 15193:2007 (Aghemo et al., 2016)

In order to estimate the total energy use for lighting the following terms have been defined:

- built-in luminaires;
- control glare;

- power: for luminaires, parasites and emergency;
- energy: for lighting, parasitic and emergency;
- time: operating, daylight and non-daylight usage;
- useful area;
- dependency factors: daylight dependency factor (F_D), occupancy dependency factor (F_O), absence factor (F_A), constant illuminance factor (F_C), maintenance Factor (MF).

These parameters have been analysed for the case study for calculating the total estimated energy required for the analysed period in the monitored room.
In this section the LENI has been calculated according to the EN 15193.

6.1.1. Application of EN 15193 using the comprehensive method

As already said, the energy requirements calculated applying this method can be yearly, monthly or hourly (even if, as it will be shown it could be better to define them "daily"). For this reason, it is necessary to select a timestep (t_s).

In case of yearly calculation t_s is equal to 8760 hours; in case of monthly calculation it is equal to 730 hours, in case of hourly calculation it is equal to monthly/730. In order to apply this method, it is necessary to gather the above-mentioned information data for each zone and room. For the case study analysed in this thesis the zone considered was only the work area. Data about the luminaires system are present in section 5 where the lighting system is largely described. For this application, since it has been considered only the work zone, only the dimmed lamps have been taken into account. In the space considered three dimmed lamps are installed.

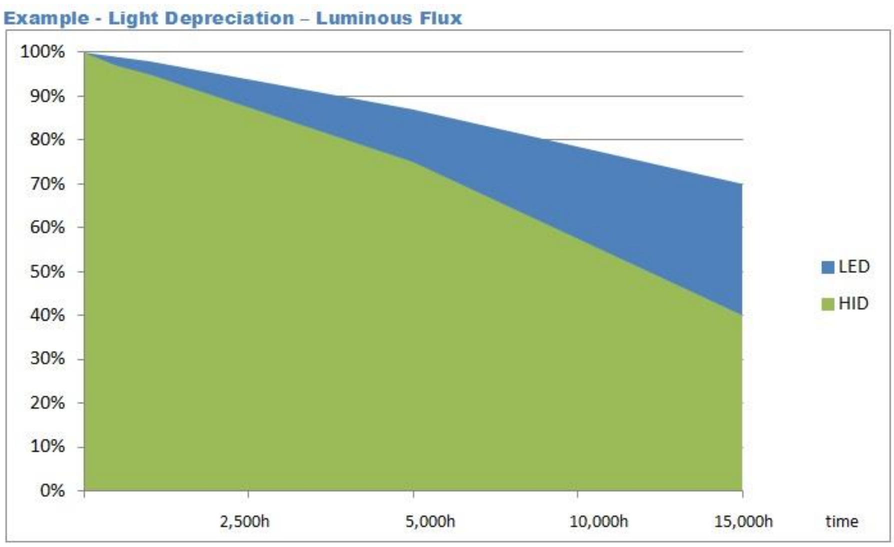

Figure 104. Light depreciation-Luminous flux (source: My Led Lighting Guide)

In Figure 104, the graph shows the depreciation that two typologies of lighting sources (LED and HID) can have during their lifetime. It can be noted that LED lamps, which have a longer lifetime, suffer a lower decreasing of the luminous flux during their lifetime. As well-know, this depreciation can be caused as well by many environmental factors.

The Maintenance Factor (MF) is referred to a "decline of light" that the luminaires can have during their lifetime. Indeed, after a certain time the luminous flux can decrease and, therefore, as well the illuminance on the workplane due to pollution and ageing of the installation and room surfaces.

It has been calculated as:

$$MF = RMF \cdot LMF \cdot LSF \cdot LLMF \tag{9}$$

The Room Surface Maintenance Factor (RMF) is the ratio of the room surfaces reflectance before and after cleaning. It indicates the reduction of the lighting level according to soiling of the room. The dirtier the room, the lower the maintenance factor.

The Luminaire Maintenance Factor (LMF) is the ratio of the luminaires luminous flux before and after cleaning and depends on the luminaire construction and design (open housing or closed one) as well as on environmental conditions (dirty or clean). The higher the luminaires protection degree from dust and the cleaner the room, the higher the maintenance factor. The more difficult to reach, the more the maintenance costs will be.

The Lamp Maintenance Factors (LMF) is the ratio of luminous flux at a specific time compared to a new lamp. It depends on the aging of the lamp or the reduction of light intensity over time. In general, it is a data provided by tables given by manufacturers about the lamps luminous flux behaviour.

The Lamp Survival Factor (LSF) depends on the luminaires service lifetime of a lamp. The frequent switching on and switching off can decrease the lifetime of the luminaires. As well this value is provided by the lamp manufacturers. If a lamp does not work and it is replaced immediately, the LSF can be set to 1. LSF 1 is saying that there will be no loss of light because of lamp failure.

The life and maintenance of the luminous flux (LLMF) depends on the combination of choice of LEDs (manufacturer and type Low/Medium/High Power) and design of the LED luminaire. The combination of these two parameters is unique for each luminaire. It is the ratio of luminous flux at a specific time compared to a new lamp and indicates the aging of the lamp or the reduction of light intensity over time. Manufacturers offer comprehensive tables about their lamps luminous flux behaviour.

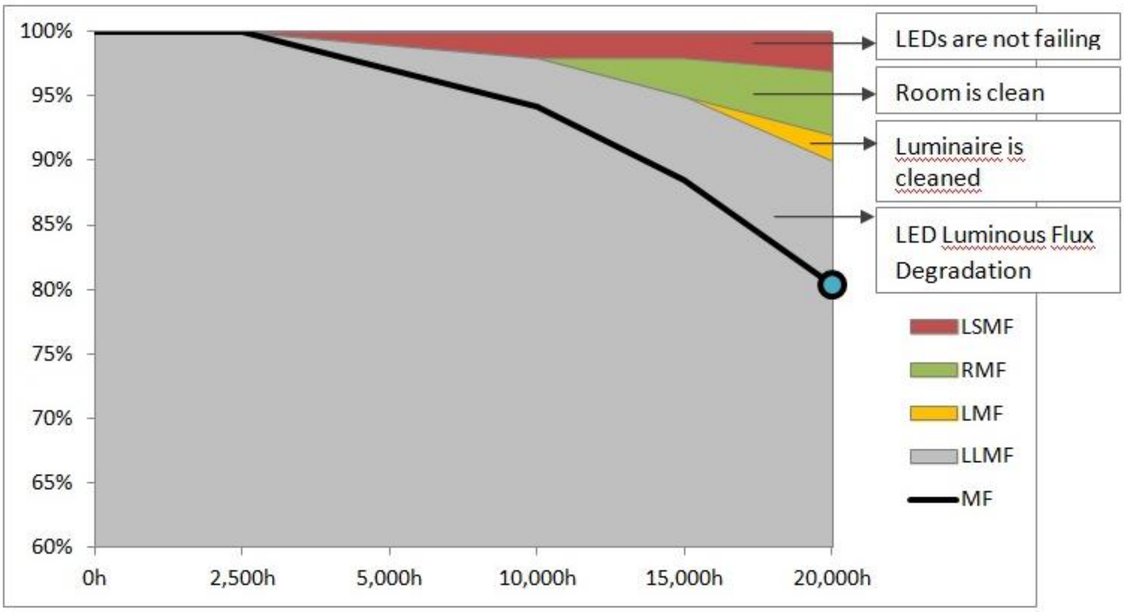

Figure 105. Scheme of maintenance Factor of an open plan Office with LED (source: My Led Lighting Guide)

For the case study the data in Table 19 have been considered and a Maintenance Factor of 0.75 has been calculated.

RMF	LMF	LSF	LLMF	**MF**
Dirty room	Closed luminaires	LED is not failing	LED luminous flux degradation over 40,000h	
0.9	0.92	1	0.9	**0.75**

Table 19. MF calculation

A maintenance factor of 0.75 means, the new lighting system is over-driven by 75% not to undercut the minimum required illumination level. LED lighting systems are flexible and easy to connect to control systems. Also, it is necessary to know the installed lighting power, P_n, P_{em} and the lighting control stand-by power (P_{pc}) and to estimate the impact of occupancy, daylight and over design/maintenance factors on the lighting controls by determining the values of the dependency factors, F_O, F_D and F_C.

In the analysed case P_n is equal to 106 W. P_{pc} changed according to the tested control system. It must be underlined that the aim of this section is to compare and validate with measured actual data, the results obtained applying the methods suggested by the standard. For this reason, the data applied are referred to an actual lighting system and to two different control systems. They are presented in section 5. One of the two control systems is characterized by an absorbed power of 18 W, while, the other one is characterized by an absorbed power of 10 W.

FA is a tabled index that depends on the end use. In this case it has been considered equal to 0.20. F_o is equal to 1 because there is not a motion detection.
The factor F_D has been calculated as:

$$F_D = 100 - (F_{D,S} \cdot F_{D,c}) \tag{10}$$

even if the standard suggests to calculate F_D as:

$$F_D = 1 - (F_{D,S} \cdot F_{D,c}) \tag{11}$$

For the $F_{D,s}$ calculation it is necessary to consult the ANNEX C of the standard ISO 10916. It suggests the following equation:

$$\overline{F}_{D,S} = \sum_{n=1}^{N} \sum_{j=1}^{J} \frac{F_{D,S,j,n} \cdot A_{D,j,n}}{A_{D,j,n} + A_{ND,j,n}} \tag{12}$$

$F_{D,S,j}$ has been calculated as:

$$F_{D,s,j} = t_{rel,D,SNA,j} \cdot F_{D,s,SNA,j} + t_{rel,D,SA,j} \cdot F_{D,s,SA,j} \tag{13}$$

where $t_{rel,\ D,\ SNA,\ j}$ is the relative portion of the total operating time during which the solar and/or glare protection system is not activated as given in a table.
It is a function of the latitude γ of the considered site H_{dir}/H_{glob} representing and facade orientation.
$t_{rel,D,SA,j}$ is the relative portion of the total operating time during which the solar and/or glare protection system is active. $t_{rel,\ D,SA}$ can be obtained by $t_{rel,D,SA}$=1- $t_{rel,D,SNA}$
$F_{D,s,SNA,j}$ is the daylight availability factor of the area j being evaluated at times when the solar and/or glare protection system is not activated, as given in a table. It is a function of the latitude γ of the considered site, H_{dir}/H_{glob} representing the climate, the facade orientation, daylight availability (daylight factor), and the maintained illuminance;
$F_{D,s,SA,j}$ is the daylight availability factor of the area j being evaluated at times when the solar and/or glare protection system is activated. It is a table value.
$F_{D,s,SNA,j}$ has been selected according to the latitude and the longitude of Palermo. Being the case study without solar protection, an $F_{D,s,j}$ value of 73.2 has been considered.

It was useful to calculate the $F_{D,s}$ values together with the $A_{D,j,n}$ (15 m^2) and $A_{ND,j,n}$ considered equal to 0, being the considered area lit by daylight.

For the dimmer case a "dimmed, no stand-by losses, switch-on" system has been considered and an $F_{D,c}$ of 0.78 has been applied for the calculation. For the ON-OFF case a "daylight-responsive off" system has been considered and an $F_{D,c}$ of 0.73 has been assumed for the calculation.

The standard reports the calculation of F_C as follows:

$$F_C = 1 - \frac{1}{2} F_{cc} \left(1 - MF\right) \tag{14}$$

where F_{CC} is the efficiency factor of the constant illuminance control and MF is the maintenance factor for the scheme.

But, as suggested by the standard, the F_{CC} can be considered equal to 1.

For this reason, the F_C for the case study is equal to 0.87, while the F_D is equal to 42.9. Following, it will be explained that, for a monthly calculation, it must be calculated using monthly weights.

Regarding the t_D and t_N time, they are listed in a table according to the end use. For an office case, t_D is equal to 2250 hours and t_N is equal to 250 hours.

Furthermore, as reported by the standard, the total estimated energy required for lighting for a period in an area or zone of the building shall be estimated by using the equation:

$$W_t = W_{L,t} + W_{P,t} \quad \left[\frac{kWh}{t_s}\right] \tag{15}$$

where $W_{L,t}$ is the estimated lighting energy required to fulfil the illumination function in an area or zone of the building. It shall be established using the following equation:

$$W_{L,t} = \sum \frac{\left\{\left(P_n \cdot F_C\right) \cdot F_O\left[\left(t_D \cdot F_D\right) + t_N\right]\right\}}{1000} \quad \left[\frac{kWh}{t_s}\right] \tag{16}$$

where $W_{P,t}$ is the estimated standby energy required during non-lighting periods to provide charging energy for emergency lighting and the activation energy for lighting controls in an area or zone of the building. It shall be established using the following equation:

$$W_{P,t} = \sum \frac{\left\{\left\{P_{pc} \cdot \left[t_s - \left(t_D + t_n\right)\right]\right\} + (P_{em} \cdot t_e)\right\}}{1000} \quad \left[\frac{kWh}{t_s}\right] \tag{17}$$

The total lighting energy can be estimated for any required time step period t_S (hourly, monthly or yearly) in accordance with the time interval of the dependency factors used. The annual energy for electric lighting within a building shall be calculated using the equation:

$$W = \frac{8760}{t_s} \cdot \sum W_t \qquad \left[\frac{kWh}{year}\right] \tag{18}$$

summed across all areas and zones within the building. The LENI for the building shall be established using the following equation:

$$LENI = \frac{W}{A} \qquad \left[\frac{kWh}{m^2 \cdot year}\right] \tag{19}$$

where W is the total annual energy required for lighting for the building [kWh/year] and A is the total useful floor area of the building [m^2].

According these formulae and considering a P_{pc} equal to 10 W, for the case study a $W_{L,t}$ of 112.4 kWh, a $W_{P,t}$ of 67.6 and, therefore, a W_t of 180 kW / t_s have been calculated. The yearly LENI index for the case study is 12 kWh/m^2anno for the dimmer case. For the ON-OFF case a $W_{L,t}$ of 120 kWh, a $W_{P,t}$ of 67.6 and, therefore, a W_t of 187.7 kW/t_s have been calculated. The yearly LENI index for the case study is 12.51 for the dimmer case.

According these formulae and considering a P_{pc} equal to 18 W, for the case study a $W_{L,t}$ of 112.4 kWh, a $W_{P,t}$ of 121.7 kWh and, therefore, a W_t of 234 kW/t_s have been calculated. The yearly LENI index for the case study is 15.61 kWh/m^2anno for the dimmer case. For the ON-OFF case a $W_{L,t}$ of 120 kWh, a $W_{P,t}$ of 121.7 kWh and, therefore, a W_t of 241.7 kW / ts have been calculated. The yearly LENI index for the case study is 16.11 for the dimmer case.

In order to calculate the LENI monthly and hourly, or better, daily following different parameters different t_s and F_D have been considered. In particular, as already said, the F_D values have been modified for each month applying tabled weights.

Facade system	**Month**, *i*											
	1	2	3	4	5	6	7	8	9	10	11	12
	Jan	Feb	March	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
	$V_{Month,\ i}$											
Light-guiding systems for South facing	0.67	0.89	1.06	1.18	1.25	1.28	1.26	1.20	1.08	0.92	0.72	0.46
Light-guiding systems for East or West	0.74	0.92	1.06	1.16	1.22	1.24	1.22	1.16	1.06	0.93	0.75	0.54
Others	0.85	0.97	1.06	1.12	1.16	1.17	1.15	1.11	1.04	0.94	0.81	0.66

Table 20. Monthly distribution key factors vmonth,i for vertical facades (European standard EN 15193)

The yearly, monthly and hourly indices values are shown in tables 21, 22, 23 and 24.

Wt [kW/ts]	Wt monthly [kW/ts]	Wt hourly [kW/ts]	WL,t [kWh]	WL,t monthly [kWh]	WL,t hourly [kWh]	WP,t [kWh]	WP,t monthly [kWh]	WP,t hourly [kWh]	W [kWh /year]	W monthly [kWh/month]	W hourly [kWh/ hour]	Month	LENI [kWh/(m year)]	LENImonthly [kWh/(m month)]	LENIhourly [kWh/(m hour)]
180.01	16.49	0.54	112.41	10.85	0.35	67.60	5.63	0.19	180.01	16.49	0.536	J	12.00	1.10	0.04
	15.30	0.53		9.66	0.35			0.18		15.30	0.531	F		1.02	0.04
	14.41	0.47		8.77	0.28			0.19		14.41	0.469	M		0.96	0.03
	13.81	0.46		8.18	0.27			0.18		13.81	0.459	A		0.92	0.03
	13.42	0.44		7.78	0.25			0.19		13.42	0.437	M		0.89	0.03
	13.32	0.44		7.68	0.26			0.18		13.32	0.442	J		0.89	0.03
	13.52	0.44		7.88	0.25			0.19		13.52	0.441	J		0.90	0.03
	13.91	0.45		8.28	0.27			0.19		13.91	0.453	A		0.93	0.03
	14.61	0.49		8.97	0.30			0.18		14.61	0.485	S		0.97	0.03
	15.60	0.51		9.96	0.32			0.19		15.60	0.508	O		1.04	0.03
	16.88	0.56		11.25	0.37			0.18		16.88	0.561	N		1.13	0.04
	18.37	0.60		12.73	0.41			0.19		18.37	0.597	D		1.22	0.04

Table 21. Yearly, monthly and hourly results for dimmer case considering a P_{pc}=10 W

Wt [kW/ts]	Wt monthly [kW/ts]	Wt hourly [kW/ts]	WL,t [kWh]	WL,t monthly [kWh]	WL,t hourly [kWh]	WP,t [kWh]	WP,t monthly [kWh]	WP,t hourly [kWh]	W [kWh/year]	Wmonthly [kWh/month]	W hourly [kWh/hour]	Month	LENI [kWh/(m year)]	LENImonthly [kWh/(m month)]	LENIhourly [kWh/(m hour)]
234.1	20.99	0.69	112.4	10.85	0.35	121.7	10.14	0.34	234	20.99	0.685	J	15.61	1.40	0.05
	19.80	0.68		9.66	0.35			0.32		19.80	0.680	F		1.32	0.05
	18.91	0.62		8.77	0.28			0.34		18.91	0.618	M		1.26	0.04
	18.32	0.61		8.18	0.27			0.33		18.32	0.608	A		1.22	0.04
	17.92	0.59		7.78	0.25			0.34		17.92	0.586	M		1.19	0.04
	17.82	0.59		7.68	0.26			0.33		17.82	0.591	J		1.19	0.04
	18.02	0.59		7.88	0.25			0.34		18.02	0.589	J		1.20	0.04
	18.42	0.60		8.28	0.27			0.34		18.42	0.602	A		1.23	0.04
	19.11	0.63		8.97	0.30			0.33		19.11	0.634	S		1.27	0.04
	20.10	0.66		9.96	0.32			0.34		20.10	0.657	O		1.34	0.04
	21.39	0.71		11.25	0.37			0.33		21.39	0.710	N		1.43	0.05
	22.87	0.75		12.73	0.41			0.34		22.87	0.746	D		1.52	0.05

Table 22. Yearly, monthly and hourly results for dimmer case considering a P_{pc}=18 W

Wt [kW/ts]	Wt monthly [kW/ts]	Wt hourly [kW/ts]	WL,t [kWh]	WL,t monthly [kWh]	WL,t hourly [kWh]	WP,t [kWh]	WP,t monthly [kWh]	WP,t hourly [kWh]	W [kWh/year]	Wmonthly [kWh/month]	W hourly [kWh/hour]	Month	LENI [kWh/(m year)]	LENImonthly [kWh/(m month)]	LENIhourly [kWh/(m hour)]
187.6	17.03	0.55	120	11.39	0.37	67.6	5.63	0.19	187.6	17.03	0.554	G	12.51	1.14	0.04
	15.91	0.55		10.28	0.37			0.18		15.91	0.553	F		1.06	0.04
	15.08	0.49		9.45	0.30			0.19		15.08	0.491	M		1.01	0.03
	14.52	0.48		8.89	0.30			0.18		14.52	0.483	A		0.97	0.03
	14.15	0.46		8.52	0.27			0.19		14.15	0.461	M		0.94	0.03
	14.06	0.47		8.43	0.28			0.18		14.06	0.467	J		0.94	0.03
	14.25	0.46		8.61	0.28			0.19		14.25	0.464	J		0.95	0.03
	14.62	0.48		8.98	0.29			0.19		14.62	0.476	A		0.97	0.03
	15.27	0.51		9.63	0.32			0.18		15.27	0.507	S		1.02	0.03
	16.19	0.53		10.56	0.34			0.19		16.19	0.527	O		1.08	0.04
	17.40	0.58		11.76	0.39			0.18		17.40	0.578	N		1.16	0.04
	18.79	0.61		13.15	0.42			0.19		18.79	0.611	D		1.25	0.04

Table 23. Yearly, monthly and hourly results for ON-OFF case considering a P_{pc}=10 W

Wt [kW/ts]	Wt monthly [kW/ts]	Wt hourly [kW/ts]	WL,t [kWh]	WL,t monthly [kWh]	WL,t hourly [kWh]	WP,t [kWh]	WP,t monthly [kWh]	WP,t hourly [kWh]	W [kWh/year]	Wmonthly [kWh/month]	W hourly [kWh/hour]	Month	LENI [kWh/(m year)]	LENImonthly kWh/(m month)	LENIhourly [kWh/(m hour)]
241.7	21.53	0.70	120.0	11.39	0.37	121.7	10.14	0.34	241.7	21.53	0.703	G	16.11	1.44	0.05
	20.42	0.70		10.28	0.37			0.32		20.42	0.702	F		1.36	0.05
	19.59	0.64		9.45	0.30			0.34		19.59	0.640	M		1.31	0.04
	19.03	0.63		8.89	0.30			0.33		19.03	0.632	A		1.27	0.04
	18.66	0.61		8.52	0.27			0.34		18.66	0.610	M		1.24	0.04
	18.57	0.62		8.43	0.28			0.33		18.57	0.616	J		1.24	0.04
	18.75	0.61		8.61	0.28			0.34		18.75	0.613	J		1.25	0.04
	19.12	0.63		8.98	0.29			0.34		19.12	0.625	A		1.27	0.04
	19.77	0.66		9.63	0.32			0.33		19.77	0.656	S		1.32	0.04
	20.70	0.68		10.56	0.34			0.34		20.70	0.676	O		1.38	0.05
	21.90	0.73		11.76	0.39			0.33		21.90	0.727	N		1.46	0.05
	23.29	0.76		13.15	0.42			0.34		23.29	0.760	D		1.55	0.05

Table 24. Yearly, monthly and hourly results for ON-OFF case considering a P_{pc}=18 W

6.1.2. Application of EN 15193 standard using the quick calculation method

As well in this case, it is necessary to calculate the installed power (P_n) required for electric lighting for an area. The final installed power shall be calculated by using the comprehensive lighting system design process as:

$$P_n = \sum_{i=1}^{i=n} P_i [W] \tag{20}$$

where n is the number of individual luminaires in the area defined in the lighting system. In existing buildings where the luminaire power (P_i) is not known this power can be estimated as:

- for lamps operating directly on mains supply voltage e.g. mains voltage incandescent lamps, self- ballasted fluorescent lamps etc.

P_i = (the lamp rated power) × (number of lamps in the luminaire)

- for lamps connected to the mains supply via a ballast or transformer in the luminaire

P_i = 1.2 × (the lamp rated power) × (number of lamps in the luminaire)

For the case study, also in this case, is 106 W.

The required standby energy for battery charging of emergency luminaires (W_{pe}) and for standby energy for automatic lighting controls (W_{pc}) are tabled values as 1 and 1.5 W.

As well in this case the F_A index has been considered as 0.20 that is a tables value indicated for office-use. An F_O of 1 has been selected for both cases because there is not motion detection.

Regarding the Daylight supply dependency factor (F_D), the quick method for estimating F_D for vertical façades shall be calculated by selecting the zone segmentation and use of the following three equations:

$$D = 0.34 \cdot \left(4.13 + 20 I_{Tr,j} - 1.36 I_{RD,j}\right) \tag{21}$$

where D is the daylight factor

$$I_{Tr,j} = \frac{A_{Ca}}{A_D} \tag{22}$$

$$I_{Tr,j} = \frac{a_D}{h_{Li} - h_{Ta}} \tag{23}$$

As for the first method an $I_{Tr,j}$ value of 1.6 and a $I_{RD,j}$ value of 1.5 have been calculated. Being the main facade located at south and without shading or glare protection, following equation has been used:

$$F_{D,S} = 0.65 F_{D,S,SNA} + 0.25 \tag{24}$$

Values for $F_{D,S,SNA}$ for various daylight factors has been determined equal to 66.4 from a provided table.

Then

$$F_D = 1 - 0.52 F_{D,S} \tag{25}$$

For the case study the F_D is equal to 64.55. Also in this case, in order to have a proper order of magnitude it has been dived by 100.

The F_C factor of 0.85 has been determined from a provided table according to the MF. Unfortunately, few lamps typologies and MF are proposed in this table. The F_C index has been selected considering an MF equal to 0.70 and LED light source in surface mounted dimmable enclosed luminaire, clean environment, luminaires cleaned annually, that was the closer condition.

Finally, $LENI_{sub}$ and LENI have been calculated as follows:

$$LENI_{SUB} = \left\{ F_C \cdot \left(\frac{P_j}{1000} \right) \cdot F_O \left[\left(t_D \cdot F_D \right) + t_N \right] \right\} + 1 + \left\{ \frac{1{,}5}{t_y} \cdot \left[t_y - \left(t_D + t_N \right) \right] \right\} \qquad \left[\frac{kWh}{m^2 year} \right] \tag{26}$$

where $LENI_{sub}$ is the Lighting Energy Numeric Indicator for the area [kWh/(m^2 year)]; F_C is constant illuminance factor for the area; P_j is the power density of the area [W/m^2]; F_O is the occupancy dependency factor for the area.

For the case study a $LENI_{sub}$ of 13.92 kWh/m^2 year has been calculated.

t_D is daylight time [h] for the area; F_D is the daylight dependency factor for the area and

t_N is the daylight absence time [h] for the area; t_y are the annual operating hours [h] for the area.
The annual energy required for electric lighting within the area or zone shall be established by

$$W_{az} = LENI_{sub} \cdot A \qquad \left[\frac{kWh}{year}\right] \tag{27}$$

where W_{az} is the total annual energy required for lighting for the zone or area [kWh/year]; $LENI_{sub}$ is the Lighting Energy Numeric Indicator for the relevant zone or area [kWh/(m^2 year)].
For the case study a W_{az} of 209 kWh/year considering an area of 15 m^2.
Being the A_i (total useful floor area of the relevant zone or area) for the case study the same of A that is the relevant area in the building, the LENI is also 13.92 kWh/m^2 year.
The standard suggests a method to calculate P_n as:

$$P_n = P_j \cdot A[W] \tag{28}$$

The power density for the lighting in an area of building may be assessed using equation:

$$P_j = P_{j,lx} \cdot E_{task} \cdot F_{MF} \cdot F_{CA} \cdot F_L \qquad \left[\frac{W}{m^2}\right] \tag{29}$$

where P_j is the power density of the area [W/ m^2], $P_{j.lx}$ is the power density per lux of the area [W/lx]. E_{task} is the maintained illuminance that the lighting system will be designed to provide [lx], FMF is the correction factor to account for the maintenance factor that will be used in the lighting system design, F_{CA} is the factor to account for the reduced power required if parts of the area are lit to a lower level, F_L is the correction factor to account for the efficiency of the lighting equipment that will be used in the lighting system.

The value of $P_{j,lx}$ depends on the photometric distribution of the luminaires used and the shape of the room that they are illuminating. The shape of the room is classified in accordance with its room index (k), which may be evaluated using following equation:

$$k = \frac{L_R \cdot w_R}{h_m(L_R + w_R)} \tag{30}$$

where L_R is the length of the room [m], w_R is the width of the room [m], h_m is the height of the luminaires above the working plane in the room [m].

Furthermore, a note says that if the calculated room index (k) results in a value below 0.6 then the tabular method of estimating installed power should not be used. If the room index is found to be greater than 5.0 then the value for 5.0 should be used in looking up the value of power density per lux in a provided table. It gives values of the power density per lux for values of room index between 0.6 and 5.0 for luminaires with upward flux fractions (UFF) of 10 %, 30 %, 70 % and 90 %.

The calculated value of k in our case is 0.45, therefore, the tabled method can not be used. Doing a proportion, a value of 0.057 has been found.

The FMF has been calculated equal to 1.06 as:

$$F_{MF} = \frac{0.8}{MF} \tag{31}$$

In order to calculate F_{CA} following formula has been applied:

$$F_{CA} = \frac{A_s \cdot E_{task} + \left(A - A_s\right) \cdot E_{sur}}{E_{task} \cdot A} \tag{32}$$

Considering 100 m^2 as area of the whole room (A), 15 m^2 as sum of the task areas within the room (A_S), 300 lx as illuminance in surrounding area (E_{sur}) and 500 lx as illuminance in the task area (E_{task}), an F_{CA} index of 0.66 has been calculated.

Regarding the correction factor to account of the efficiency of the lighting equipment F_L, it can be found in a provided table according to the lamp typology. For the light emitting diode (LED) light source an F_L of 0.86 is suggested.

It has been found in a provided table that gives the values for luminaires with common lamp types. The table is based on a survey of a large number of luminaires and gives the median value for all luminaires surveyed with a particular lamp type.

Following this calculation, a P_n value of 1735 W has been calculated considering the relevant area in the building. Obviously, it is more precise to consider only the area where the luminaires have been installed. In this case the P_n value could be 260 W. Considering this value of P_n, the LENI should be 27.27 kWh/m^2 year.

6.1.3. Application of standard using the metering method

The energy used for electric lighting W_t for time step t_s shall be obtained from the meter reading. The t_s as well in this case is 8760 hours because the calculation is yearly. The total metered energy (W_{mt}) used for electric lighting in the building for time step (t_s) shall be calculated by summation of the energy usage reported by each meter for all the meters used for measurement in different parts of the building.

$$W_{mt} = \sum W_t \qquad \left[\frac{kWh}{t_s}\right] \tag{33}$$

For the analysed case study, calculating the W_t as sum of $W_{P,t}$ and W_{Lt}, following W_t values have been calculated:

- a W_t equal to 180 kW/t_s has been calculated considered a P_n equal to 106 W a $W_{P,t}$ of 10 W,
- a W_t equal to 343 kW/t_s has been calculated considered a P_n equal to 260 W (calculated by standard suggestion) and a $W_{P,t}$ of 10 W,
- a Wt equal to 234 kW/t_s has been calculated considered a P_n equal to 106 W and a $W_{P,t}$ of 18 W,
- a W_t equal to 397 kW/t_s has been calculated considered a P_n equal to 260 W (calculated by standard suggestion) and a $W_{P,t}$ of 18 W.

The summation of annual energy for electric lighting within the building (W) has been calculated as

$$W = \frac{8760}{t_s} \cdot W_{mt} \qquad \left[\frac{kWh}{year}\right] \tag{34}$$

but for the case study it is the same of W_t.
The *LENI* for the building shall be established using the following equation:

$$LENI = \frac{W}{A} \qquad \left[\frac{kWh}{m^2 \cdot year}\right] \tag{35}$$

Following LENI values have been calculated:

- a LENI equal to 12 kWh/(m year) has been calculated considered a P_n equal to 106 W a $W_{P,t}$ of 10 W,
- a LENI equal to 23 kWh/(m year) has been calculated considered a P_n equal to 260 W (calculated by standard suggestion) and a $W_{P,t}$ of 10 W,
- a LENI equal to 15.6 kWh/(m year) has been calculated considered a P_n equal to 106 W and a $W_{P,t}$ of 18 W,
- a LENI equal to 26.5 kWh/(m year) has been calculated considered a P_n equal to 260 W (calculated by standard suggestion) and a $W_{P,t}$ of 18 W.

The three methods are very different and can be used to calculate the LENI index in different situation and with different aims.

The first one is more complicated, but also the more precise. Indeed, in order to apply this method many parameters are necessary and their calculation can be a "matryoshka effect". Furthermore, sometimes, within the general description not right Annexes are indicated. Finally, some indices have very similar name (e.g. $F_{D,s,j,n}$ and $F_{D,s,n,j}$).
Applying the monthly calculation, the sum of the weights in table is not equal exactly to 12 and, for this reason, the sum of the F_D calculated yearly is not exactly the same of the sum of the F_D calculated monthly.

The LENI values are similar but not the same. First of all, because, applying the comprehensive method it was possible to calculate LENI value yearly, monthly and hourly and applying different types of control strategies. While, by applying the other methods it is possible to calculate the LENI only yearly and do not differentiate the control system strategies.

Applying the first method, the LENI has been calculated for the two control strategies and the results are very similar. It is very strange given that, as largely demonstrated, the dimmer system can provide higher energy savings. Following graph shows the comparison between the energy consumption calculated using the first method suggested by the standard and the measured consumption.

It must be remembered that the consumption has been measured testing the two different control systems. They were characterized by different absorbed power (about 10 and 18 W). For this reason, the LENI have been calculated considering these absorbed powers.

Obviously, the actual measured consumption has been compared with the $LENI_{hourly}$ calculated considering the absorbed power according to the test period and, therefore, according to the tested system.
As it is possible to see from the graphs, the consumption calculated using the method suggested by the standard are more statics even if they have been calculated applying some tabled monthly weights. The error is very high, but it changes based on the tested system. Comparing the daily consumption calculated applying the comprehensive method and the measured consumption in dimmer and ON-OFF case, it is possible to affirm that for the first case the calculated consumption has an error of 24.4% and for the second one an error of 25.6%. In general, the error is very similar by splitting the error for the two systems. Comparing the data for the first system in dimmer case the error is the 25.5% and 26.6% for the ON-OFF case. While, for the second system the error is the 23.7% in dimmer case and the 25.3% for the ON-OFF case.

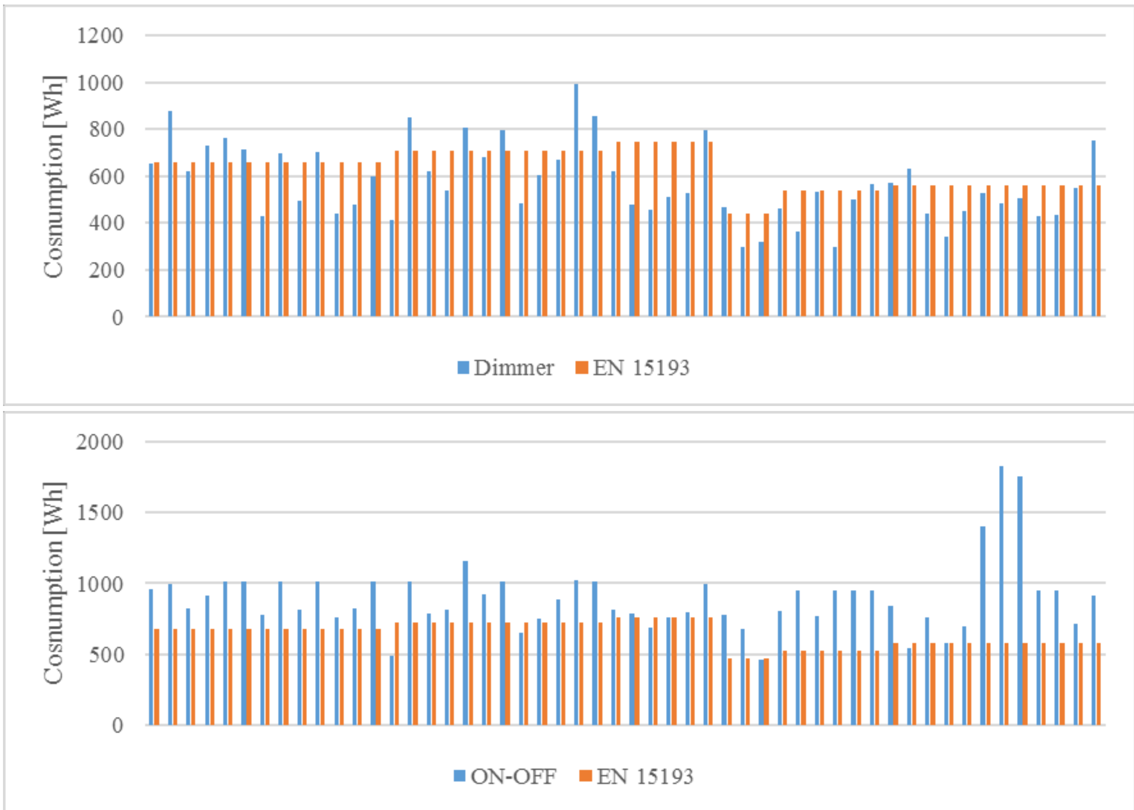

Figure 106. Comparison between consumption calculated using the comprehensive method and measured consumption for some scenarios in dimmer and ON-OFF cases

Taking into account only the days when the tested system worked better, the errors are lower. In particular, the energy consumption calculated by the comprehensive method has an error equal to 18.85 % for the dimmer case and equal to 19.75% for the ON-OFF one.

6.2. The Standard EN 15232

The aim of the European standard EN 15232 ("Energy performance of buildings – Impact of Building Automation, Controls and Building Management") is to establish conventions and methods for estimation of the impact of building automation control systems (BACS) and technical building management (TBM) on energy performance and energy use in buildings.

This standard should be used for existing buildings and for design of new or renovated buildings.

The European Standard EN 15232 has been developed in conjunction with the Europe-wide implementation of the directive for energy efficiency in buildings (Energy Performance of Buildings Directive EPBD) 2002/91/EG.

As well this document is part of a set of CEN (Comité Européen de Normalisation, European Committee for Standardization) standards.

In particular, this standard provides a structured list of control, building automation and technical building management functions, which have an impact on the energy performance of buildings. Furthermore, it proposes:

- a method to define minimum requirements regarding the control, building automation and technical building management functions to be implemented in buildings of different complexities;
- detailed methods to assess the impact of these functions on the energy performance of a given building. These methods enable to introduce the impact of these functions in the calculations of energy performance ratings and indicators calculated by the relevant standards;
- a method to get a first estimation of the impact of these functions on the energy performance of typical buildings.

In order to estimate the impact of the BACS and TBM systems on the energy performance of the building in a reference period of one year, such standard uses a set of energy efficiency factors, named BAC factors, that are calculated by comparing the yearly energy consumption of a system (cooling, lighting, etc.) of a reference "class" (Class C) building with the consumption of the same system calculated in the same working conditions (occupation time, load profile, weather, solar irradiation, etc.) after the application of a BAC/HBES automation system in the different classes (A, B, C, D). In the following, these four efficiency classes (A, B, C, D) of functions are defined either for non – residential and residential building as described by the standard:

- Class D corresponds to non-energy efficient BACS. Building with such systems shall be retrofitted. New buildings shall not be built with such systems
- Class C corresponds to standard BACS;
- Class B corresponds to advanced systems BACS and BMS;
- Class A corresponds to high energy performance BACS and BMS.

The case study building, object of the analysis, is equipped with a building automation and control systems that will be assigned to one of these classes according to Table 107. The potential savings for thermal and electrical energy can be calculated for each class on the basis of the building type and building purpose. The values of BAC for the energy class C are used as the reference for comparing the efficiency. In order to assign easily the class, the standard provides a table with the function list and the correspondent assignment to energy performance classes.

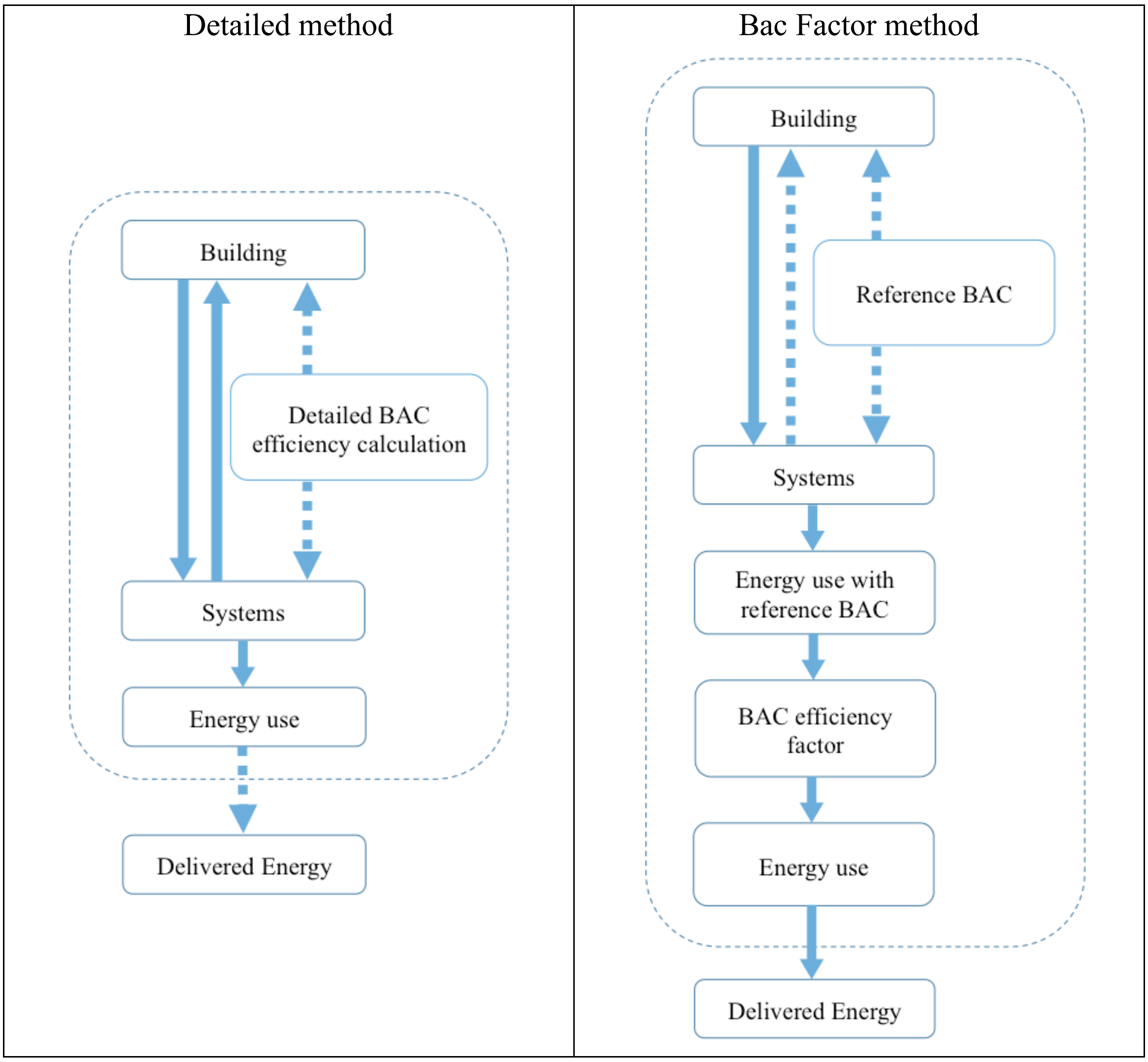

Figure 107. Difference between Detailed and BAC Factor method methods (European Technical Standard EN 15232)

As already mentioned, the standard proposes a detailed method and the so-called BAC Factor method to calculate the impact of the BACs. In Figure 107 the difference between the two methods is shown. In this chapter of this thesis only the BAC factor method is analysed and BAC factors proposed by standard are compared to the factors calculated using the collected data in the laboratory described in section 5.

6.2.1. Empirical application of the BAC Factor method for the case study

As already said, this method uses a set of energy efficiency factors, named BAC factors. In order to calculate them, the yearly energy consumption of a system (heating, lighting, etc.) of a reference "class C" building is compared with the consumption of the same system calculated in the same working conditions (occupation time, load profile, weather, solar irradiation, etc.) after the application of a BAC (Building Automation Control Systems) and HBES (Home and Building Electronic Systems) automation

system in the different classes (A, B, C, D). The EN 15232 BAC factors are pre-calculated values of the ratio between the last and the previous figures.
The EN 15232 BAC factors are pre-calculated values of the ratio between the last and the previous figures. A first method’s application and comparison with actual results has been published by the author in (Beccali et al., 2017).

The experimental validation of the BAC factors for lighting systems proposed in this thesis, has been done starting from the assumption that whichever realistic scenario includes automatic control of some lamps as well as manual control of other lamps. Therefore, in our case study, the manual control of the mono-optic luminaires has been considered as a condition consistent with the assumption of for the experiments. Although BAC factors are usually referred to a reference scenario with a slight presence of automation (class C), whose values are reported in Table 25, for the aim of our study, such factors have been calculated assuming class D (no automation). The reason lay on the choice assuming that the baseline scenario is fully manual controlled. In this way, the “corrected” values listed in Table 26 have been obtained.

For each considered scenario, the energy consumption of the lighting system has been measured:

- in absence of automatic control of all the lamps (as in class D building);
- presence of automatic ON/OFF control of the pendant luminaires (installed in the living and in the dining zones) as function of the established illuminance set-point;
- in presence of dimming control of the artificial lighting.

	D	C	B	A
Residential Buildings	1.08	1	0.93	0.92
Office Buildings	1.10	1	0.93	0.87

Table 25. EN 15232 BAC factors for electricity consumption in residential and office buildings (reference class C)

	D	C	B	A
Residential Buildings	1	0.93	0.86	0.85
Office Buildings	1	0.91	0.85	0.79

Table 26. Corrected BAC factors for electricity consumption in residential and office buildings with reference class D

Regarding the energy consumption calculated in absence of BAC systems, it worth noting that the power absorbed by the control system is not to be accounted for. Therefore, in some cases it has been experienced that the energy consumption calculated in presence of ON-OFF control systems are higher than the one calculated in absence of BAC systems. This happens when the daylight is not enough to achieve the task illuminance and so the luminaires were very frequently, or always, switched on.

According to Standard EN 15232, in the first case (absence of BAC system) the lighting system is considered of class D, while in the other cases the lighting system can be assumed of class C and A, respectively. The actual BAC factor BF is calculated as the ratio:

$$BF = \frac{E_{AUT}}{E_D} \tag{36}$$

where E_{AUT} is the daily energy consumption of the lighting system in presence of automation and E_D is the theoretical consumption that the lighting system would have in the same day in absence of automatic control. Tables 27, 28 and 29 report values calculated with (37). The two tables contain also the calculated average continuous Daylight Autonomy (cDA) the performances are different along the year. For this reason, the comparison of the three different systems using the BAC Factor method has been done separately for winter and summer, as well on a year basis. Indeed, a correct evaluation of BF must take into consideration the actual contribution of natural lighting during daytime, especially in presence of dimming control that, during winter or in rooms characterized by insufficient natural lighting can become ineffective. Nevertheless, as it can be noticed from

Figure 109, there is not a good correlation between BF and cDA values in the presence both of ON/OFF and of dimming control. This is probably due to the quota of energy consumption due to not controllable loads (three pendant luminaires) and stand-by consumption. Tables 27, 28 and 29 report a comparison between the actual BAC factors, daily calculated, and the theoretical ones.

		Residential			**Office**		
Class A		Winter	Summer	Yearly	Winter	Summer	Yearly
	Measured	0.98	0.64	0.81	0.74	0.66	0.70
	Theoretical	0.85			0.79		
	Percentage difference	15.29%	25.22%	4.96%	6.12%	17.08%	11.60%
Class C		**Residential**			**Office**		
		Winter	Summer	Yearly	Winter	Summer	Yearly
	Measured	0.99	0.92	0.96	0.95	0.68	0.82
	Theoretical	0.93			0.91		
	Percentage difference	6.45%	0.72%	2.86%	4.29%	25.00%	10.35%

Table 27. Calculated average values of BF for Bticino system and comparison between actual and theoretical BAC factors

		Residential			**Office**		
Class A		Winter	Summer	Yearly	Winter	Summer	Yearly
	Measured	0.98	0.53	0.76	0.33	0.53	0.43
	Theoretical	0.85			0.79		
	Percentage difference	15.29%	59.65%	11.03%	58.44%	32.59%	45.51%

		Residential			Office		
Class C		Winter	Summer	Yearly	Winter	Summer	Yearly
	Measured	0.98	0.69	0.83	0.44	0.75	0.60
	Theoretical	0.93			0.91		
	Percentage difference	5.38%	25.84%	10.23%	51.36%	17.58%	34.47%

Table 28. Calculated average values of BF for Zumtobel system with photosensor in position I and comparison between actual and theoretical BAC factors

		Residential			Office		
Class A		Winter	Summer	Yearly	Winter	Summer	Yearly
	Measured	0.98	0.64	0.81	0.64	0.64	0.64
	Theoretical	0.85			0.79		
	Percentage difference	15.29%	24.81%	4.76%	19.27%	18.48%	18.87%
Class C		**Residential**			**Office**		
		Winter	Summer	Yearly	Winter	Summer	Yearly
	Measured	0.98	0.87	0.92	0.82	0.86	0.84
	Theoretical	0.93			0.91		
	Percentage difference	5.38%	6.80%	0.71%	9.88%	5.92%	7.90%

Table 29. Calculated average values of BF for Zumtobel system with photosensor in position II and comparison between actual and theoretical BAC factors

It is worth noticing that in the practice only a comparison done considering yearly average values is meaningful. Indeed, single daily or seasonal values of BF can greatly differ from the theoretical BAC factors, being highly dependent on the natural lighting contribution of the specific day.

In addition, although BAC factors are defined for assisting in the estimation of the buildings yearly consumption, a comparison on the basis of seasonal values is useful to provide important indications on the behaviour of the system throughout the year.

The comparison shows that, for the scenarios examined in this study, the calculated BAC factors values for C and A classes are quite close to the theoretical values only in some cases.

In general, the values calculated using the Bticino system are closer to the theoretical ones, but it must be noted that the performances of this system in terms of energy and visual comfort were lower than the ones of the other systems (see section 9).

In general, but mainly for the residential cases, it can be noted that there are not significant energy savings in winter period with respect to the case without automation. Indeed, being the occupancy schedules of the residential scenarios in the second part of the afternoon, hence, during winter presence of people is considered after twilight.

For this reason, due to the absence of daylight, for the most part of the time period, the luminous flux of the lamps was at 100% of their rated power. Despite the difference are not so high, it can be noted that the energy savings expected are lower than the measured one. From Table 27 (Bticino system) it is deducible that, for the residential case, the measured BAC factors for the Class C lighting systems take values very close

to the theoretical one. Indeed, in these cases the percentage differences are not over 7%. While, looking at the yearly average values, it is very low the percentage of difference also for Class A. For office case, the BAC values are very close to the theoretical one during winter period.
The BAC factors, calculated for Zumtobel I system, are very close to the theoretical ones for class C both in the residential case and in office one, mainly in winter period. Finally, the difference between BAC factor calculated for Zumtobel II system and the theoretical ones is very low mainly for class C case.

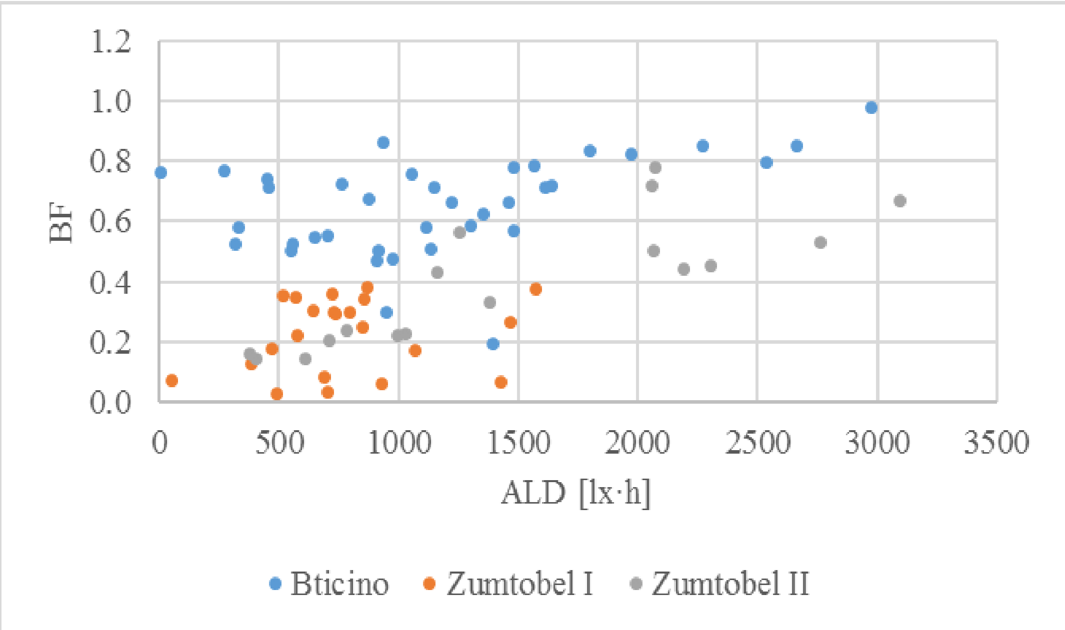

Figure 108. Relationship between BAC factors calculated for the three systems for office in dimmer operation and the ALD values.

Author has defined a new index able to represent a measure of the amount of artificial lighting that is required to fulfil the desired task over the operation time (lx·h) (Bonomolo et al., 2017). In section 9 such index, called ALD (Artificial Light Demand), will be presented. In Figure 108 the relationship between the BAC factors calculated for each system and the ALD is shown.

Looking at the graph in Figure 108 it can be noted that in general, as expected, there is not a good correlation between the BAC Factors and the ALD mainly for Bticino system.

In general, the values calculated for the Bticino system show that the performances of this system in terms of energy and visual comfort were lower than the performances of the other systems.

Figure 109. Relation between continuous daylight autonomy and BAC factors

The graphs in Figure 109, show the relationships between the BAC Factors calculated and the continuous Daylight Autonomy.

6.3. Final remarks

In conclusion, analysing with more detail the difference between the BAC factors calculated for the case studies and the theoretical ones, it must be noted that they are different for each case and each system. Indeed, in some cases the results allow one to affirm that the BAC factor method, besides characterized by a certain degree of approximation, but also by a remarkable simplicity, can be used with sufficient precision for evaluating the final energy consumption of C class lighting systems, both in residential and in office buildings (e.g. Zumtobel II system). But, in other case (e.g. Zumtobel I system, office case) the difference is very high for class A and mainly during the summer period. In particular, the expected energy savings are lower than the actual ones.

Main differences are due to the fact that theoretical ones do not consider several parameters such as the influence of specific daylight contribute in a yearly analysis, the different usage pattern assumed for the lighting system, the imposed task illuminance values, the stand-by energy consumption of lamps and control devices, etc. On other hands, the actual performances of these systems were not as the expected ones. This made the factors closer to the theoretical ones.

In addition, the EN15232 does not consider many important aspects of a lighting system and of a lighting control system and other parameters that can influence their behaviour and their performances. First of all, it does not take into account the parameter related to the daylight contribution such as the building location, the season, the characteristics of the transparent surfaces of the building envelope. Furthermore, the characteristics (e.g. absorbed power, photosensor typology, etc.) are not considered. Finally, the BAC factors determination is previous to the LED technology spread (prEN15232, 2011).

For this reason, the expected savings seem lower than the actual ones. They do not take into account the higher efficiency of this kind of sources and of the new control systems. On the contrary, as seen in first part of this section, the EN 15193, and in particular the first proposed method, considers in the calculation of the energy demand all these parameters. The procedure is very complicated and a lot of factors must be calculated or adopted by assumptions. These could lead to an error propagation and, in addition generate calculations gives different results according to the analyst. Nevertheless, in general, it can be affirmed that the errors of the BAC factors are not so high even if the standard EN 15232 suggests to apply the method provided by the standard EN 15193, for which the error are higher. As will be shown largely in this thesis, one of the reason, is because this kind of systems cannot work as expected.

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7. Neural Network as a method for data prediction: study, design and application

The distribution of the lighting in a room is a very important parameter for the design and the configuration of a Daylight Linked Control system. It has been discussed in many parts of this thesis that DLCs system behaviour is greatly influenced by the sensors' position. Indeed, very often the illuminance on the work-plane is not fully correlated with illuminance measured by the photo-sensor used to control the luminaires. This leads to wrong information for the DLCs and thus decreases energy savings and causes improper illuminance and discomfort. The artificial intelligence of the Neural Networks can be exploited to provide a method to find the best correlation between the illuminance on the workplane and the tone in a point of the space where the photosensor used to control the lighting system is located.

In section 1, some example of studies based on neural network to predict daylight contribution and energy consumption for lighting have been presented. This approach found many applications as well in different areas of energy modelling.
Regarding the lighting topic and in general, the influence of weather data on building performances, it is useful to briefly remind some of these interesting works.

Hu and Olbina (Hu and Olbina, 2011) carried out a model based on ANN for predicting the optimum slat angles of split blinds system to achieve the designed indoor illuminance. They fixed the illuminance data, obtained by the simulation software Energyplus (Energyplus, 2010), close to the ceiling as output of the ANN and the weather determinants (e.g. horizontal illuminance and sun angles) as input. Finally, they valuated the model by evaluating the errors in the calculation of the illuminance and optimum slat angles. The validation results showed that the power of their model to predict illuminance was 94.7% while its ability to calculate the optimum slat angles was 98.5%. For about 90% of time in the year, the illuminance percentage errors were less than 10%, and the percentage errors in calculating the optimum slat angles were less than 5%.

Kalogirou and Bojic (Kalogirou and Bojic, 2000) using an ANN predicted the energy consumption of a passive solar building. The energy consumption of the building depends on whether all walls have insulation, on the thickness of the masonry and insulation and on the season. For this reason, they investigated two different cases and in different seasons conditions using simulated data to train the network. The aim of their work was to produce a simulation program, using ANNs, to model the thermal behaviour of the building. The results obtained for the training set were such that they yield a coefficient of multiple determination (R^2 value) equal to 0.9985. The network was used subsequently for predictions of the energy consumption for cases other than the ones used for training. The coefficient of multiple determination obtained in this case was equal to 0.9991, which is very satisfactory. The ANN model proved to be much faster than the dynamic simulation programs.

Beccali et al. (Beccali et al., 2017) applied the Neural Network Method to develop a

decision support tool for a fast prediction of the energy performance of buildings and for a first selection of energy retrofit actions that can be applied. To do this, a large set of data, obtained from the energy audits of 151 existing public buildings located in four regions of South Italy have been analysed, elaborated, and organised in a database, in order to find the best architectures of two ANN. The first ANN provides the actual energy performance of any building; the second ANN assesses key economic indicators.
In this section on original application of ANN is presented.

Ascione et al. (Ascione et al., 2016) developed a ANNs MATLAB® by using the outcomes of EnergyPlus simulations to predict energy performance and retrofit scenarios, investigating a case study, office buildings. Finally, they compared the ANNs' predictions with EnergyPlus targets end estimated a regression coefficient between 0.960 and 0.995 and an average relative error between 2.0% and 11%.

For the purpose of finding a good placement of DLCs photosensor, an ANN methodology has been used.

Five different ANNs have been optimised and trained and the results have been compared in order to know the best correlation of the illuminance measured on the work-plane and the illuminance measured on another point. The measuring campaign has been carried out in a laboratory where a DLCs system is installed.
In other terms, five different neural networks are presented. They can be used as method:

- to select the position of a photosensor;
- to provide reliable prediction of the illuminance on the workplane and so implement a better an effective behaviour of the control system.

In a first step, four networks have been used to find the best position, between four positions on the DEIM laboratory, where the photosensor should be installed in order to achieve for most time values close to the task illuminance, i.e. the point of the room where the illuminance has the best relation with the illuminance on the workplane.
In a second step a more complex network processing at the same time as input the data coming from the four photosensors has been tested. The aim was to compare the results of the best of the four “mono sensor” net with this one that could be supposed to be more precise.

Before to start with the description of the five networks, some elements regarding ANN definitions and methodologies are described.

7.1. Neural network method

Kalogirou and Bojic (Kalogirou and Bojic, 2000) defined ANN models as a method that operates like a "black box" model, requiring no detailed information about the system "able to learn the relationship between a big set of data variable in input and the controlled and uncontrolled variables by studying previously recorded data, similar to the way a non-linear regression might perform".

Haykin (Haykin, 2009) described the neural network method as a great parallel distributed processor that has a natural propensity for storing experiential knowledge and making it available for use. It resembles the human brain in two respects; the knowledge is acquired by the network through a learning process, and inter-neuron connection strengths, known as synaptic weights, are used to store the knowledge. As already said, this method found successful application in the area of energy modelling. Many researchers demonstrated the great capability of the ANN method over the other conventional well know methods. Karatasou et al. (Karatasou et al., 2006) affirmed that the main advantage of the ANN is the high potential to model non-linear processes, such as utility loads or individual buildings' energy consumption. In particular, they used a neural network to predict energy consumption in buildings and specifically hourly load profiles. It is possible to define the artificial neural network (ANN) as a method similar with regression in statistics, a method used for finding the mathematical model from the input and output data. The function of the ANN is inspired by the human brain. The fundamental unit of an ANN is called neuron and consists of three elements: a collection of synapsis characterized by their weights, a processing element (PE) that receives connections from other PE and/or itself and an activation function to limit the amplitude of the output. ANNs are distributed, adaptive, generally nonlinear learning machines built from many different PEs organized in layers (Lo Brano et al., 2014). Each layer consists of neurons. A neuron has a set of inputs that are weighted and summed and then processed through an activation function (usually a linear or sigmoid function) (Alsina et al., 2016). Activation function restricts the output of a neuron to the range usually between [0,1] or [-1,1] (Pacelli and Azzollini, 2011).

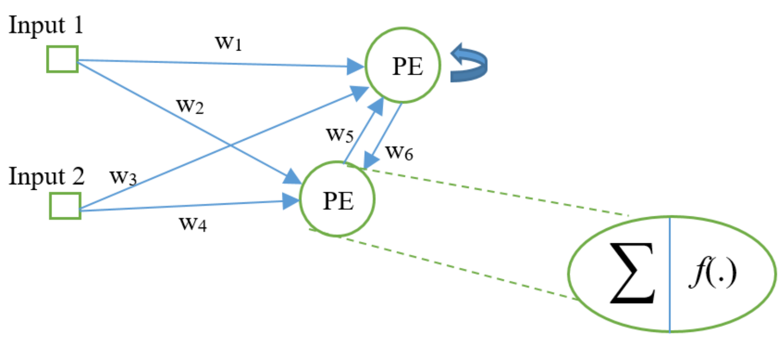

Figure 110. Example of a conceptual scheme of an ANN

The weighted output of a neuron can be written as an equation (37).

$$y_i = \sum_{j=1}^{N} w_{i,j} \cdot x_j - b_j \tag{37}$$

where *w* is a weight, *x* is an input value and *b* correspond to a bias.

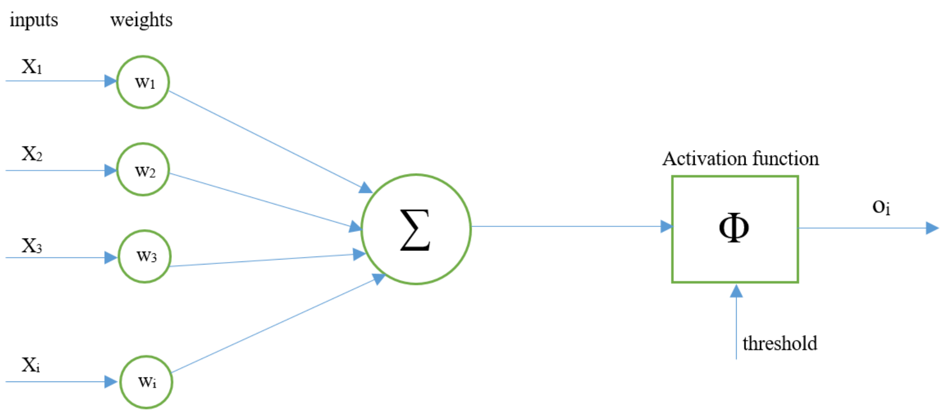

Figure 111. Conceptual scheme of a neuron

The activation function can be a sigmoid type in the following form:

$$o_i = x_j = \frac{1}{1+e^{-k \cdot y_i}} \tag{38}$$

The learning process, called "training", consists in the tuning of the weights in the neurons depending on the outputs. The process is iterative and every iteration is called an epoch (Alsina et al., 2016). The iterations continue until the point of surpassing a defined number of epochs or when the difference between the calculated output and the desired output is below a certain threshold.

The back-propagation algorithm is used to train the neural network. Its function is based on comparing the output from the neural net with the output that is measured in the form of a cost function (MSE) and changing the weights in the layers in the way of minimizing the difference between ANN's output and the desired output (Rumelhart et al., 1988)

For the calculation of the error the Mean Squared Error (MSE), or Mean Absolute Error (MAE) criteria is used, which can be described by the formulas (Lo Brano et al., 2014).

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|y_{calculated} - y_{observed}\right| \quad (39)$$

$$MSE = \frac{1}{N}\sum_{i=1}^{N}\left(y_{calculated} - y_{observed}\right)^2 \quad (40)$$

Once the network has been trained, a further "validation" can be made using data that the net has never processed in the training step.
If the validation test confirms low errors in the output data, the network is ready to be utilised.

7.2. Four "mono sensor" Neural Networks to find the best photosensor location

7.2.1. Data description

The input data used for the training of the four "mono sensor" neural nets have been as follows:

- Illuminance values measured by 4 different sensors [lx];
- Absorbed power [W];
- Global irradiation [Wh/m^2];
- Number of the day in a year, 1÷365;
- Number of minutes of the day, 0÷1440;
- Solar elevation [°];
- Solar azimuth [°].

Output value has been only one:

- Illuminance value on the work plane level [lx].

	C1 [lx]	**C2 [lx]**	**W1 [lx]**	**W2 [lx]**	**WP [lx]**	**Power [W]**	**GHI [Wh/m^2]**	**Elevation [°]**	**Azimuth [°]**
Max	2860	2864	3760	26636	22162	189.8	1020.3	75.3	360
Min	14	2	14	26	10	16.7	0	-75.3	0
Mean	246.4	242	212.9	977.8	473.3	29.6	198.9	-0.6	178.1
StDev	444.6	411.7	391	3098.4	1615.5	25.4	286.6	37	98.6

Table 30. Statistical attributes of the data (South = 0°)

A data set from monitoring campaigns, containing data of different daylight conditions and seasons has been utilised. The measurements have been taken with a definite timestep of 5 minutes for 8 months. Table 30 gives main statistical attributes of the data population.

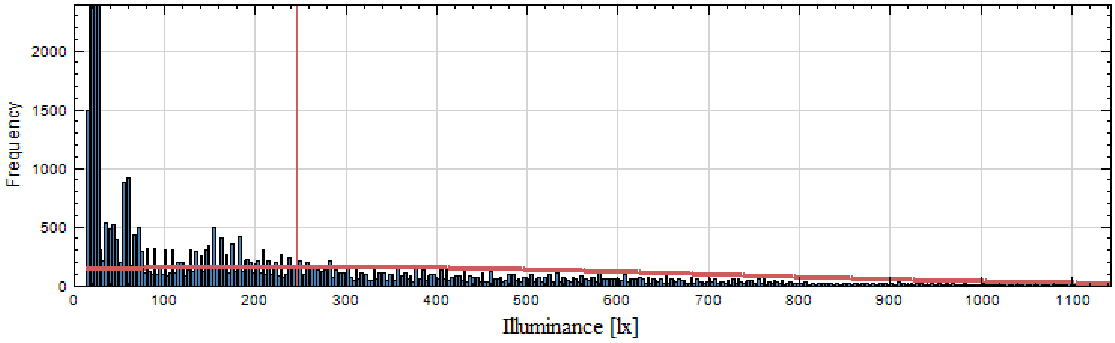

Figure 112. Frequency distribution of the data measured by sensor C1 of the training set

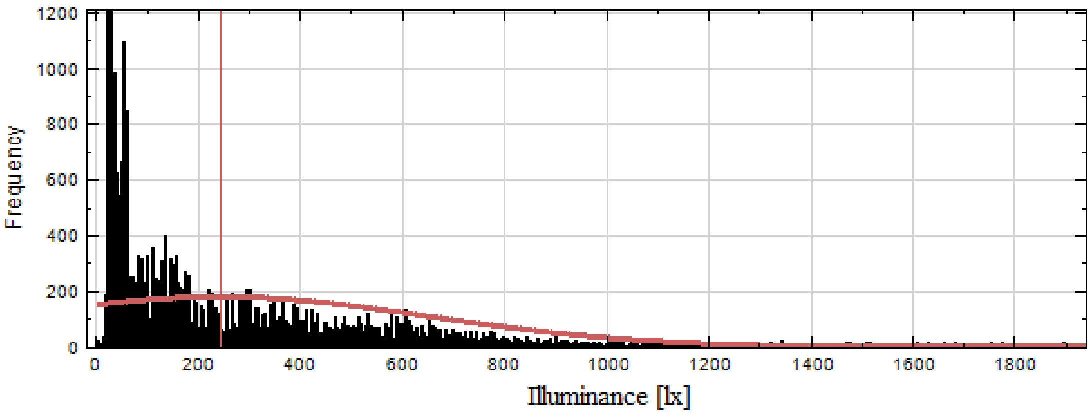

Figure 113. Frequency Distribution of the data measured by sensor C2 of the training set

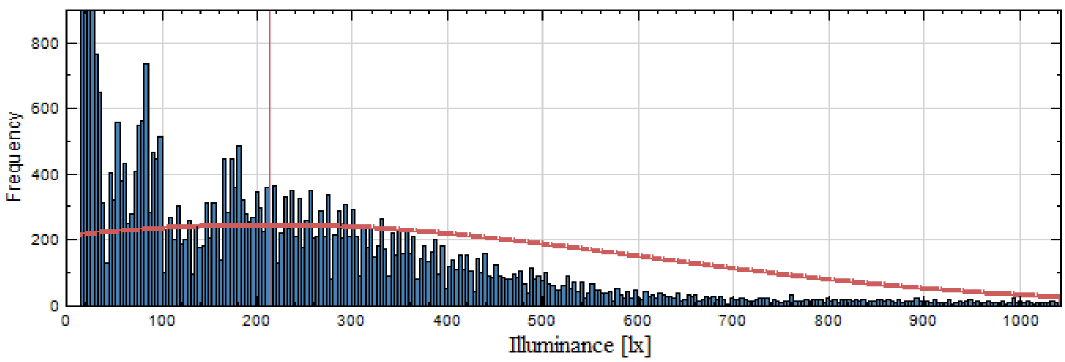

Figure 114. Frequency distribution of the data measured by sensor W1 of the training set

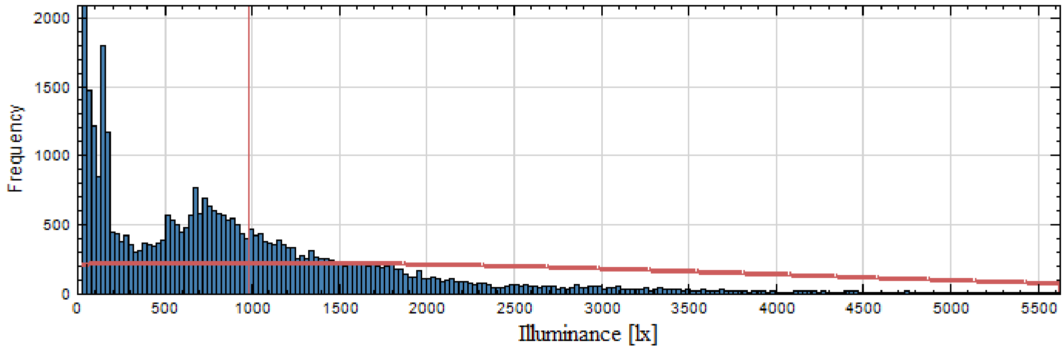

Figure 115. Distribution of the data measured by sensor W2 of the training set

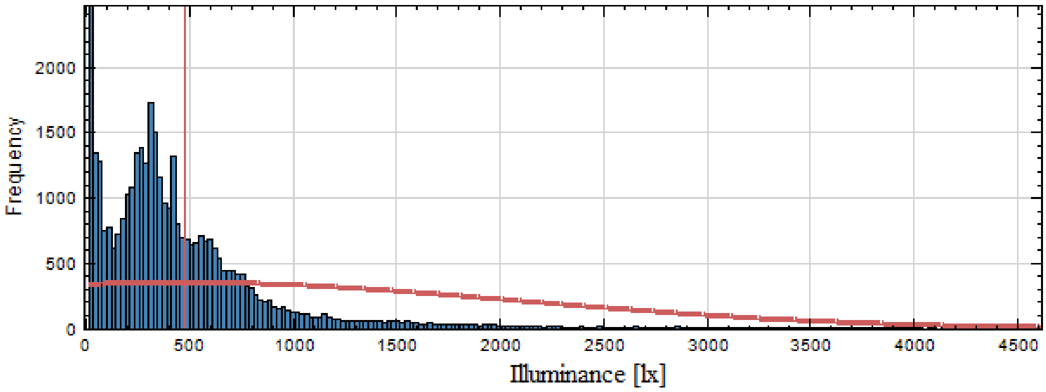

Figure 116. Distribution of the data measured by sensor WP of the training set

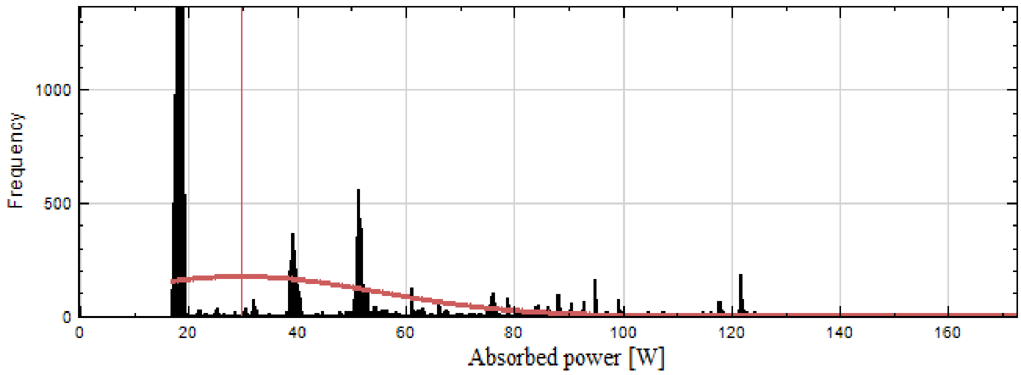

Figure 117. Frequency distribution of the absorbed power data of the training set

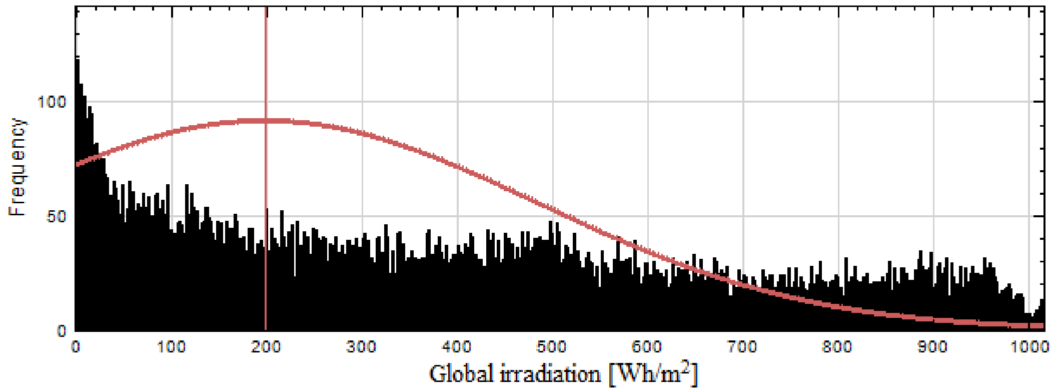

Figure 118. Frequency distribution of the absorbed global irradiation data of the training set

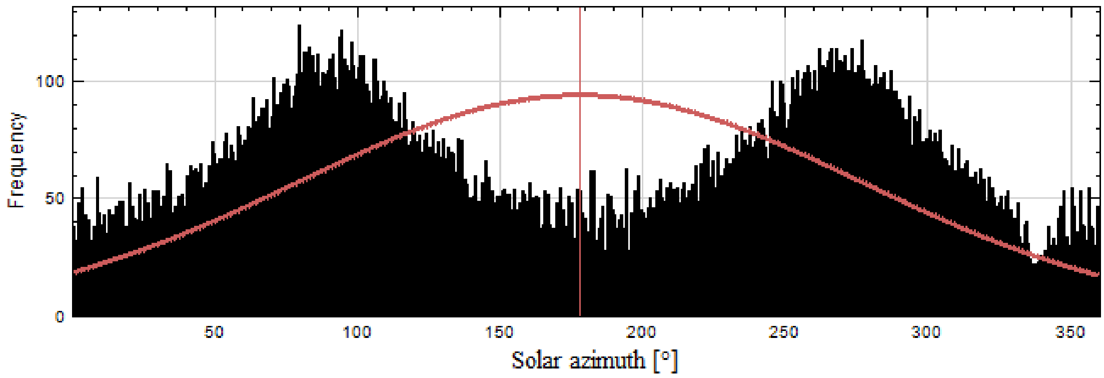

Figure 119. Frequency distribution of the azimuth data of the training set

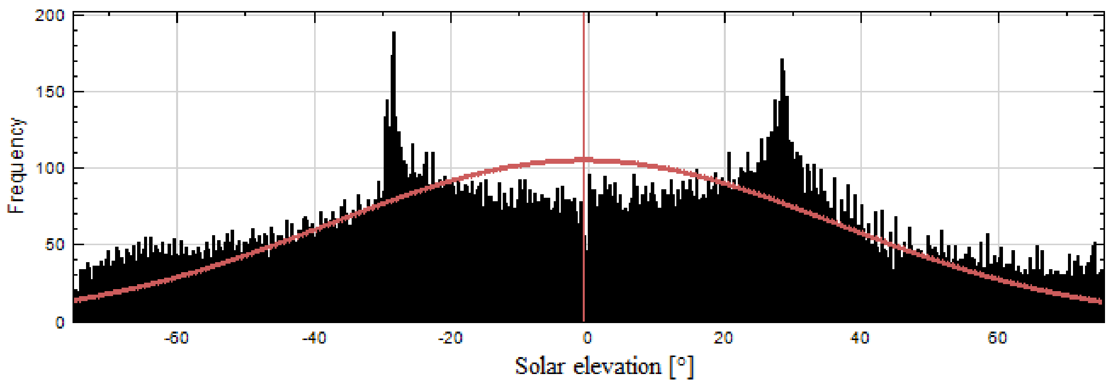

Figure 120. Frequency distribution of the solar elevation data of the training set

In figures above are shown the frequency distributions of the values for each data input. Regarding the first input parameter (i.e. the illuminance values), each of the four ANNs has been trained with the illuminance values measured by a photosensor in one of the four different positions.

All the graphs show that the frequency distributions of the illuminance measured by the photosensors have the highest amount of values (more than 10,000) around 0-20 lux. They correspond to the data measured during night-time when the illuminance in the room was minimal or non-existent. For this reason, in the graphs above, these data are not completely represented. The graphs in Figures 112 and 113 are respectively referred to the frequency distribution of the illuminance measured by the two photosensors installed on the ceiling (C1 and C2). It can be noted that in the points where these two sensors are installed, comparing all the graphs referred to the data measured by the other sensors, the illuminance values during the whole day are the lowest.

Not considering the above-mentioned peak of data measured during the night-time, the frequency is higher for values around 60 lx and 150 lx. Similar values measured have been measured by C2, but slightly lower (around 120 lx). Also, the values referred to the sensor W1 are similar, but with two peaks at around 70 lx and 185 lx. As can be seen in Figure 115, the highest frequencies concerning values measured by the photosensor W2 are around 170 lx and 670 lx, always excluding the values measured during the night-time. Indeed, this sensor is installed on the wall in front on the windows. Finally, the graph, where the WP sensor values are reported, show that during major part of the day the illuminance is around 320-420 lx.

Because of the use of artificial lighting in the room, also the absorbed power has been used as input for the neural net to learn to distinguish the values of illuminance due to the contribution of only daylight, the illuminance due to the artificial light contribution and the one due to both contributions. Also in this case, there is an important peak around 18 W. It is the absorbed power from the control system. So, it is always present, even when the luminaires are switched off. This period in this case includes, not only the power measured during night-time, but also most part of the daytime (if the lighting system was turned off).

The other peak values are easily linked to the luminaires absorbed power. In fact, the spotlight luminaires are characterized by a power of about 39 W, the single fixture installed in the bedroom/manager room (see section 5), by a power of around 54 W and the three pendant luminaires placed in the largest space by a power of around 121 W (when they are turned on at the same time).

Looking at the graph where the global irradiance values are reported, it is possible to see a more homogeneous distribution of them with an exception of big amount of data close to 0, also in this case referred to the night-time. Lastly, the temporal pattern is well shown in the graphs of the azimuth and of the elevation. Because the latitude of the experimentation site and of the period considered, the second one is low symmetric.

Data from satellite provided by CAMS Radiation service have been used as other input data (CAMS radiation service). Furthermore, solar elevation and solar azimuth have been calculated using an Excel sheet from National Oceanic and Atmospheric Administration (Earth System Research Laboratory). Finally, time shift during the year has been considered and incorporated into the calculations of solar elevation and solar azimuth.

Figure 121 shows a preliminary correlation analysis between input data and the value of the lighting sensor on the work plane level. It has been made by the software PELTARION SYNAPSE (Peltarion Synapse, 2017). The blue part of the graphs represents the positive correlation; while the red part the negative one.

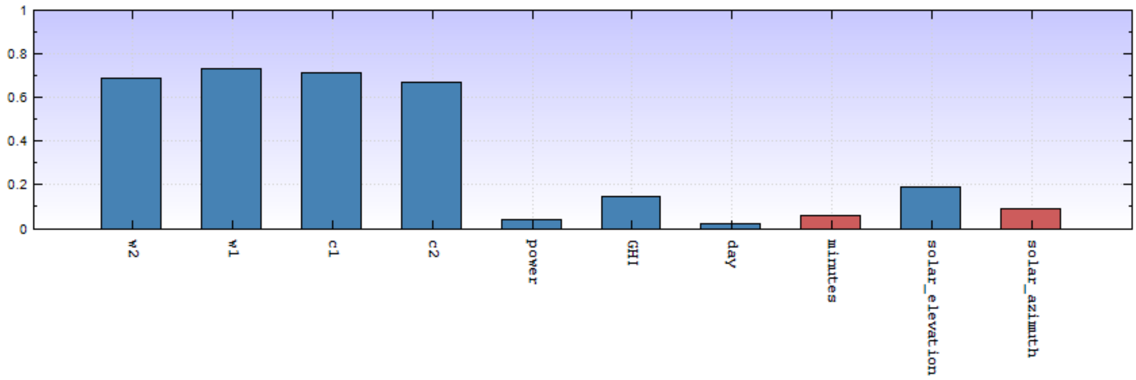

Figure 121. Preliminary correlation analysis between input data and the value of the lighting sensor on the work plane level

Figure 121 shows that the illuminance data used as input carry a very similar weight on the total of data. Furthermore, comparing them with the other data, they have a greater weight.

7.2.2. Model development

PELTARION SYNAPSE software has been used also to create the ANN models. In this study, a combination of genetic algorithm and a multi-layer neural network have been used to find the optimal model.

A genetic algorithm has been employed to test different ANN architectures. At the beginning, a set of trials had been run with different kinds of ANN out of which a simpler model has been chosen.

On this ANN (Figure 122) a genetic optimisation procedure has been carried out with the aim of improving the prediction reliability. The genetic algorithm is inspired by biology and consists of 4 different stages. At the beginning a set of “chromosomes” (a group of ANNs) is randomly chosen as the population to search for the best solution.

The chromosomes are tested and compared calculating a fitness function and afterwards another population is created using the chromosomes with the best fitness from the previous population. A child chromosome in the new population is created combining two parent chromosomes from the first population, called crossover, and then from time to time some of the information in the new chromosome can be changed by mutation.

First, a genetic algorithm examined 25,000 ANNs trained for 200 epochs to obtain the fitness functions of each. The algorithm chose the ANNs with best results (in this case the lowest MSE) and from these continued to create the new ANNs with optimised parameters. Finally, the best ANN was trained for 100,000 epochs using back-propagation algorithm.

The genetic algorithm needed 6.2 hours to finish its calculations and the back-propagation learning terminated after 5.8 hours, so, when put together, the whole training needed 12 hours. The final and optimized ANN itself was composed of 7 input neurons and 15 output neurons in the hidden layer, then transferred through the sigmoid function and then through the last layers with just one output neuron and a linear output function. The sigmoid function had the properties reported in Table 31.

Amplitude	Bias	Offset	Slope
1.7159	0	0	0.6666

Table 31. Properties of the sigmoid function

The data have been divided into two groups, a training group and a validation group, 85% (64 786 values) for the training set and 15% (11 432 values) for the validation set. MSE calculation is also commonly used by SYNAPSE as one of the evaluation indices of the model. Each model performance can be also assessed by using error distribution and its standard deviation.

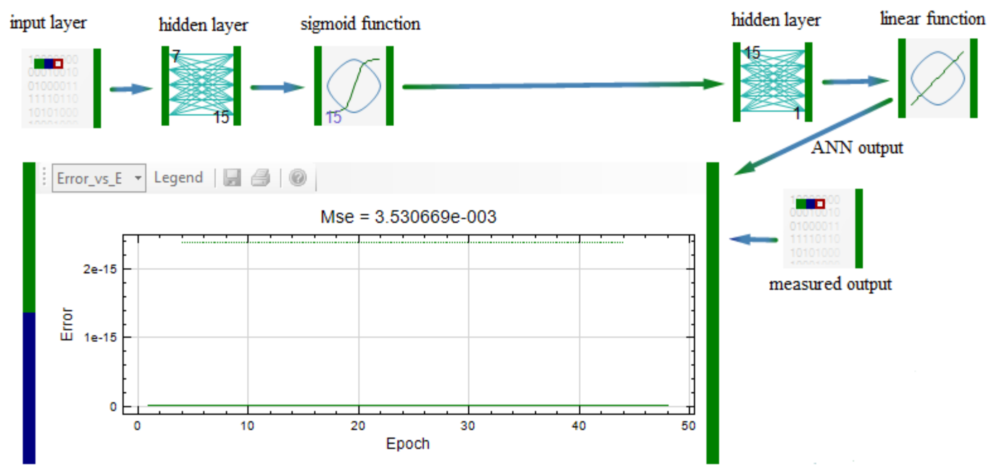

Figure 122. A scheme of the final form of the ANN from Synapse software

7.2.3. Results

For the comparison of the models the error distribution has been considered as the main indicator of the performance of the neural network along with the MSE values for each model. On the following graphs the error distribution for each neural net can be seen along with the statistical information in the Table 32.

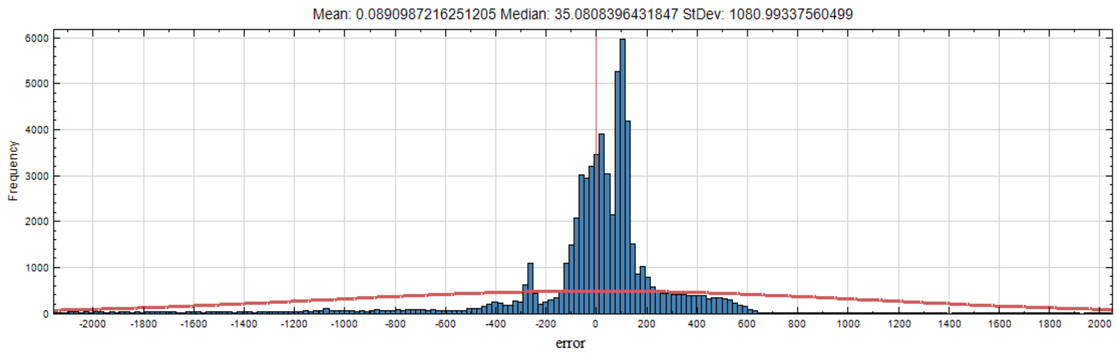

Figure 123. Frequency error distribution of the training data of the neural net using the sensor C1 as input

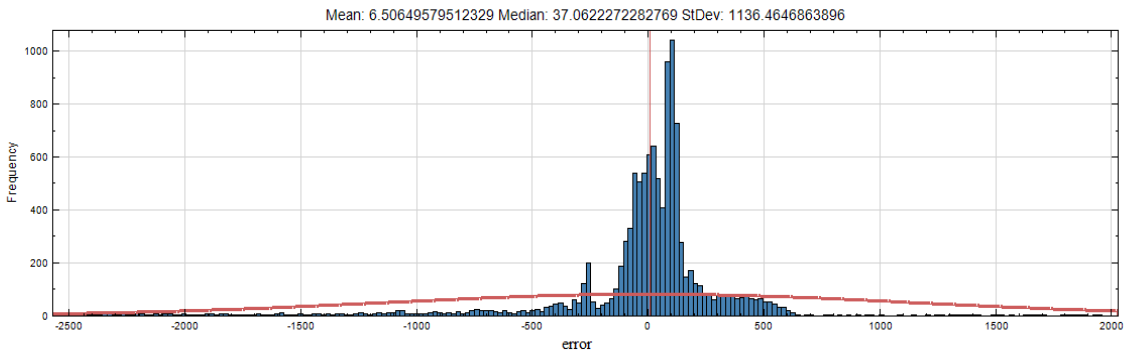

Figure 124. Frequency error distribution of the validation data of the neural net using the sensor C1 as input

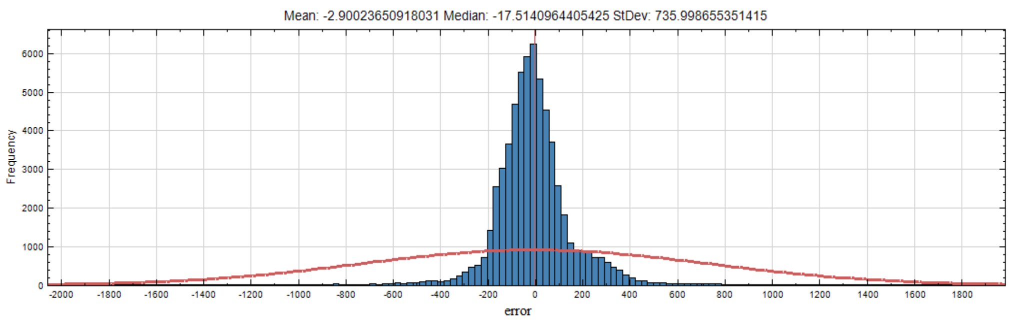

Figure 125. Frequency error distribution of the training data of the neural net using the sensor C2 as input

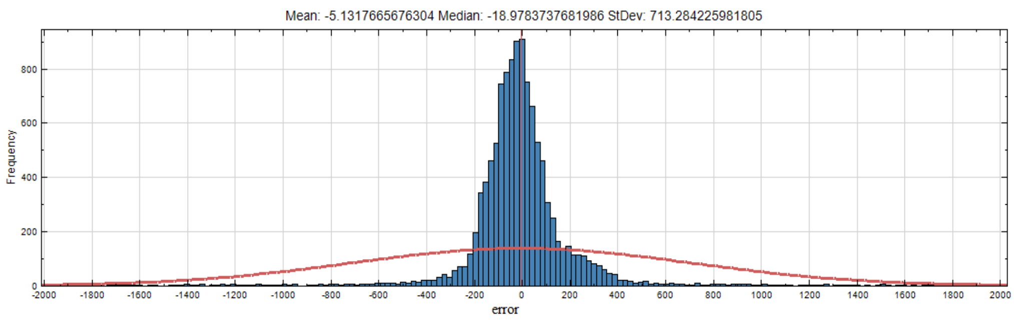

Figure 126. Frequency error distribution of the validation data of the neural net using the sensor C2 as input

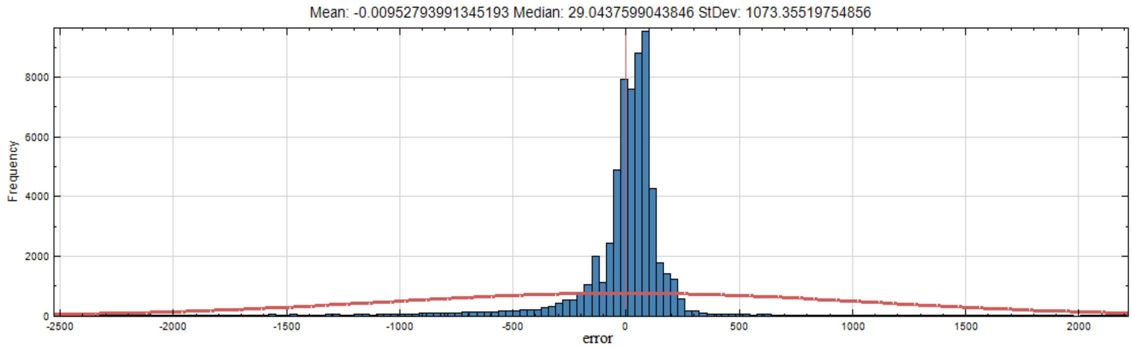

Figure 127. Frequency error distribution of the training data of the neural net using the sensor W1 as input

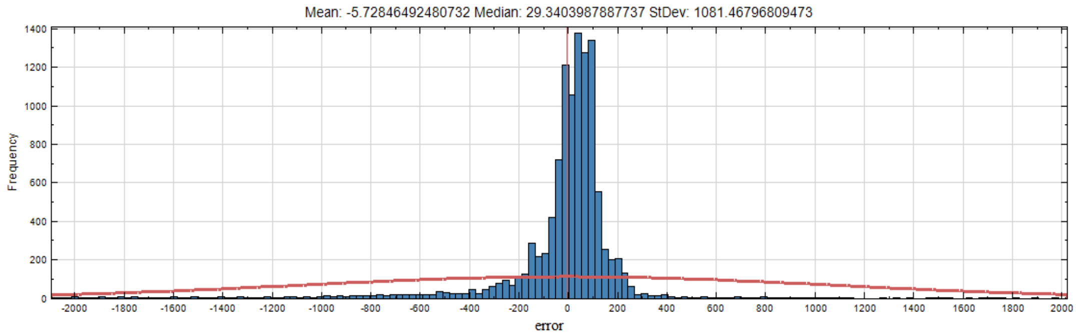

Figure 128. Frequency error distribution of the validation data of the neural net using the sensor W1 as input

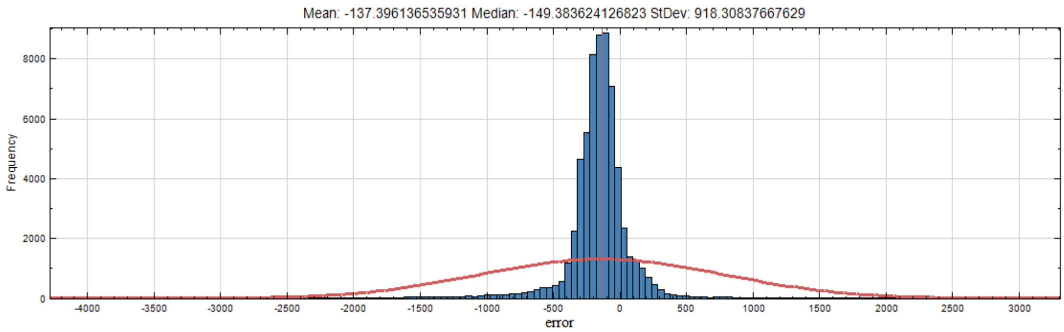

Figure 129. Frequency error distribution of the training data of the neural net using the sensor W2 as input

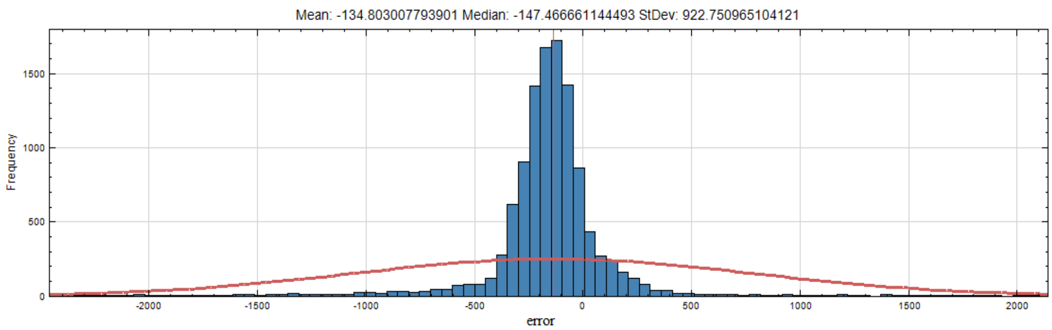

Figure 130. Frequency error distribution of the validation data of the neural net using the sensor W2 as input

Overall information			**Training**			**Validation**		
Neural net	MSE	Epochs	Mean	Median	StDev	Mean	Median	StDev
ANN_C1	$4.75e^{-3}$	100,000	0.09	35	1081	6.50	37.06	1136.46
ANN_W1	$4.5e^{-3}$	100,000	0	29	1073	-5.73	29.34	1081.47
ANN_C2	$2.20e^{-3}$	100,000	-2.9	-17.5	736	-5.13	-18.98	713.28
ANN_W2	$3.53e^{-3}$	100,000	-137.4	-149.4	918.3	-134.80	-147.47	922.75

Table 32. Statistical evaluation of the neural nets' behaviour

Observing the charts and the Table 32 above, the models that used C2 and W2 sensors show the best results. The ANN, where the values collected by the C2 sensor have been used as input, has a median very close to 0 and the minimal value of MSE of all the models. However, the ANN that has used the values collected by W2 sensor shows very promising results thanks to the accumulation of most of the data around the Median. The Median of -147.47 shows a shift to the negative values from 0 but the shift remains constant for many values. Otherwise it would make it a great candidate for the optimal model. The error values are obtained comparing the difference of the value calculated by the model with the real value that has been measured. The high values of the standard deviations correspond to the Gaussians indicated in red on the graphs and are mainly informative because the real distributions are very narrowly accumulated around specific values close to 0.

Comparing the error distribution graphs, it is possible to note that the best correlation occurs with the sensor C2, but also the other models show good results, especially the one that used W2 sensor which, if it weren’t for the shift to the negative values, would show a great correlation. This solution is the result of the long-duration experimental measurements and of a large set of data, used to train and implement the networks. The model is able to predict the illuminance values on the work-plane in order to know if they fulfil the visual comfort requirements. In addition, it can be used also in other application and environment where a DLCs system is applied, contributing to a better design and, so, to the implementation of its performance.

7.3. Neural Network to further provide reliable prediction of the illuminance on the workplane and so implement a better an effective behaviour of the control system

7.3.1. Data description

The input data used for the training of the neural net have been as follows:

- Illuminance values measured by 4 different sensors [lx], but all together;
- Absorbed power [W];
- Global irradiation [Wh/m^2];
- Number of the day in a year, 1÷365;
- Number of minutes of the day, 0÷1440;

- Solar elevation [°];
- Solar azimuth [°].

Output value has been only one:

- Illuminance value on the work plane level [lx].

The input data used for this network are a subset of the data used for the above presented networks. the same of the one utilised selectively (one sensor per time) in the other four “mono sensor” networks.

7.3.2. Model development

Also in this case, PELTARION SYNAPSE software has been used to create and optimise the ANN model and its structure (Figure 131).

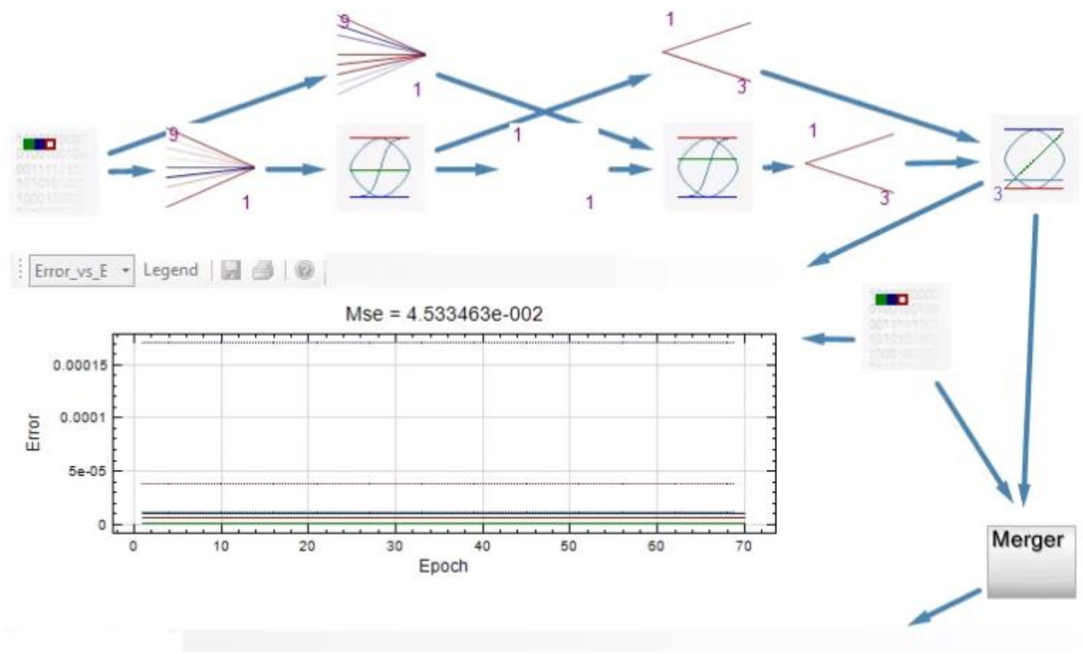

Figure 131. A schematic of an ANN from Synapse software

The architecture of the network generated by the algorithm is more complex than the algorithm of the first networks as shown in Figure 131.
One of the reason is that this network handles the “noise” due to the power absorbed by the system is always present.

7.3.3. Results

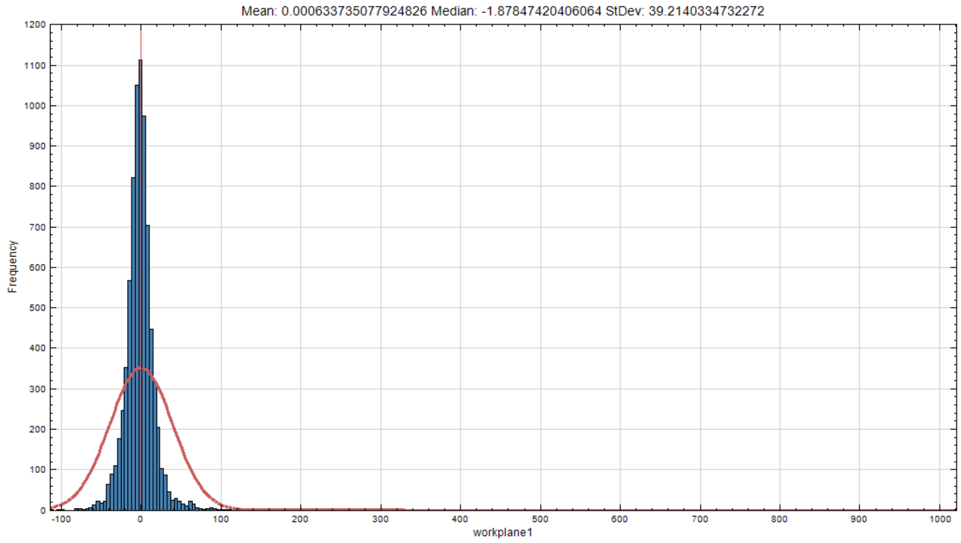

Figure 132. Frequency error distribution of the training data of the neural net using the four sensors

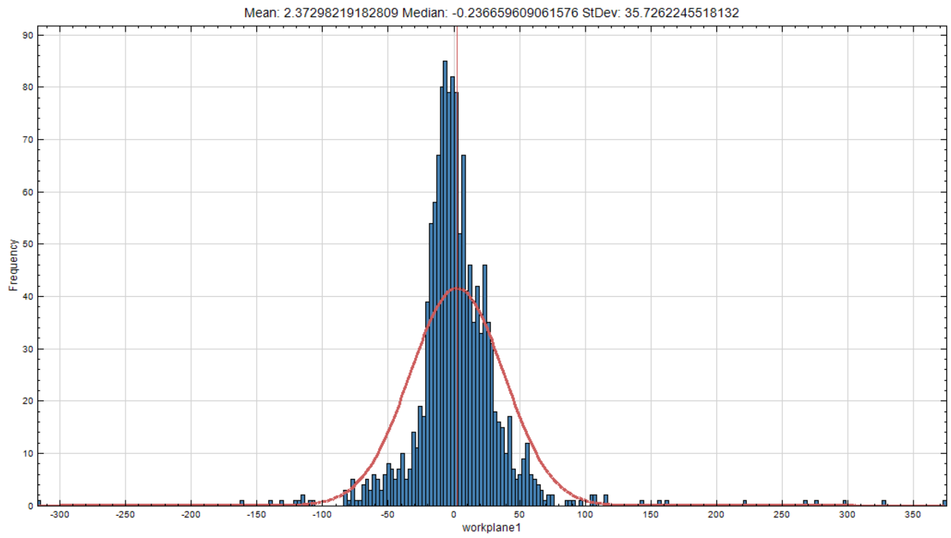

Figure 133. Frequency error distribution of the validation data of the neural net using the four sensors

Overall information			**Training**			**Validation**		
Neural net	MSE	Epochs	Mean	Median	StDev	Mean	Median	StDev
ANN_FOUR SENSORS	$4.5x10^{-2}$	10,000	$3.6\ 10\text{-}^{4}$	-1,878	39,21	2,37	-0.236	35.7

Table 33. Statistical evaluation of the neural nets' behaviour

As can be noted the “four sensors” network performed well. As shown in Figure 133, the error distribution is close to the zero. Therefore, the network does not underestimate and not overestimate and the standard deviation is low.

All the nets have as output the expected value of illuminance on the workplan. This means that a hypothetic control system which can use a “on-line” calculation of this value can effectively use such input to switch and dim the lamps.
In case the DLC system has to run with one sensor (most frequent), a preliminary analysis (i.e. using a kit of mobile photo-sensors for collecting the data) based on this ANN approach can help in selecting the best positioning.
In case the system can work with four (or another number) of sensors, an ANN processing all the signals in the same time will provide the workplane illuminance with more precision.

7.4. Final remarks

In general, all the presented ANNs performed well. Results demonstrated that the developed models could be used as method to optimize the performance of the control system both during the design step (i.e. using the first four ANNs) and during the operation time.

Further research will deal with the possible implementation and/or interface of this tool directly in control system software. Moreover, authors aim to exploit ANN capabilities for building algorithms and Dynamic-link library (DLL) for adaptive control of DLCs able to overcome the problematic handling of weak correlations between photosensors and task area illuminances.

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8. Control systems for indoor lighting in computer simulation: analysis and comparison between software capabilities and between results from two software

In chapter 1, some methods used to predict the daylight contribution and, therefore, the consumption and the energy savings have been described. As well known, indeed, buildings are characterized by complex geometries, materials, boundary situations and climatic conditions.

Many software are able to handle in their calculation several design these parameters in less or more precious way. Several specific simulations software for heating and cooling systems, for ventilation and also for lighting have been developed in recent years in order to predict the performance of the installed system and the consumption. Moreover, for the increasing attention for energy efficient buildings combined with sensors systems to control the environmental condition, in last years, in some of this software have been added the possibility to simulate the control.

Many researchers did comparison among lighting software. The first one has been made in 1998, and before in 1988, by Ubbelohde and Humann (Ubbelohde and Humann, 1998). Of course, in the last years computer capabilities have evolved rapidly and also the systems to simulate are changed and more developed, as already cited.

In the work of Ashmore and Richens (Ashmore and Richens, 2001) a comparison between the LIGHTSCAPE (v3.1.1), RadioRay (v2.0), Microstation/j (v7.1 beta) and ADELINE (v2.0 NT) and with a physical model under two types of artificial sky as a means of predicting daylighting of interior spaces has been carried out. In particular, in this analysis they considered main aspects of operation, physical accuracy of the output, visual quality of the renderings and user interface of the software. The software investigated calculates daylight factors within an average error of 30% of those produced by a physical model. According to the location in the room an estimated experimental error of between 25% and 40\% has been estimated.

Bellia et al. (Bellia et al., 2015) studied the impact of the software's choice on dynamic daylight simulations' results comparing comparison between DAYSIM and 3DS MAX DESIGN. They simulate a simple office located in 4 different cities and exposed according to the 4 main orientations. Authors demonstrated that the results are more or less different. It depends on several factors such as outdoor daylight conditions, window's orientation and considered internal calculation point.

Reinhart et al. compared the results of 3DS MAX DESIGN of daylight measurements in a test room located in Canada with the results of simulations carried out with DAYSIM and 3DS MAX DESIGN. They found that the results are more similar for work plane sensors than for ceiling sensors. In particular, in sunny days, illuminance peaks due to sunlight can be wider for 3DS MAX DESIGN® than for DAYSIM and this is probably due to the different way the two software predict sun position on the sky dome and this influences indoor daylight spatial distribution.

Yu et al. (Yu et al., 2014) used the simulation software RELUX to know energy saving potential from daylighting in an educational atrium building, the Engineering and Science Learning Centre (ESLC), in the University of Nottingham, UK, using various methods. The annual energy saving potential in artificial lighting from daylighting is determined by European Standard EN15193, that is included in RELUX calculation, and also estimated using static climate-based Daylight Factor (DF) method and dynamic climate-based Daylight Coefficient (DC) methods.

Shailesh and Raikar (Shailesh and Raikar, 2010), investigated the interaction between natural and artificial light and the related illumination conditions and energy savings expected in a commercial office building in Mumbai, through simulation did by RELUX. With the latter scheme a saving of 80% can be achieved on energy and operating costs for a period over 25 years. Christakou and Silva (Christakou and Silva, 2008) studied daylighting simulation in the architectural design process, through the evaluation of two simulation tools – ECOTECT 5.5 (as interface to RADIANCE) and RELUX2006 VISION. They took into account user interface, geometry, output, daylight parameters, material description, processing, validation, and user support, from an architect’s point of view. In their paper a large number of simulations in tropical climate, aiming at testing the simulation tools in different daylight conditions in Brazil has been included. The results of this evaluation show a great potential for improving the use of simulation tools in the design process, through a better understanding of these tools.

Shikder et al. (Shikder et al., 2009) compared AGI32, DIALux, RADIANCE and Relux focussing their attention on the accuracy in calculating illumination level and luminaire number for interior spaces and validating them by comparing simulation results with analytical and manual method calculation.

	Ecotect	**DIALux**	**Relux**	**AGI32**
Dxf	√	- [1]	√	√
Dwg		- [1]		√
3ds	√	√	√	
VRML Object	√		√	

[1]Imports as lines only, no 3d surface or object

Table 35. Acceptability of standard 3d formats (Shikder et al., 2009)

Output features	Ecotect + RAD	DIALux	Relux	AGI32
View of working plane with iso-illuminance contours	√	√	√	√
View iso-illuminance contours in scene	√	√	√	√
False colour in camera view	√	√	√	√
Illuminance at a reference point	√	√	√	√
Photorealistic renderings	√	√	√	√
Luminance at a reference point	√	√	√	√
Virtual Reality Markup Language	√		√	
Walkthrough animation (rendered)				√
Luminance and illuminance level with pointer scene or camera	√			
Simulation data manipulation in scene	√			
Simulation data export	√			

Table 35. Comparison of output features of different simulation packages (Shikder et al., 2009)

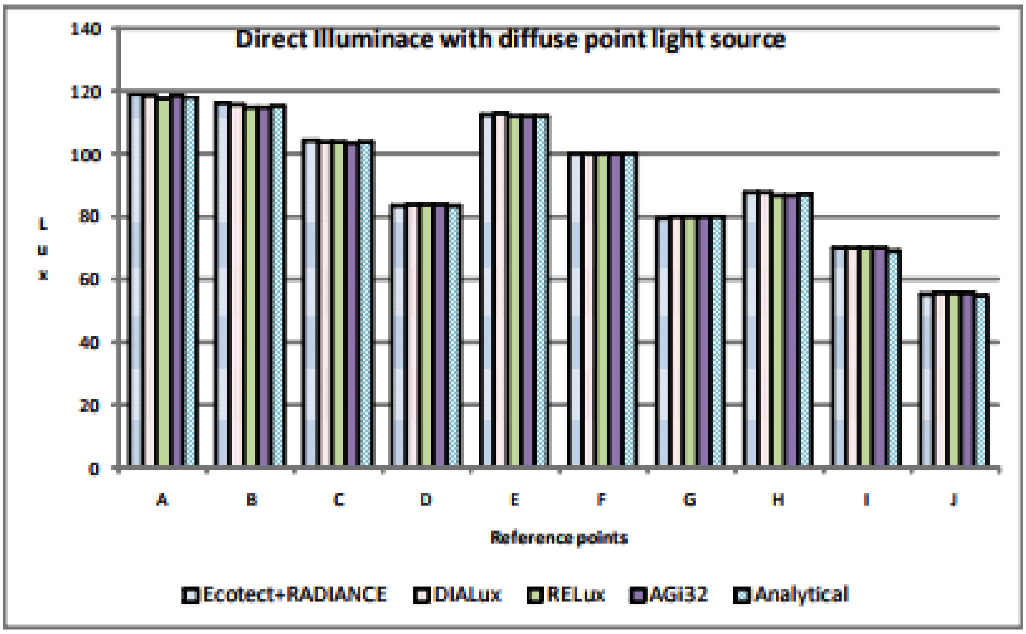
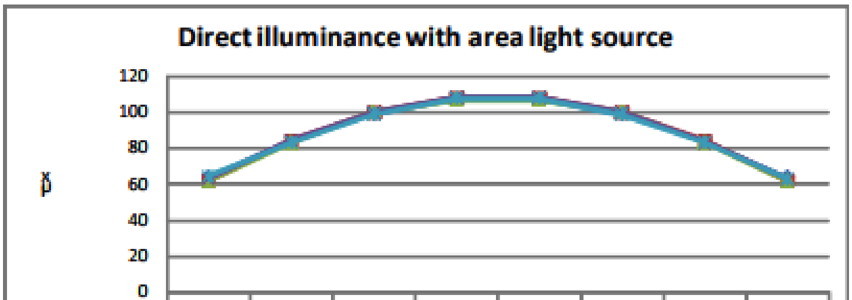


Figure 134. Comparison of illuminace level simulation with analytical calculation by area light source (Shikder et al., 2009)



	G	H	I	J	K	L	M	N
Eco+RAD	63.43	83.55	99.2	107.22	107.22	99.2	83.55	63.43
DIALux	62	84	100	108	108	100	84	62
RELux	62	83	100	107	107	100	83	62
AGi32	63.1	84.2	99.5	107.9	107.9	99.5	83.2	63.1
Analytical	64.2	83.2	98.5	107.6	107.6	98.5	83.2	63.1

Figure 135. Comparison of illuminace level simulation with analytical calculation by point light source (Shikder et al., 2009)

Name of the program	Calculation method	Luminaire number calculated	Luminaire used in design	Configuration	Consider ceiling grid in arrangement
RELux	Average Indirect Fraction	102	110	11x10	No
DIALux	Efficiency Method	Not showing	110	11x10	No
Agi32	Zonal Cavity Method	104	104	13x8	Yes
Manual Calculation	Lumen Method (CIBSE)	100	104	13x8	N/A

Table 36. Comparison of luminaires number calculation between different packages and manual methods (Shikder et al., 2009)

Yun and Kim (Yun and Kim, 2013) evaluated the predictive accuracy of lighting energy consumption carried out by the EnergyPlus program and by the integrated simulation method (ISM), using the Daysim program. They found that simulated lighting energy consumption differs from the measurement, because of the different interior illuminance calculation algorithms in the simulation programs.

Each simulation software is developed with a less or more similar aim, using different algorithms and models and to be used by different people profile specialist, architects, engineers, installers, etc.

The aim of this section it is to analyse if and how the most common lighting simulation software have introduced the control lighting function. To do this briefly review of the main functions and characteristics of most common lighting and energy software is presented.

Finally, the model of the laboratory, application case study of this thesis, has been built with some of the described software and the results, in terms of energy consumption achieved, of the simulation have been compared.
The software below described are:

- Ecotect
- Green Building Studio/Revit;
- Daysim
- Relux;
- Dialux;
- Diva For Rhino;
- Design Builder (Energyplus);
- Pleiades.

8.1. Overview on some existing software

8.1.1. Ecotect

Autodesk Ecotect Analysis (Ecotect Analysis, 2013) is an environmental analysis tool, useful to simulate the building performance in the earliest stages of conceptual design (Yang, 2014). It is a building simulation program introduced by Square One Research. Several functions and settings permit to create an accurate enough building model.
The input final file can be exported in different formats to can be imported in other software as IFC, SBEM, gbXML, Radiance, EnergyPlus, DOE-2 Nist FDS, POV-Ray, VRML HTB2 and ESP-r.

The most powerful calculation engine is available using RADIANCE. It provides illuminance and luminance values over a customized analysis grid, or image output. In particular, it uses RADIANCE to do the lighting analysis using Monte Carlo backward ray tracing tools mainly. The results of this tool are very reliable and for this reason it is used in several scientific studies. Indeed, it has been largely validated (Reinhart and Andersen, 2006). Furthermore, it uses the backward ray-tracing algorithm. Using it, the rays come from the observer, go to the luminous sources and bounce of the walls, taking into account the reflection, transmission and refraction phenomena. It is possible to see the results as colour images, numerical values and contour plots.

RADIANCE is able to simulate complex geometries with flexible reflection and transmittance material properties using a mixed stochastic, deterministic backward raytracing algorithm. It is possible to draw a simple 3D model and select some typology of lamps. Unfortunately, the library is not large (Figure 136), but it is possible to set the candela values in output, the power, the cut-off angle, the luminous flux and the colour.

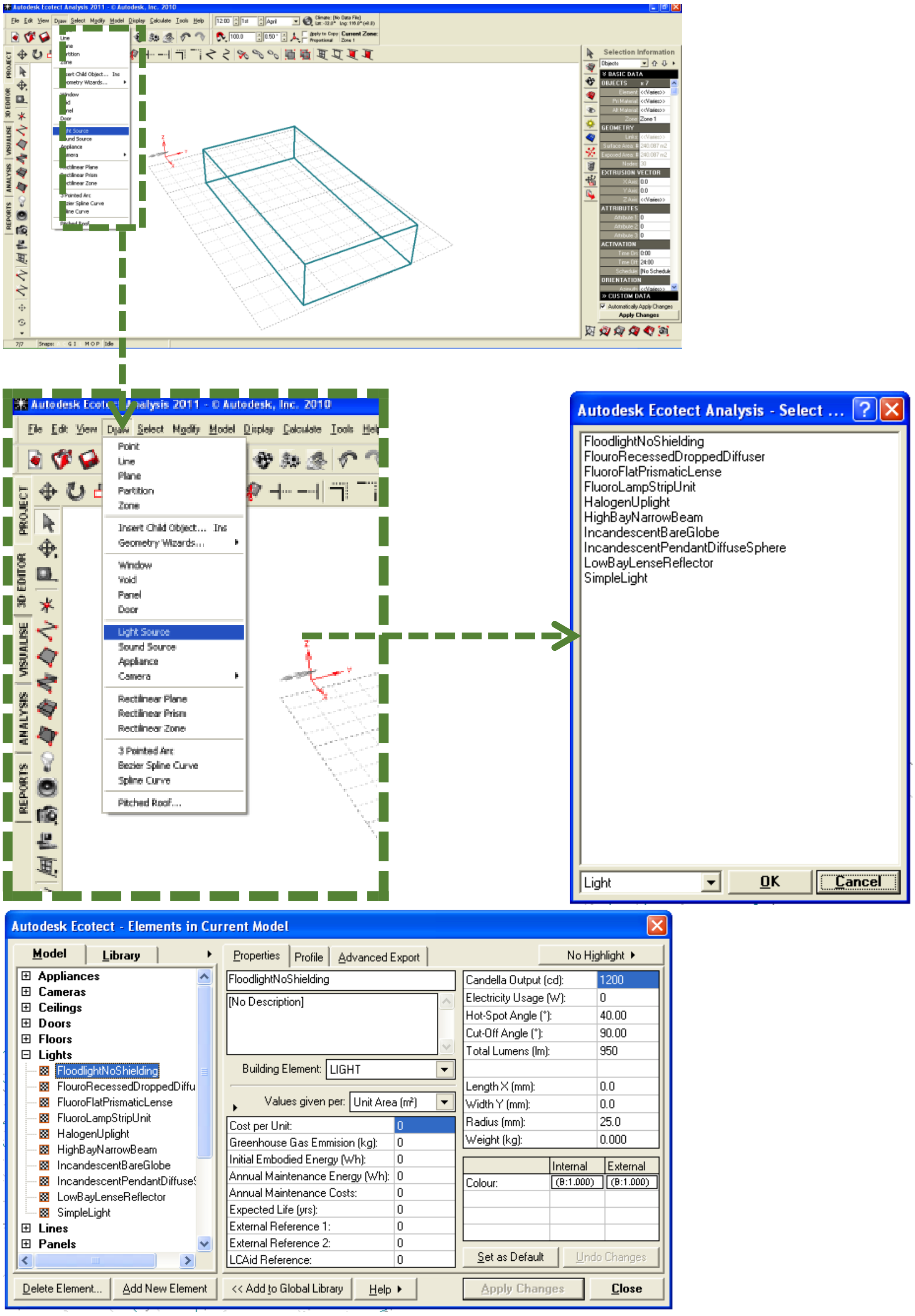


Figure 136. Screenshots of the software Ecotect

About the lighting control, with Ecotect is possible only to set manually the operating schedules and the percentages of power. Nowadays, it is not largely used, but it is a good example of software that performs dynamic simulations including natural lighting contribution and artificial light system.

8.1.2. Green Building Studio

Autodesk team developed other software and tools to perform energy analysis called "Green Building Studio" (Green Building Studio, 2017). One of them is the Energy Analysis feature in Revit. Revit permits a good interoperability of many software able to do different analysis. It is integrated into Revit's massing and building element-modelling environments making it much easier to integrate energy analysis into the workflows. It means that it is not necessary to switch to a different tool for energy analysis.

Working within Revit, it is possible to set parameters, e.g. location and climate information directly in Revit. With the Energy Analysis integration in Revit, it is possible to set other basic, but fundamental parameters: building type, constructions, and HVAC system type.

Regards the lighting control, it is possible to select only a density for the lighting system and use the lighting control functions both according to the daylight contribute or adding a motion detector.

8.1.3. Daysim

DAYSIM (Reinhart, 2011) is a well-validated free tool. As well as Ecotect, it is based on RADIANCE daylighting analysis software. It is a computer-based dynamic daylight simulation program developed by the National Research Council Canada (NRCC). The main aim is to predict the amount of daylight available in a building during the course of the entire year, under changing sky conditions (Reinhart, 2010) Daysim uses the ray-tracing method in the calculation of daylight illuminance. Ray-tracing simulates the performance of the light rays in the space, and calculates the lighting distribution at a certain point. An advantage of ray-tracing is that more accurate results can be derived, even from complex geometries.

It is possible to model dynamic facades systems ranging from standard venetian blinds to state-of-the-art light redirecting elements, switchable glazing and combinations thereof. It is based on a series of models to perform different analysis, such as Annual Illuminance Calculations, Dynamic Shading the Glare Analysis.
Simulation outputs range from climate-based daylighting metrics such as daylight autonomy and useful daylight illuminance to annual glare and electric lighting energy use. DAYSIM also generates hourly schedules for occupancy, electric lighting loads

and shading device status that can be directly coupled with thermal simulation engines such as EnergyPlus, eQuest and TRNSYS.
As well as RADIANCE, DAYSIM is a *simulation engine* meaning that it consists of a series of command line programs that carry out the different simulation steps described above. DAYSIM users may choose from a variety of Graphical User Interfaces as Rhinoceros, SketchUp and Ecotect.

It is able to calculate many factors such as Daylight Autonomy, Continuous daylight autonomy, Daylight Factors, Spatial Daylight Autonomy and the Daylight Factor.
For the Annual Illuminance Calculations analysis, it calculates the daylight coefficient based on the Radiance program, and the sky model developed by Perez et al. (Perez et al., 1990). It uses the RADIANCE backward ray-tracer. The resulting time series of illuminances, luminances, radiances or irradiances at user defined sensors points can be used to derive climate-based daylighting metrics and to calculate annual electric lighting use for different lighting controls based on available daylight.

To perform the Glare Analysis, DAYSIM uses the daylight glare probability metric to predict discomfort glare from daylight for different viewpoint in a scene through the year. Similarly, as for the annual illuminance profiles DAYSIM generates annual daylight glare probability profiles for different shading device settings that in a post-process are then used to predict the setting of a dynamic shading system throughout the year.

To calculate the Electric Lighting Use DAYSIM uses an occupant behaviour model called Lighswitch to predict based on annual illuminance profiles and occupancy schedules how occupants in a space are going to manually operate electric lighting controls and shading systems. Users may thus further specify complex electric lighting systems and controls including manual light switches, occupancy sensors and photocell controlled dimming.

The position of the sensor can be imported from file produced with other software. Moreover, the shading device type can be selected. In case of dynamic shading device model (advanced), it can be imported the position of the shading device “open” and the position of the shading device “close”.

Furthermore, DAYSIM is able also to model spaces with multiple dynamic shading systems such as venetian blinds, roller shades and electrochromic glazing. In spaces with dynamic shading systems DAYSIM automatically generates multiple annual illuminance profiles each with the shading system(s) in a static position throughout the year. In a post-processing step it then uses the Lightwitch model to predict in which state the shading systems is going to be.

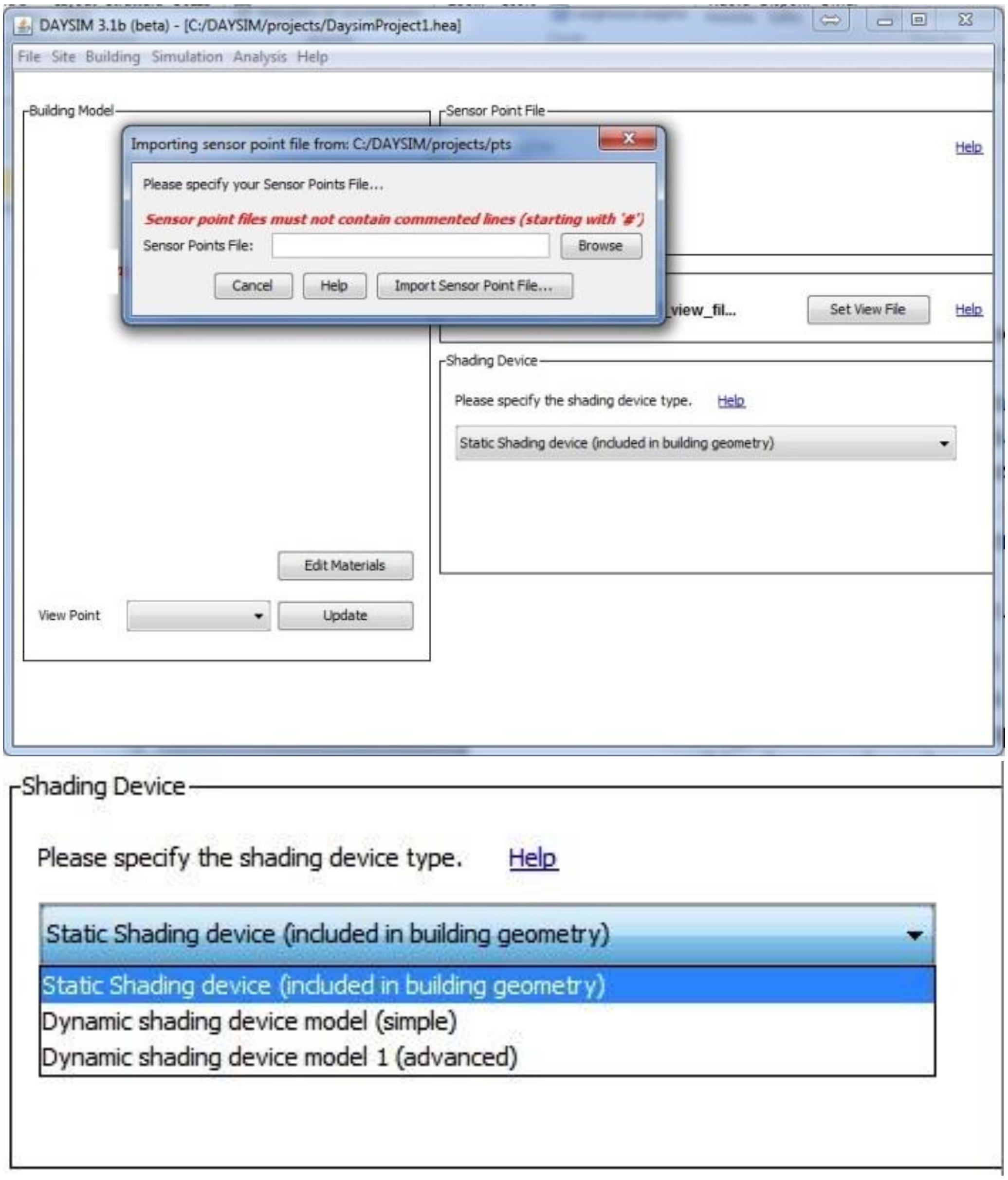


Figure 137. Screenshots of the software Daysim

8.1.4. Dialux

Dialux (V 4.12) (Dialux, 2017) is a free commercial software that permit to install plug-in from luminaires and lamps producers. For this reason, it is a very widely used commercial package in lighting design. It has been developed by DIAL GmbH and it is used mainly to do interior and road lighting simulation. The program provides output in customized pdf format and additionally uses POV Ray to produce photorealistic images. The program permits to calculate natural lighting, artificial lighting or both in indoor or in outdoor scene, achieving results to verify with values suggested by the standards (average illuminance value, minimum illuminance value, maximum illuminance value,

uniformity and glare. It is possible to import CAD file for background and add objects, e.g. furniture or trees. Every luminaire can be added in control groups and dimmed differently for each group and for each scene. In this case, luminaires can be selected among a large database of catalogue downloaded from the luminaires producers' websites. Also, it calculates the Daylight Factor.
About the lighting control, it is not possible to choose the position of the motion sensors and the lighting ones. Adding a ''energy assessment'' and selecting the intended use of the building, it calculates the occupancy hours and, therefore, energy consumption. Moreover, it is possible also to select the manual control lighting or automatic/depend on daylight.
As in RELUX, in DIALUX was implemented the calculation methodology of energy performances of buildings of the EN 15193: "Energy performance of buildings – Energy requirements for lighting" and of the DIN 18599: "Energy efficiency of buildings", being DIALUX a software developed in Germany (as the other member states of the EU, Germany implemented the European directive into national one).
Therefore, for the indoor scene of lighting it is possible to do an energy evaluation for all the room or only for part of it. The scene for the evaluation identifies automatically the properties of the room and the project (geometry, obstruction, location and north alignment) and the all the architectural parts (windows and roof lights). All technical information about luminaries and lamps are transferred as well. DIALUX divide the room in daylit and non-daylit zones.

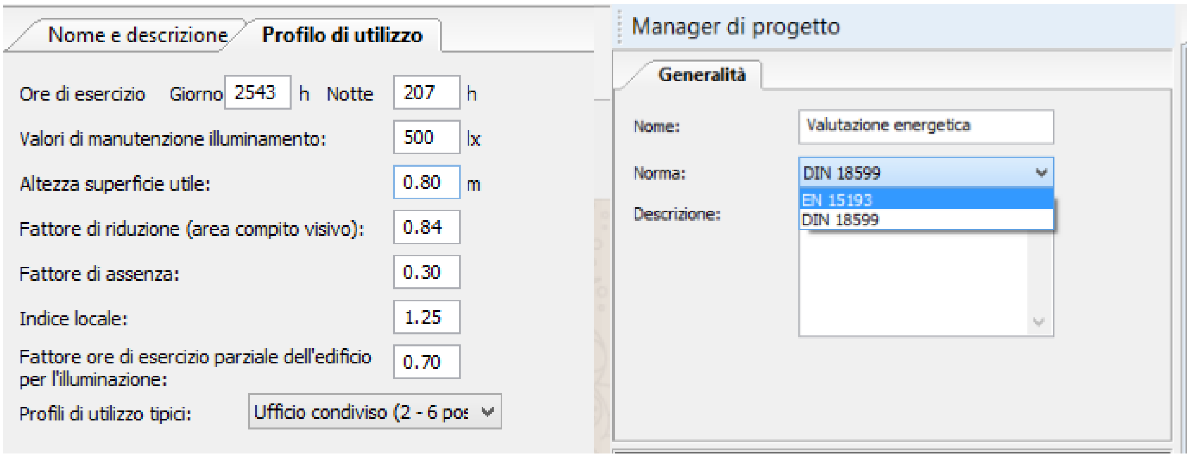


Figure 138. Screenshots of the software DIALUX

With this function the energy demands for rooms can be evaluated, also without doing any lighting planning for them. It is a good method to take into account multiple times during the energy evaluation. The "Absence Factor" and the "Occupancy Control Factor" (EN 15193) can be edited. The parameter "Occupancy Dependency Factor" results from these two parameters by expressions and formulas from the EN 15193, but this parameter can be edited in the usual way. Using the DIN planning the "Absence Factor" is only readable, because it belongs to a utilization profile. The same occurs as well as the “Factor for Occupancy Control”. Indeed, it can be changed by the selection of “With Occupancy Sensor”. For the “Occupancy Dependency Factor” the same holds as with EN 15193. There are a lot of relations and dependencies between parameters.

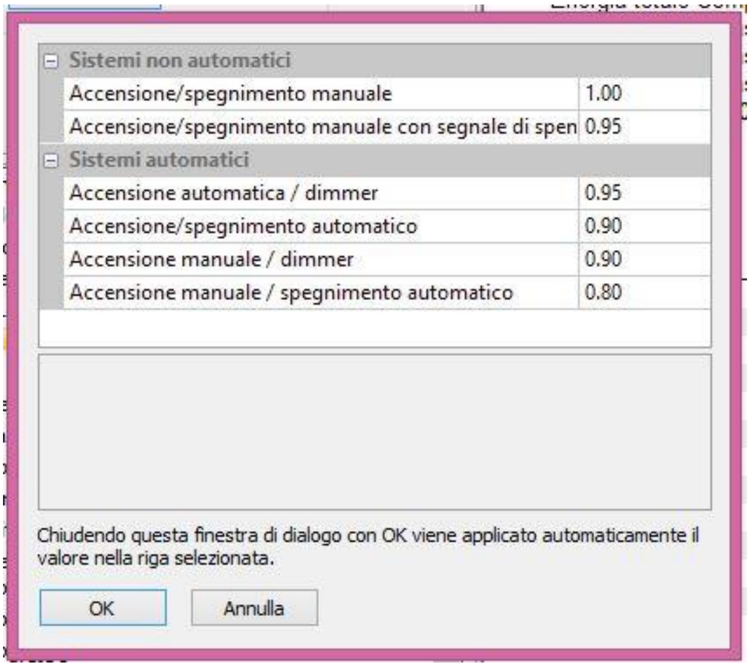


Figure 139. Options for control strategies base on occupancy in DIALUX

The total energy demands for lighting and other energetic characteristics can be calculated and shown for the complete energy evaluation project, for each contained utilization zone, each energy evaluation room and for each assessment zone. Moreover, a subdivision in monthly values is also possible for each object. A complete output can be printed with important parameter requested by several energy performance standards. A version called “Dialux EVO” is available in parallel. More functions are implemented in this version, but the user can select the version based on the aim of the simulation.
In section 4, an alternative method to use Dialux to estimate energy savings, using lighting simulation is shown and described. It has been applied for a case study in Stuttgart.

8.1.5. DIVA for RHINO

DIVA-for-Rhino (DIVA for Rhino, 2017) is a sustainable plug-in that allows users to carry out a series of performance evaluations of individual buildings and urban landscapes including: radiation maps, visualizations, climate-based metrics, glare analysis and LEED IEQ Credit 8.1 Compliance. In particular, it is able to optimize daylighting and energy modelling plug-in for the Rhinoceros. It has been developed at the Graduate School of Design at Harvard University and is now distributed and

developed by Solemma LLC. The new DIVA-3.0 can simulate the IES-LM-83 sDA and ASE standards as well as detailed electric lighting.
Lighting controls can be implemented in any Climate-Based Simulation, with or without dynamic shading devices. After running a climate-based analysis, hourly lighting schedules will be generated, and a false colour visualization of the schedules will be provided.

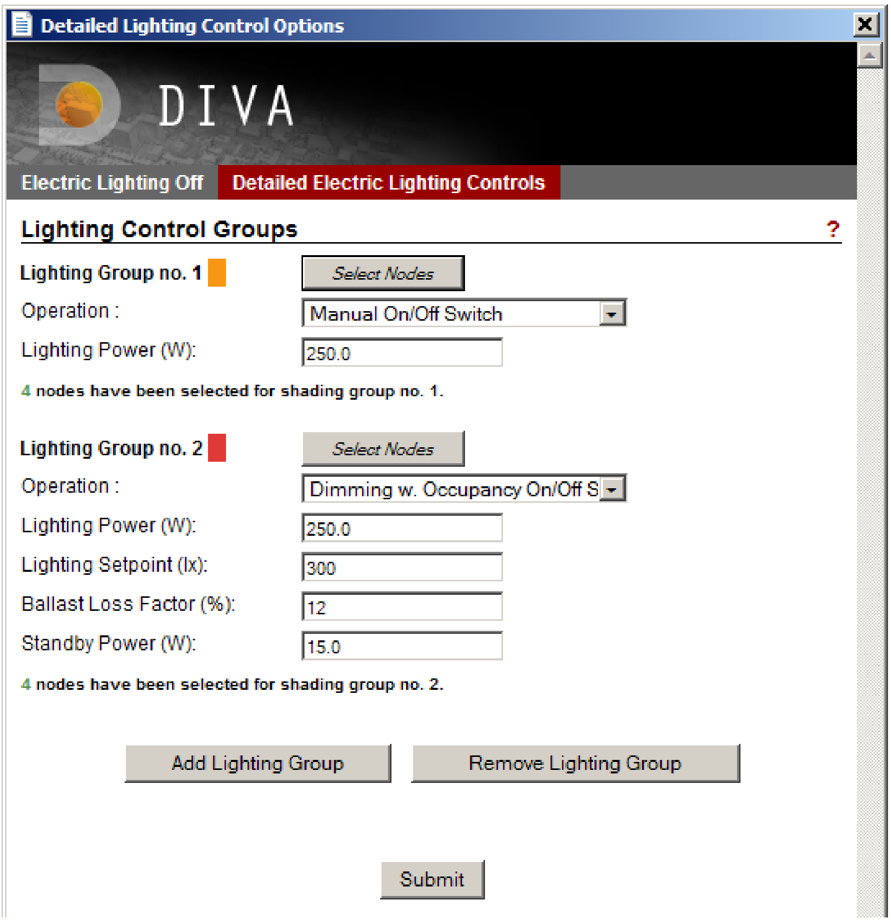


Figure 140. Screenshot of the software Diva

The following control strategies can be implemented:

- Manual Controls: selecting "*Manual On/Off Switch, Switch Off with Occupancy, Switch On/Off with Occupancy"* to mimic the behaviour of a user based on the statistical analysis of the 2002 Lightswitch study. Users occupying a space (defined by selected sensor nodes) are likely to turn off the lights at levels of around 250lx.
- Automated Controls: selecting "*Photosensor Controlled Dimming, Dimming w. Occupancy Off Sensor, Dimming w. Occupancy On/Off Sensor"* it mimics a continuous dimming sensor with a user-defined setpoint, ballast loss factor

and sensor standby power. The locations of sensors are defined by the selected sensor nodes.

- Occupancy Sensors: "Switch Off", it makes sure that occupants do not leave the lights on at night; however, as DIVA/DAYSIM considers conscientious occupants, the statistical likelihood is low.
- Switch On/Off : "Switch On/Off", it maintains lights always on while occupants are in the space. This mode is especially useful when modelling a scheduled continuous dimming system without a physical light switch.
- Standby power refers to small amount of energy drawing by some automatically lighting systems even when the system is "off".
- Ballast Loss Factor represents the Percentage of peak energy used by a dimming system when fully dimmed down.

8.1.6. Design Builder

Design Builder (Design Builder, 2017) is an advanced modelling tools, but with an easy-to-use interface. By default, Design Builder uses the *EnergyPlus* (ENERGYPLUS, 2010) *Daylighting engine, a detailed* routine able to model the control of electric lighting according to daylight illumination levels. Different versions of this software have been developed according to the technicians' typologies (e.g. architects, engineers, assessors, etc.). It integrates set of high-productivity tools to assist with sustainable building design and can be used by many analysis and building simulations in less or more complex tasks. Apart from the HVAC plant, ventilation plant, CFD, cost analysis, etc., it is able to perform daylight simulation.
The function of lighting control has been implemented and it can be used in zone with windows. Indeed, it is possible to control the electric lights according to the availability of natural daylight. Setting the illuminance setpoint, the software calculates the illuminance level and so how much the electrical lighting can be reduced according to the daylight illuminance level, the typology of lighting control system selected and the fraction of the zone controlled. Larger spaces can be divided in 2 Lighting Areas because they could need more sensors and also zone with different activity areas. In this case the setpoint can be different and so two different lighting sensors are necessary. The calculations done in the "Perimeter Area", defined as the zone that are close to a window, to a fixed distance, of 6 m, from a normal direction to the perimeter. Users can, by the way, create a separate thermal zone to model the different lighting and solar conditions in the perimeter area. The sensor is always located in the working plane which, by default, is 0.8 m above the floor. Different kinds of regulation are available. The Linear control regulates the luminous flus from the maximum power to the minimum light output as long as the daylight illuminance increases. The "Minimum output fraction" for linear control type, is the lowest lighting output the lighting system

can dim down to, expressed as a fraction of maximum light output. "Linear/off control is the same as Linear control except that the lights switch off completely when the minimum dimming point is reached". With the "Stepped control" the lamps are switched on or off, according to the illuminance of daylight, in steps. Design Builder simulates also the automation of shading systems according to the discomfort daylight glare.

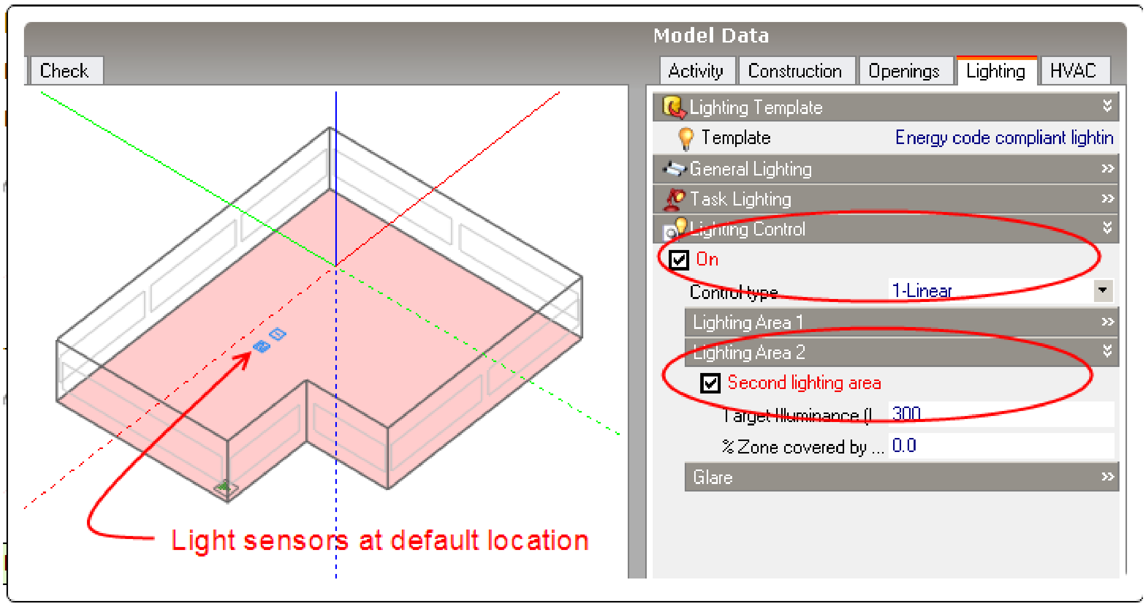


Figure 141. Screenshot of the software Design Builder

The software can generate as output a 10 x 10 grid of additional daylighting reference points that can be saved as .cvs file and imported into a spreadsheet program for rapid visualization.

8.1.7. Pleiades

SketchUp 3D models' files can be imported or built in PLEIADES (Pleiades + COMFIE, 2017), using large databases with several options. The interface is friendly, but the 3D model is not visible.

Adding *COMFIE*, a multizone calculation engine developed by ARMINES/Mines ParisTech, it can run dynamic energy simulations of buildings, taking into account heating, cooling and ventilation systems, natural ventilation, PV generation, ground-air heat exchanger, artificial lighting also. Also, it computes indoor natural lighting and check the compliance with light target of HQE and BREEAM labels. About the lighting control, it is possible to select the buildings typologies, the different illuminance request, W/m^2 request, and occupancy schedules and lighting management. It is not possible to select the lamps and luminaires typologies and to choose the position of them.

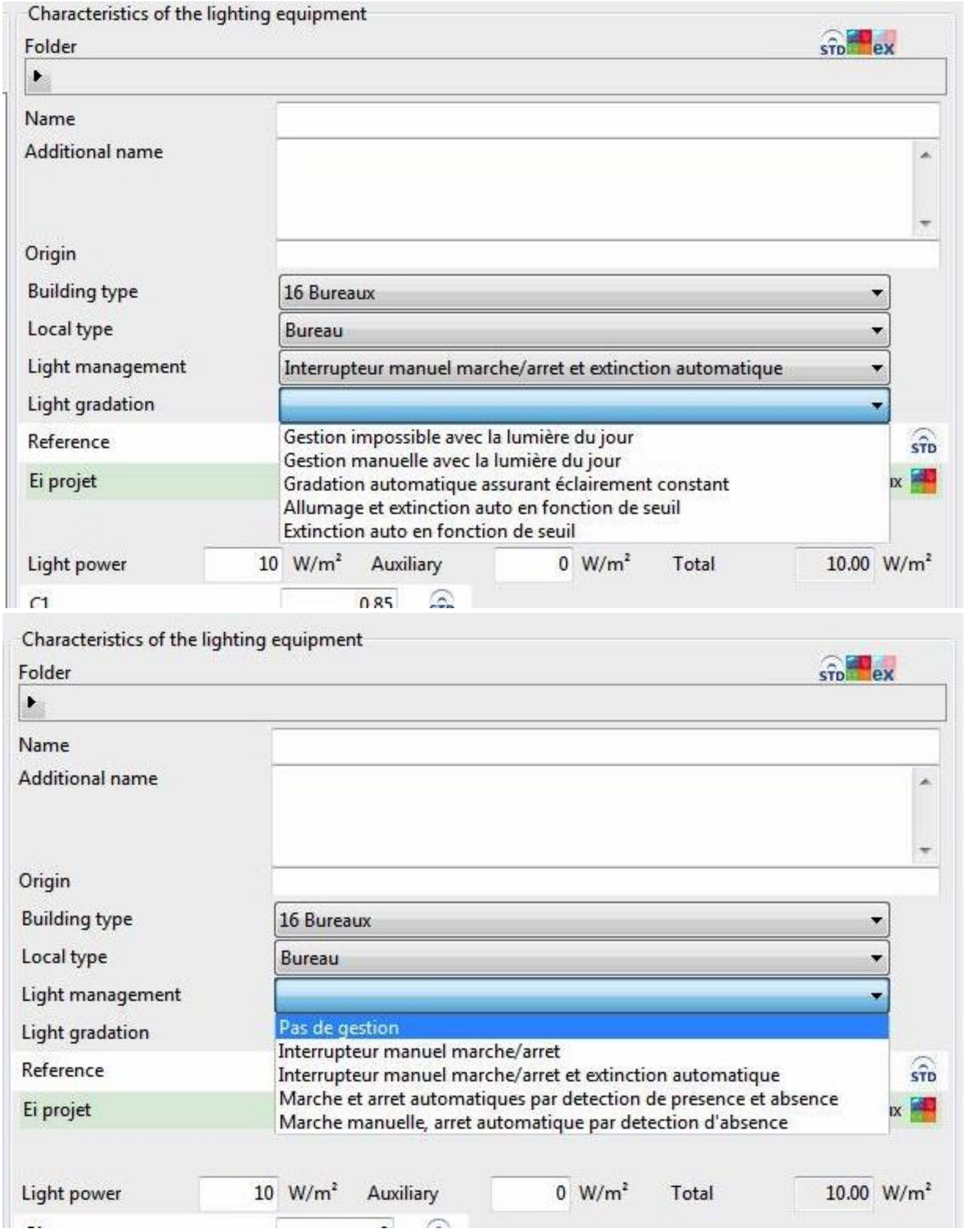


Figure 142. Screenshot of the software Pleiades

8.1.8. Relux

RELUX (Relux, 2017) is a freeware software developed by RELUX Informatik AG in Switzerland. It is free because it is supported by a number of luminaire, sensor and lamp companies. It is very user-friendly. It can be used both for interior and exterior and uses average indirect fraction methodology for calculation and can produce photorealistic image output by RADIANCE through Relux Vision interface. It can calculate daylight, artificial lighting and the combination of artificial and daylight, using position and orientation command, setting the hour and date and choosing the CIE sky conditions and if the lighting is direct, partially direct or indirect. RELUX gives the possibility to set also visual design elements as materials properties, furnishing and colour.

The rendering allows physics rules and are based on photometric data developed with radiosity process. Adding the Vision plug-in, based on RADIANCE, it is possible to add many objects and characteristics to make the model realistic. 3D model can be drawn and the luminaire and lamps typologies can be chosen in a large library or downloaded from many commercial website of luminaires producers. They can be added to the model in exact location of the room or of the external scene. Maamari et al. validated, within IEA SHC Task 31, Reluxe and Lighscape, for 32 different scenarios (Maamari et al., 2006). Using a feature of RELUX, it is possible to import directly from the manufactures' database the plug-in of the selected product.

About the lighting control, it is possible to select motion sensors from catalogue of producers online and choose exact position. It is not possible to do the same with lighting sensor.

But with RELUX Energy the yearly energy consumption can be calculated involving the application of occupancy sensing, automatic switching and dimming according to the availability of daylight.

Daylight harvesting systems are typically designed to maintain a minimum recommended light level. All daylight-harvesting systems use a light level sensor to detect the prevailing light level. The signal from the sensor is interpreted by a lighting control module in the electric lighting system and the electric lighting can be reduced, if appropriate. If the electric lighting is dimmable, then the artificial lighting may be continually reduced in proportion to the amount of daylight available. If the electric lighting is on-off only, then the electric lighting must remain on at full output until daylight can meet the entire recommended light level for the space.

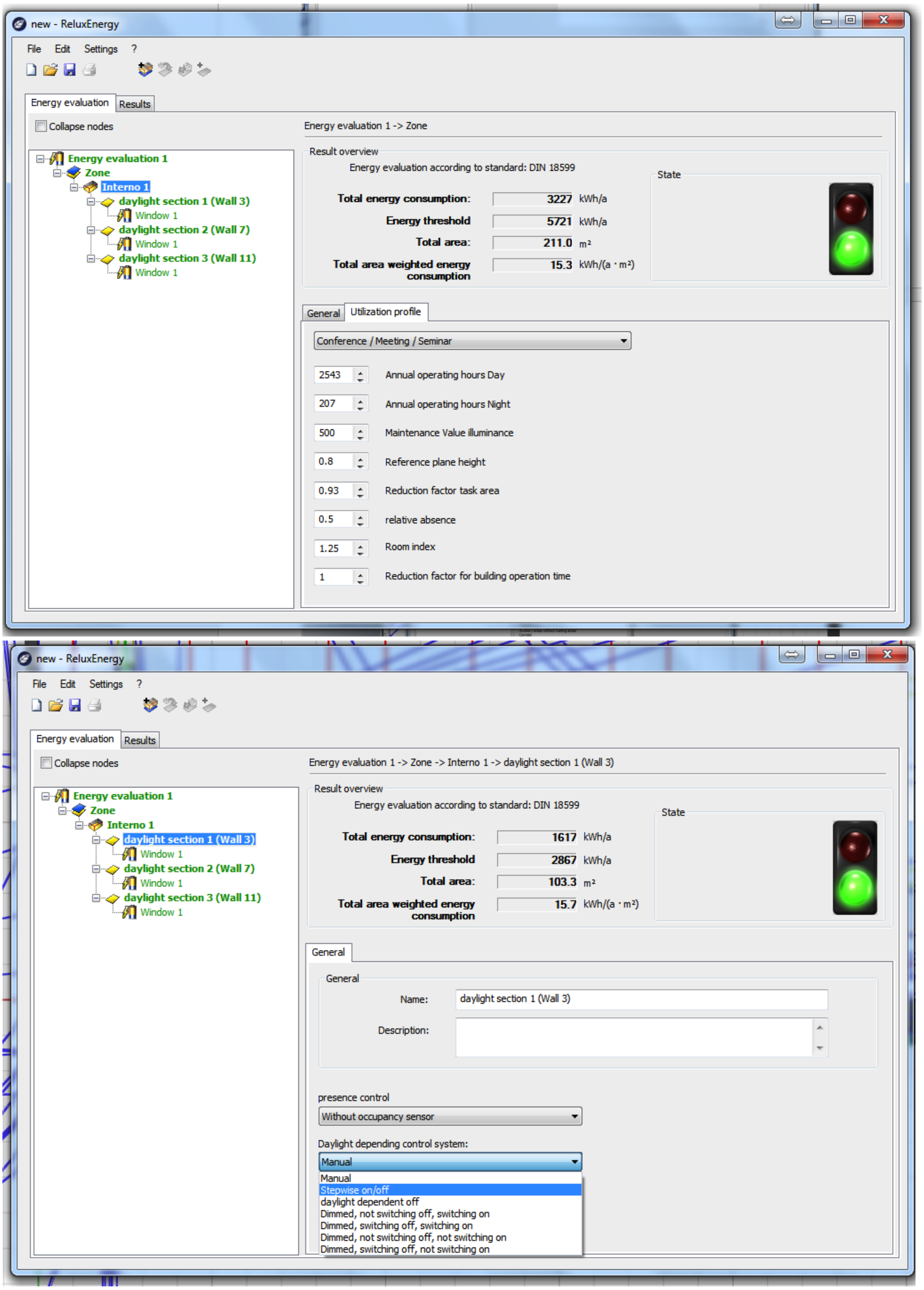


Figure 143. Screenshots of the software ReluxEnergy

It is possible to select or the standard DIN18599 or the EN15193. Each standard gives the possibility to choose different options of control strategies. Regards first standard, it is possible to carried out the calculation with or without occupancy sensors. Once chosen one of these options, several strategies based on the daylight control can be selected:

- Manual;
- Stepwise on/off;
- Daylight depend off;
- Dimmed, switching off, switching on;
- Dimmed, not switching off, not switching on;
- Daylighting dimmed, switching off, not switching on

Regards the EN 15193, the options that can be selected are:

- Manual;
- Manual+automatic sweeping extinction signal;
- Auto on-dimmed;
- Auto on/off;
- Manual on/dimmed;
- Manual on/auto off.

While the options for the daylight depending control system are:

- Manual;
- Automatic, Daylight dependent.

8.1.9. TRNSYS

TRNSYS (TRNSYS, 2017) (Thermal Energy System Specialists report) is a software dedicated to the simulation of dynamic systems, developed by the Solar Energy Laboratory (SEL), University of Madison in the United States. It is able to perform dynamic simulations of the thermal behaviour of a mono or multi-zone building also following hourly consumption (heating, air conditioning) or production (solar panels) annual energy facilities of a building. For this reason, it must be underlined that lighting simulation and control function have been introduced mainly with the aim to know the heat gains due to the artificial light (Duffy et al., 2009).
The new TRNSYS 18 integrates dynamic daylight simulation based on DaySIM into the TRNSYS multizone building model Type 56. The 3-D geometries of the existing building model are used to calculate illuminance levels for sensor points. The daylight model as well as the thermal simulation consider various shading configurations, which

can be controlled by different strategies. As in actual building environments, the newly implemented daylight simulation determines the artificial lighting control according to the available daylight illuminance. An on/off hysteresis control, a dimming function and a combination of both can be chosen to regulate up to three areas per zone. TRNSYS works compiling different linked modules (called "types") to simulate each part of the simulation. Up to version TRNSYS 17 the following types regarding lighting control were available: 726, 727, 728.

The TYPE 726 has been developed to calculate "PROPORTIONAL LIGHTING CONTROLLER". The Tess Component library describe it as follows:

"This component returns a control signal between a user defined minimum value and 1 that is related to the value of an input signal at the current time step and compared to user defined minimum and maximum values. The component can be used to simulate an ON/OFF controller by setting the minimum and maximum set point values equal to one another. The controller differs from other proportional controllers in that it generates its maximum signal at the lower set point and its minimum signal at its upper set point. In this regard, the output is inverted from that of a typical controller".

TYPE 727 can be used to simulate the "CONTINUALLY STEPPED LIGHT FIXTURES".

"This component is intended to model one of many control strategies for reduced energy usage lighting. It takes two control signals and is only ON if both control signals are ON. One of the two control signals is digital, the other an analog value between 0 and 1. The light supplied by the fixture (and its corresponding heat gain) are stepped linearly with the value of the analog control signal. In a typical application, the digital control signals might be connected to the occupancy of a room, while the analog signal is connected to a daylight level sensor. The model also features an automatic delayed shut off as would be appropriate to model lighting connected to a motion sensor. 19 When the digital control signal drops to zero, the lights stay on (and continue to draw power and create a heat gain in the space) for a user settable amount of time."

Finally TYPE 728 is used for MULTIPLE POWER LEVEL LIGHTS.

"This component is intended to model one of many control strategies for reduced energy usage lighting. It takes two control signals and is only ON if both control signals are ON. In a typical application, one of the control signals might be connected to the occupancy of a room, while the other is connected to a daylight level sensor. The model also features an automatic delayed shut off as would be appropriate to model lighting connected to a motion sensor. When one of the two control signals drops to zero, the lights stay on (and continue to draw power and create a heat gain in the space) for a user settable amount of time. Finally, users may specify the number of power levels at which the lighting may be operated. Both power draw and heat gain are correspondingly stepped back."

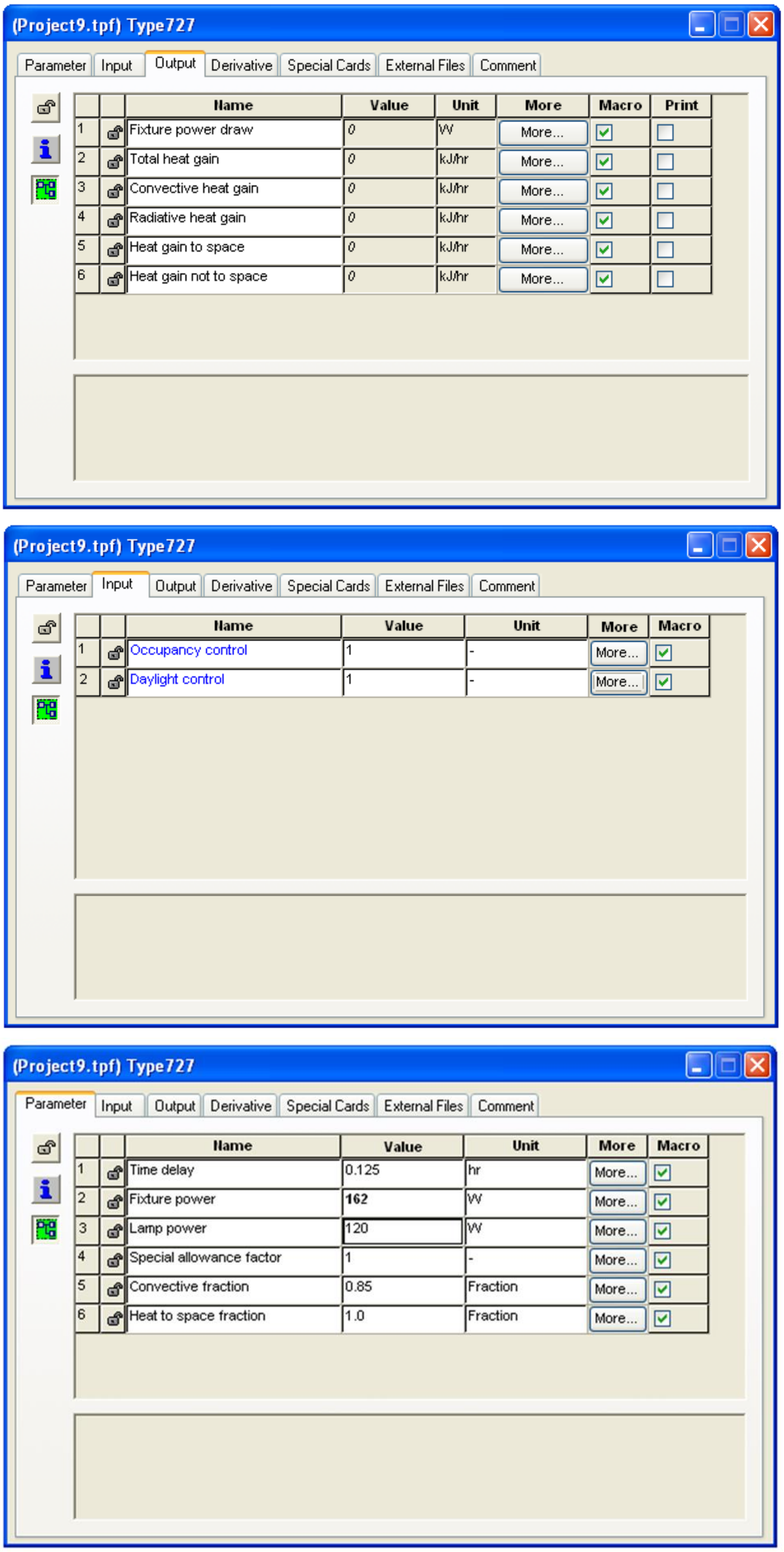


Figure 144. Screenshots of the software Trnsys of the Type 727 functions

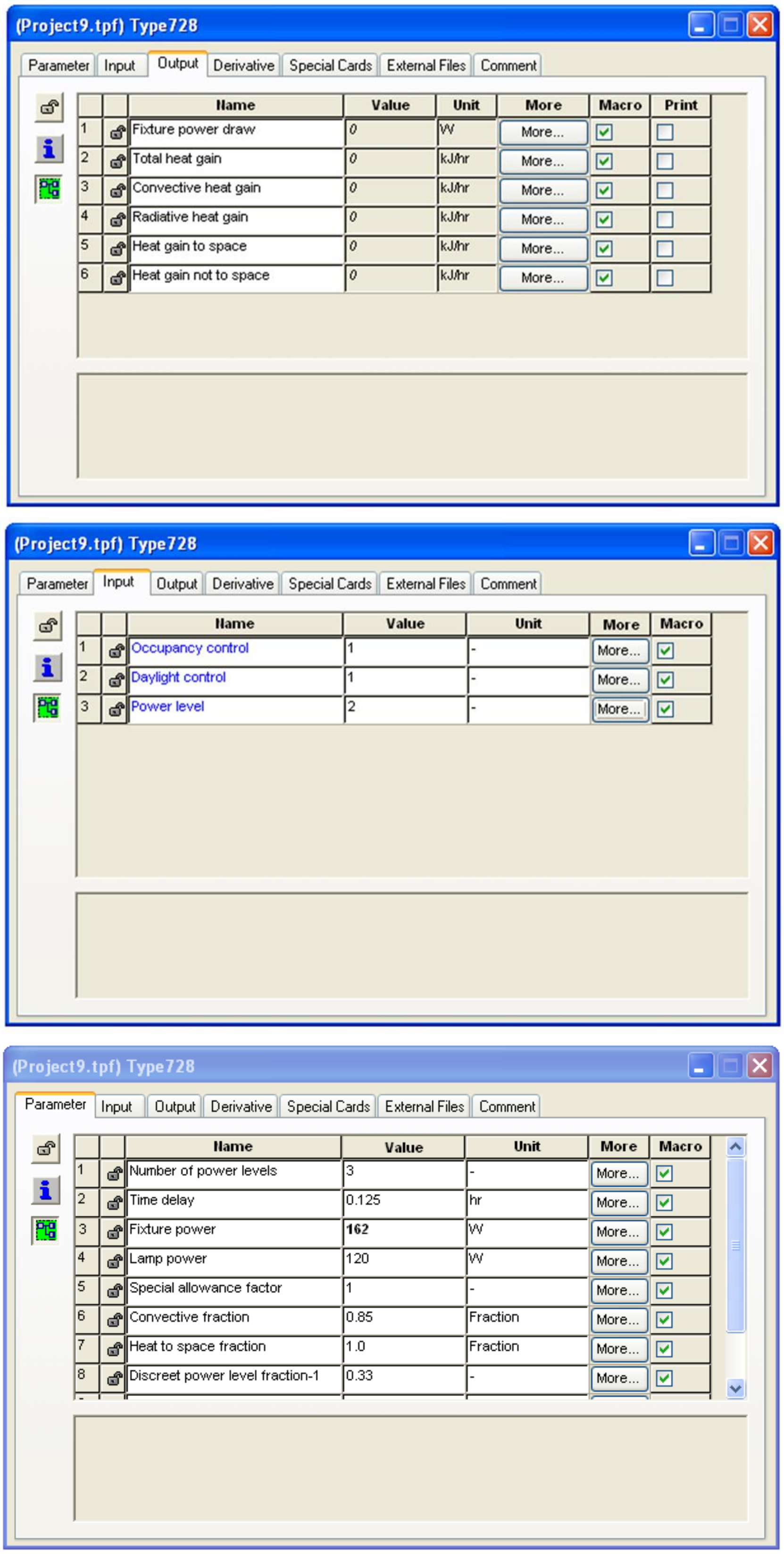


Figure 145. Screenshots of the software Trnsys of the Type 728 functions

8.1.10. Visual

The Visual Professional Edition (Visual, 2017) is a lighting analysis tool for interior and exterior scenes. The radiosity theory is used to provide efficient and highly accurate analysis of complex architectural spaces. It is possible to import PDF, Google Map images and DWG/DXF for background, to draw and model geometries, to import or export schedules.
It used Autodesk's RealDWG conversion library to select complicated drawing files. With Illuminance Recommendation Tool the luminaires typologies can be selected in the database of IES illuminances.
The daylight package adds the ability to cut window openings, select location, sky condition and time of day. The default sky uses measured sky conditions as recorded by local weather stations.
The *Interior Tool* used the principals of the lumen method to calculate the number of luminaires needed to meet an average illuminance on the workplane calculation surface (for an enclosed rectangular room). Also, user can use the Interior tool to determine the illuminance achieved by a specified lighting power density or luminaire quantity.
The *Floodlight Tool* can calculate the number of luminaires required to illuminate a surface based on user criteria. The tool can also be used to find the best. A typical scenario for using this tool would be using recessed wallwash luminaires to light an interior wall.
Using the *Economic* tool, it is possible to calculate the cost of the project, the lifecycle, the accumulated present value and the payback time, selecting the number and the typology of the luminaires to install or to replace, the occupancy hours, the total power installed, the lifetime hours of lighting sources, the hours of installation time.
About the lighting control, the type of lighting control can be chosen among the following options:

- No control system;
- BiLevel Switch;
- Daylight;
- Dusk to Dawn;
- Lumen Management;
- Manual Dimming;
- Occupancy;
- Energy Reduction;
- Time Reduction.

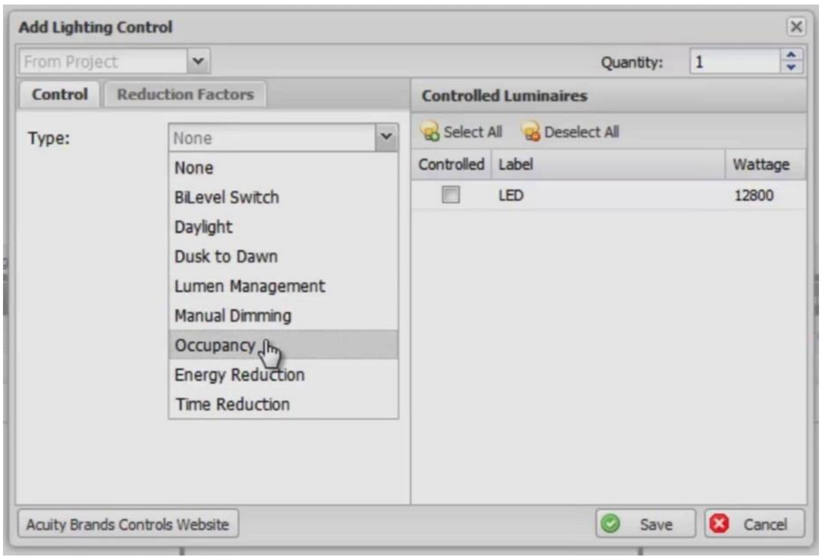


Figure 146. Screenshot of the software Visual

Unfortunately, also in this case is not possible to choose the sensor typology and position.

8.2. Comparison between software functions

As a synthesis of the description of these software, the following table reports their main characteristics. This table includes also information on other software not previously mentioned.

Software	**Building 3D**	**Daylight**	**Artificial light**	**Algorithms**	**Luminaires position**	**W/m²**	**DF**	**Sensor position**	**Lighting control**	**Standard**	**Energy consumption**
Radiance	Sketchup, Autocad, Ecotect	Y	Y	Ray-tracing	Y	Y	Y	Y	Y		Y
Daysim	Y	Y	Y	Ray-tracing	N	Y	Y	Y	Y		Y
Relux and Relux Energy	Y	Y	Y	Radiosity	Y	Y	Y	Y	Y	Y	Y
Visual 2012	Y	Y	N		Y	Y	N	N	Y		Y
Pleiades	N	Y	Y		N	Y	N	N	Y	Y	Y
Dialux	Y	Y	Y	Radiosity	Y	Y	Y	N	Y	Y	Y
Ecotect	Y	Y	Y	Ray-tracing	Y	Y	Y	N	N		Y
Design builder	Y	Y	Y	Ray-tracing	N	Y	Y	Y	Y		Y
Energyplus	Y	Y	Y	Ray-tracing	N	Y	Y	Y	Y		Y
Diva for Rhino	Y	Y	Y	Ray-tracing	Y	Y	Y	N	Y	IES-LM-83 ASE	Y

Software	Building 3D	Daylight	Artificial light	Algorithms	Luminaires position	W/m²	DF	Sensor position	Lighting control	Standard	Energy consumption
Trnsys	Y	N	N		N	Y		N	Y		Y

Table 37. Comparison between main functions of the software

8.3. Comparison between results of some software with data measured at DEIM lab

Two of the above-described software have been here tested in order to compare the results: Dialux and Daysim. They follow different approach on the consumption calculation since they have different aims. It must be remembered that the first perform static lighting simulation and calculate the electrical consumption implementing the standard EN15193 or the DIN18599.

A room model has been implemented with the same characteristics, reflection coefficients of the surfaces and the same lighting system installed at the DEIM laboratory located in Palermo (see section 5).

Regarding the model implemented for Dialux, as already said, it is possible to model the 3D directly in this software and set location and materials. While, in order to simulate the room with Daysim, the model has been developed using Sketchup (Sketchup software, 2017) and exported with the Daysim plug-in.

Table 38 regards the energy consumption calculated by the two software setting the following control strategies:

- Manual;
- DLCs system;
- Occupancy off;
- Occupancy on-off;
- Occupancy dim off;
- Occupancy dim on-off.

	Manual			Occupancy off+Dim			Occupancy on-off+dimm			DLCs			Occupancy off			Occupancy on-off		
	Dialux		Daysim	Dialux		Daysim	Dialux		Daysim	Dialux		Daysim	Dialux		Daysim	Dialux		Daysim
	EN	DIN		EN	DIN		EN	DIN		EN	DIN		EN	DIN		EN	DIN	
Occupancy [h]	2500	2543		2500	2543		2500	2543		2500	2543		2500	2543		2500	2543	
Activation [h]			2419			1892			1881			2419			1881			1892
ELEC [kWh/a]	305	168	214	109	101	107	290	109	240	136	129	171	244	146	134	275	146	300
Average consumption [kW_{ave}]	0.12	0.06	0.09	0.04	0.04	0.05	0.12	0.04	0.13	0.05	0.05	0.07	0.10	0.06	0.07	0.11	0.06	0.15

Table 38. Comparison between results calculated by DIALUX and Daysim

It is possible to see that the results are very similar in same cases (e.g. in “Occupancy off+Dimming” case), but very different in other cases (e.g. in “Occupancy off” option). It is because first of all they used different calculation algorithms in the simulation programs. Dialux calculation is more "closed". Indeed, with Daysim it is possible to set more parameters.

Regarding the automation linked to the daylight contribution, using Daysim, the user is able to set the Sensor Units. This means that it is possible to indicate the illuminance sensors that are part of the occupant's workplane, for the lighting simulation, but as well to specify the sensors location that are used for the electric consumption calculation.

Furthermore, the standard EN15193 implemented in Dialux sets the delay time at 5 minutes, while Daysim gives the possibility to change it. As seen in chapter 2, the delay time influence the consumption. Regards the occupancy schedule, it can be or imported in Daysim or selected one of the default proposed options.

Moreover, in output data Daysim specifies the number of hours when the luminaires were switched on and the effective hours of workplane occupancy. The calculation performed by Dialux used a default number of hours suggested by the standard. It is possible to change the number of hours, but only setting the total amount and not defining a detailed occupancy schedules.

In literature comparisons between the two standards implemented in Dialux are presented. The two standards take into account different occupancy time and many different parameters, as it is possible to see also looking at the results of this study. In general, indeed, the calculation performed by the standard DIN are lower.

8.4. Final remarks

This analysis shows that many simulation software included the calculation of the energy consumption for lighting taking into account different control strategies. Each software can be developed using different algorithms and with different aims. Furthermore, in some of them, it is not possible to set some important parameters that can influence the electrical consumption. For this reason, the results calculated by different software can be very different. Furthermore, consumption calculated using the same software (i.e. Dialux), but using methods proposed by two different standards can be very different. It is necessary an accurate selection of the tools to be used and it is necessary, as well in this case, to analyse critically the results.

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9. Analysis of the actual performance of daylight-linked control systems

Many methods for the assessment of the performances in terms of comfort and energy of the automated control systems and, in particular, of the control systems for lighting have been largely presented in previous sections. They have been applied and commented in some cases study and in other works.
On the other hand, the identification of crucial parameters that can influence their operation has been presented extensively. It is well demonstrated that DLC’s hardware and software configuration and, as well, inaccurate commissioning do not always allow a perfect execution of the desired tasks while, in general, the installation procedures follow generalized guidelines. Therefore, the systems could not work as expected. Also, it is well known that potential energy saving is related specifically to the variability of the light in environment.

As already explained, the aim of this thesis is to analyse design, installation, commissioning and operation steps and aspects that can influence the efficacy of the daylight linked control systems. In previous chapters, the study has been focussed on pre-analyses and on design steps. In this section, a method based on a new set of indices (Bonomolo et al., 2017) (Beccali et al., 2017) aimed to assess the actual performances of daylight-linked control system during operation is presented. These indices make possible the evaluation of the efficiency of an installed automation system for lighting control either in terms of energy consumption or the ability to maintain visual comfort targets. This assessment can be made through a set of scheduled measurements. It allows analyse the actual system operation that very often is far from the results derived from simulations or assessed by frequency indices that assume generally that the system is running in ideal ways in average conditions. For this reason, the method can be utilised in the commissioning stage or in periodic or ex post monitoring of system performances. The efficacy and reliability of these indices have been tested by using a large set of data collected during an experimental campaign in a monitored space equipped with commercial DLCs. Dealing with visual comfort analysis, these indices take into account the excess and the deficiency of illuminance over time with respect to a target illuminance set point that a lighting system should provide and make possible a critical review of the related energy consumption.

Data have been measured in the DEIM laboratory set up (described section 5) where two commercial daylight-linked control systems have been installed. Moreover, they have been tested for different end-uses, operating schedules, control strategies (dimming and ON/OFF) and, of course, daylight conditions. Finally, useful relationships between system performance and environmental conditions have been found.

9.1. Indices for the performances evaluation

As previously commented, energy consumption depends on DLCs characteristics, on settings and on daylight availability, which varies over the time. In order to appreciate this last factor, let's define the Artificial Light Demand (ALD) (Eq. (41)) as the sum, during the operation time, of the differences between the illuminance target value on task area (E_{set}) and illuminance due to available natural light (E_{nat}), when this one is lower than the set point itself, times the hours:

$$ALD = \sum_{toperation} (E_{set} - E_{nat}) \cdot \Delta t \, if \, E_{nat} < E_{set} \left[lx \cdot h \right] \qquad (41)$$

A similar approach has been utilised also by other authors as Bellia et al. (Bellia et al., 2015) who quantified the annual electric light requirement, obtained as the sum of all hourly values calculated during the year, and as L. Xu (Xu et al., 2016) et al. who determined the daylight utilization potential. Another simplified approach proposed by De Boer and Mergenthaler (de Boer and Mergenthaler, 2011) is the calculation of the relative luminous exposure: to assess the impact of daylight on indoor lighting conditions and the resulting energy needed for supplementary lighting, the (relative) usable luminous exposure is used as a time-integral assessment parameter. It is clear that for a given set point and a given period (for instance a day), ALD can change according to the sky conditions or, eventually, windows and shutters configurations. Figure 147 shows this concept for two different days.

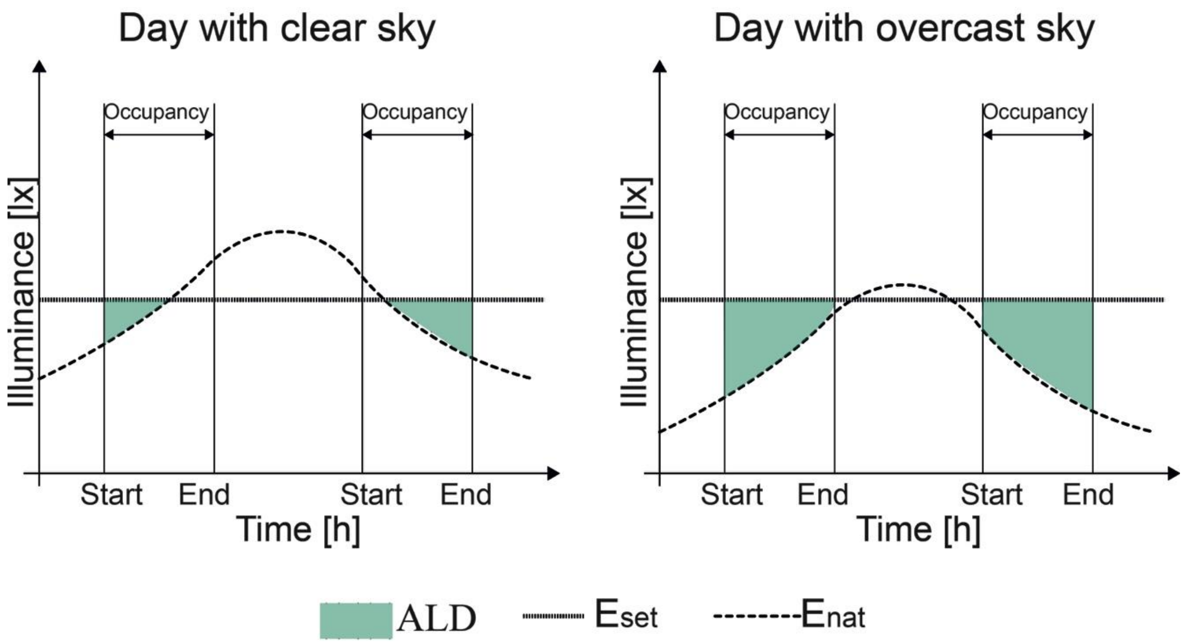


Figure 147. Conceptual scheme of ALD for two different days

As shown in chapter 1, a similar method to assess the demand of artificial lighting is based on the calculation of the availability of natural lighting for a target value of illuminance by the means of the well-known Daylight Autonomy (DA) (Reinahrt et al., 2006) and continuous Daylight Autonomy (cDA) (Rogers, 2006).

Anyway, it must be noted that ALD is conceived to account for time integral on the area of the graph where the line of measured natural illuminance is below the illuminance target, both referring to the task area. As far as the DA is a frequency calculation of time step when $E_{nat}>E_{set}$, and the cDA accounts for partial credits in illuminances below the thresholds, they are both not able to give the same information of ALD, also in the case they are calculated from measured data. If we compare calculated values of DA (or cDA) and ALD, we can observe that many values of DA are associated with very different daylight demands measured by ALD. Figure 148 shows this comparison for some scenarios.

A similar consideration can be made for cDA, which, anyway, provides more information about daylight deficiency having a relationship with ALD, which is quite good. The latter one has the characteristics to be measured in lx·h, allowing for a specific calculation of energy consumption (i.e. kWh/lx·h).

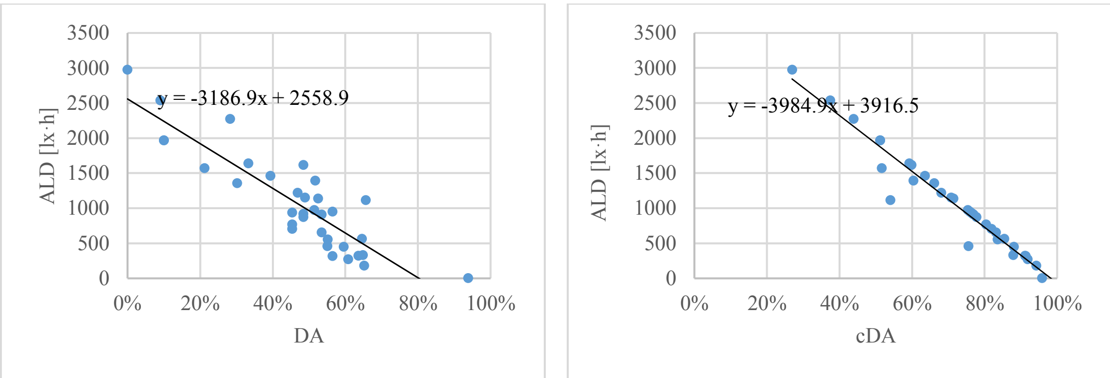


Figure 148. Comparison between DA, cDA and ALD calculated from measured data set

The normalisation of energy consumption can be useful in comparing different lighting system which would consume different amounts of energy in the same day (same ALD) according to their lighting efficiency and ability to control the illuminance on the task area over time.

Moreover, this is true also for comparing the same DLCSs but with different hardware-software configurations (e.g. photosensors position) and calibration (Doulos et al., 2017). To this aim, we can define the Energy Ratio of Illuminance (ERI) (Eq. (42)) as the ratio between the electricity consumption (ELEC measured in Wh) and ALD (lx·h) as follows:

$$ERI = \frac{ELEC}{ALD} \quad \left[\frac{Wh}{lx \cdot h}\right] \tag{42}$$

It is possible to have a metric of this item. If it is assumed that there is a direct proportional relationship between the provided illuminance over the time (lx·h) and the electricity consumption (Wh) by a factor *k* (Wh/lx·h), the latter can be intended to be a characteristic of the observed system and as well as a target value for the ERI.
In an ideal system, consumption will be strictly proportional to the ALD, while in a real system measured consumption could result higher (or lower) than *k*·ALD and ERI will have a different result from *k*.

Figure 149 shows an example of the calculation of this factor made by data measured in absence of natural light for different lamps dimming factors. In particular, for the tested system, the k value is 0.246 Wh/lx·h.

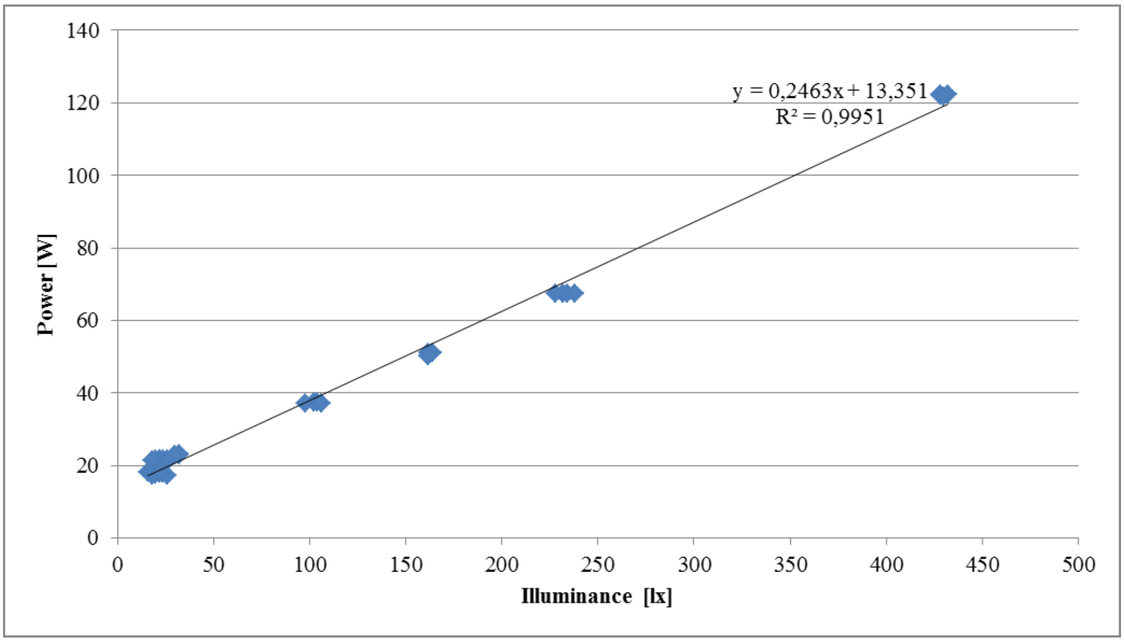


Figure 149. Measured power and average illuminance on the task area

Obviously, the line is shifted along the vertical axis by a value correspondent to the absorbed power in stand by operation.

When a system is not able to guarantee for all the operation time the minimum E_{set} value (under-illuminated space), the ELEC is not related anymore to the expected operating conditions and its low value is not related to an energy saving.
For the same reason, it is necessary to account even for values and times when the system provides an “excess” of illuminance, using more energy than required with higher ERI values.
Figure 150 shows in a graph the concept of the excess or the deficiency of illuminance compared with the illuminance target value on task area and available natural light.

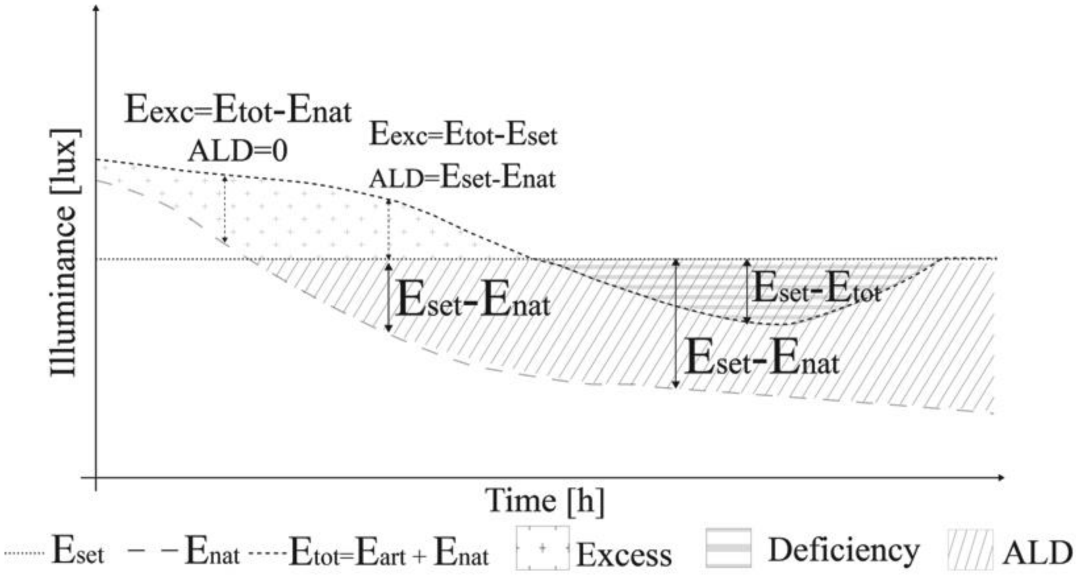


Figure 150. Conceptual scheme of the excess or the deficiency of illuminance compared to the illuminance target value on work-plane or area

In order to assess the performance of the system according to the above-mentioned visual comfort task, two more indices have been defined. The first one, named OAR (Over illuminance Avoidance Ratio), is defined as the ratio, evaluated for an observed time period, between the minimum requirement of artificial light (ALD) and the sum of it plus the artificial light eventually provided in excess by the system (E_{exc}). As can be observed in Figure 150, when the daylight is below the illuminance target value on task area (E_{set}), the eventual excess is accounted only by the difference between the total illuminance and the illuminance target value on task area by the time. When the sole natural light provides an illuminance above the illuminance target value on task area, but the artificial light is also contributing to the total illuminance, the excess is accounted by the difference among the total illuminance and the natural one by the time. In both cases, the contribution to the numerator in each time step is the same utilised for the ALD calculation while the denominator can be calculated as the difference E_{tot}-E_{nat}:

$$OAR = \frac{ALD}{\sum_{toperation} E_{excess} \cdot \Delta t + ALD} = \frac{ALD}{\sum_{toperation} (E_{tot} - E_{nat})^{*} \cdot \Delta t} \tag{43}$$

$$* \, only \; if \, (E_{tot} > E_{set})$$

Therefore, for a given ALD, the higher the over illuminance (low values of OAR) the lower the capability of the system to fulfil the maintenance of the illuminance target value on task area and thus the higher the related energy consumption.

A second index can be considered for accounting the relative weight of the under-illuminance times. This condition occurs when $E_{tot}<E_{set}$ and $E_{nat}<E_{set}$ and the system

are not capable of fulfilling the minimum target illuminance. This second index, called UAR (Under-illuminance Avoidance Ratio), can be defined as follows:

$$UAR = 1 - \frac{\sum_{t\ operation} (E_{set} - E_{tot}) \cdot \Delta t}{ALD} \tag{44}$$

The closer E_{tot} to E_{set}, the closer UAR to 1. The closer E_{tot} to E_{nat} (when $E_{nat} < E_{set}$), the closer UAR to 0

In order to give a more complete response on the performance of an observed system during the monitoring exercise, the indices must be considered contemporarily. The scheme in Figure 151 shows how several combinations of the indices values can be interpreted for a system diagnosis.

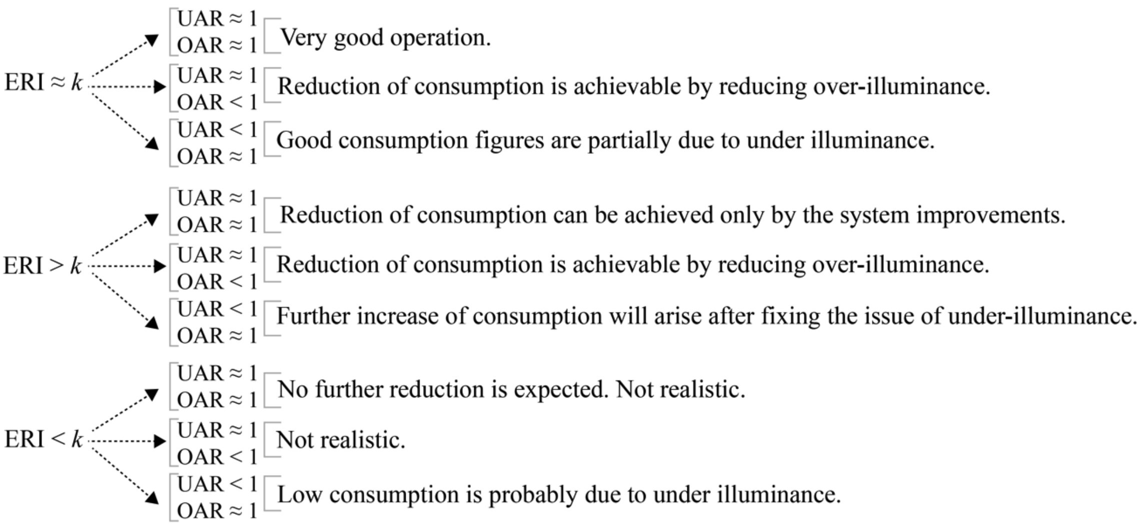


Figure 151. Possible combinations of ERI, UAR, OAR and their meaning

Moreover, it is useful to observe the ratio OAR/UAR. The higher the ratio the higher the influence of the under-lighting during the system operation. On the contrary, the lower the ratio the higher the relative weight of over-lighting.

9.2. Calculation of energy performance indices of daylight linked control systems by monitored data

The monitoring campaign of the analysed office scenarios have been carried out in periods reported in Table 16 in section 5 together with the description of the conditions selected for the two-end uses: "office" and "residential". In this section experimental results are presented.

Collected data have been analysed to make an appraisal of the system performances under the several imposed operation conditions and settings. ERI, UAR and OAR have been calculated for each day. In order to calculate the indices related to the lighted zone, the averages of the measures taken by couples of photosensors (two in the ceiling and two on the task area) have been used.
The indices have been calculated using about 47,000 illuminance measures as many electrical measures during for 179 days during a 16 months long campaign. Two different control systems, produced by two different manufactures (Bticino and Zumtobel), have been tested for a total of 359 scenarios. Furthermore, the photosensor of the Zumtobel system have been tested in two different positions of the ceiling. For the sake of clarity, the same system with the two photosensor locations will be called Zumtobel I and Zumtobel II.

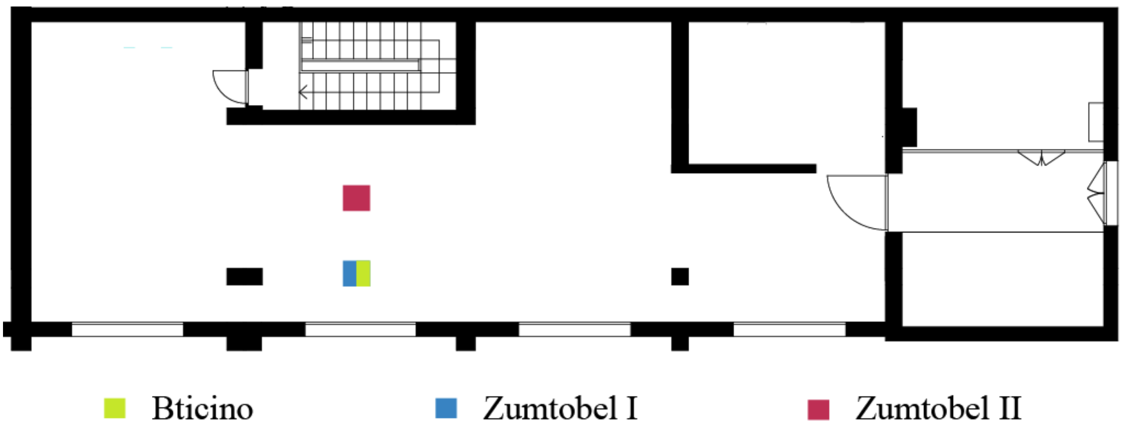


Figure 152. Plan of the laboratory with the photosensors locations

Each system configuration has been tested in all the planned occupancy schedules, both for the office and the residential cases.

The following chapters describe the results obtained and comment their operation using the three indices making also comparisons among systems. The first chapter deals with office scenarios, the second one with the residential scenarios. Indices are also utilised to make comparisons between the systems.

9.2.1. Office scenarios

As, already said in section 5, for the "office" end-use, the systems worked with different occupancy schedules. Except for some cases, they always run height hours and one hour of lunch break per day but with different time slots. Details can be found in tables in following section.

9.2.1.1. Bticino system

Starting to talk about the results of the system Bticino, Figure 153 shows an example of illuminance measured data for a spring day (on April 16th), in continuous operation (from 6:00 to 21:00) and office use (500 lx illuminance target on task area). It is clear that the system did not work perfectly. It must be underlined that commissioning and calibration have been done according to the manufacturer’s recommendations. Dimming control was not precise; therefore, a certain amount of excess of illuminance occurred mostly in the afternoon.

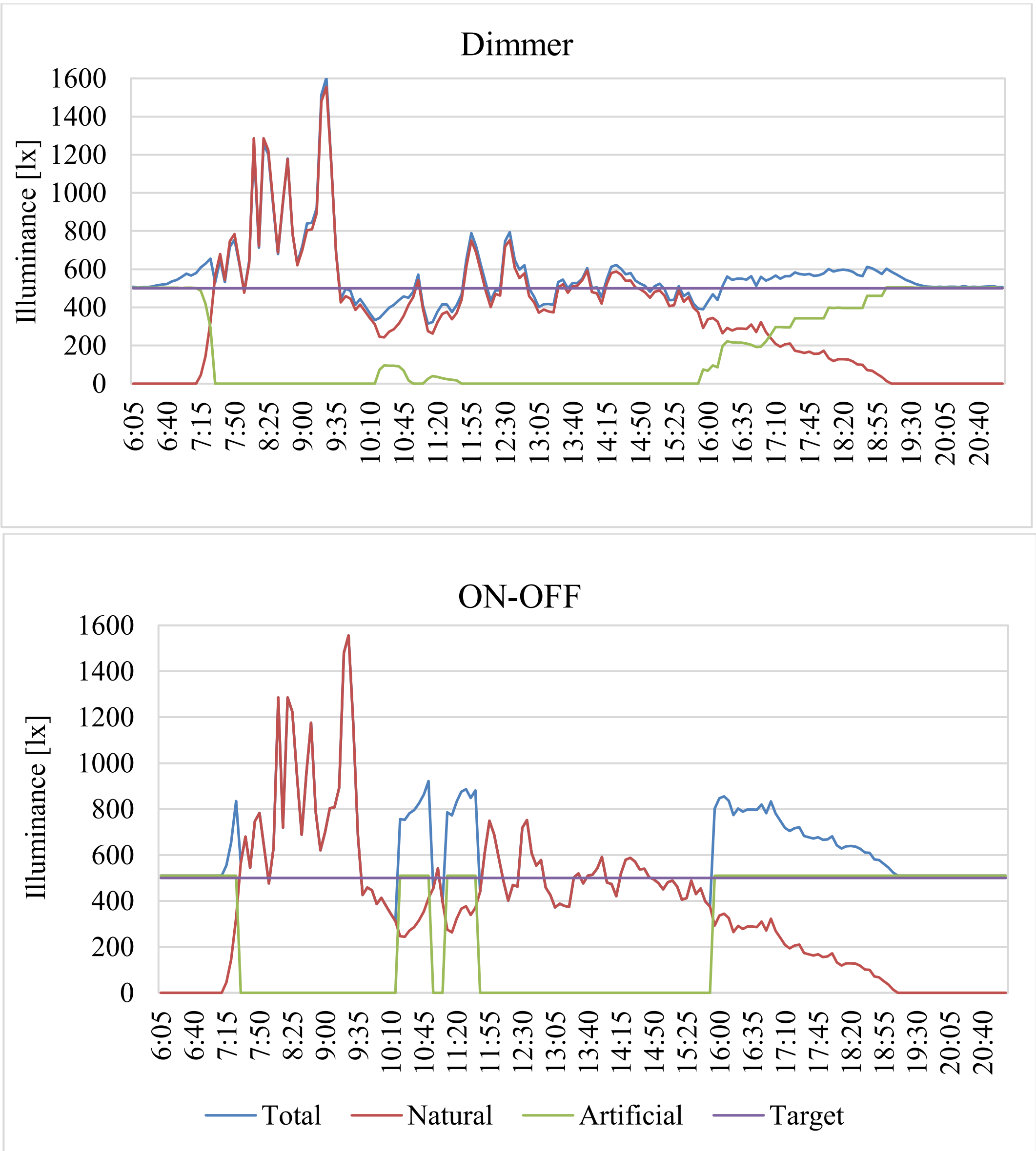


Figure 153. Example of illuminance values measured on April 16th in continuous dimming operation and in ON/OFF operation for the Bticino system

Nevertheless, there were also periods of the day with illuminance below the target value (e.g. from 10:05 to 10:45). Figure 10 reports the data for the same day in dimming operation and in "simulated" ON/OFF operation.

For dimmed operation, during this day, ERI resulted to be 0.260 Wh/lx·h while OAR was 0.91 and UAR, too. Such values of ERI are not so far from 0.246 Wh/lx·h, calculated by the linear relationship in Figure 149, correspondent to an ideal power to light proportionality.

If we consider that OAR and UAR are able to assess the visual comfort tasks, we can observe that only 9% of light is "wasted" in over illuminance and the weight of under illuminance on ALD is also about 10%. Globally, this is a situation where the system performance resulted quite satisfactory and only a slight improvement of commissioning and calibration could lead its performance to better results. In ON/OFF operation, the system has failed in some time interval to promptly switching ON (e.g. from 9:25 to 10:05).

This resulted in short periods of under illumination, accounted by a fair UAR = 0.93. In addition, the use of 100% of luminous flux makes unavoidable the presence of periods of over lighting, a fact that is measured though the value of OAR=0.73.

ERI has been calculated equal to 0.35 Wh/lx·h, quite higher than its reference value in continuous and ideal dimming operations and also than the ERI of the actual dimmed operation.

Table 39 reports for all the office scenarios the calculated ALD, UAR, OAR, measured electricity consumption and resulting ERI. For the sake of completeness also the cDA index has been calculated.

Schedules	Date	ALD [lx·h]	Cda [%]	Dimmer				ON-OFF			
				OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]	OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]
09:00-13:00 15:00-18:00	04/10/2016	874.0	78	0.36	0.97	653.7	0.75	0.02	1	961.3	1.11
09:00-13:00 15:00-18:00	05/10/2016	703.8	82	0.19	1	875.5	1.24	0.01	1	996.3	1.42
09:00-13:00 15:00-18:00	06/10/2016	1221.3	68	0.52	0.97	622.8	0.51	0.03	1	824.0	0.68
11:00-15:00 16:00-20:00	10/10/2016	1394.0	60	0.47	0.93	729.8	0.52	0.03	1	874.3	0.63
08:00-12:00 13:00-17:00	12/10/2016	314.9	91	0.18	0.01	743.1	2.36	0.02	1	996.3	0.67
08:00-12:00 13:00-17:01	13/10/2016	449.6	88	0.16	0.97	715.3	1.59	0.01	1	996.3	2.22
07:00-11:00 12:00-16:00	17/10/2016	321.8	91	0.22	1	428.5	1.33	0.01	1	764.5	2.38
07:30-11:30	18/10/2016	180.1	94	0.17	1	351.1	1.95	0.01	1	529.2	2.94

Schedules	Date	ALD [lx·h]	Cda [%]	Dimmer				ON-OFF			
				OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]	OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]
07:30-11:30 12:30-16:30	19/10/2016	332.0	88	0.25	0.91	391.3	1.18	0.01	1	539.9	1.63
07:00-11:00 12:00-16:00	20/10/2016	766.2	80	0.29	0.96	679.5	0.89	0.02	1	996.3	1.30
07:00-11:00 12:00-16:00	21/10/2016	1114.4	54	0.61	0.82	460.1	0.41	0.03	1	779.3	0.70
10:00-14:00 15:00-19:00	23/10/2016	1638.3	59	0.62	0.93	704.3	0.43	0.03	1	996.3	0.61
09:00-13:00 15:00-18:00	25/10/2016	919.2	77	0.66	0.93	425.3	0.46	0.03	1	745.7	0.81
08:00-12:00 13:00-17:00	26/10/2016	560.8	85	0.36	0.96	460.2	0.82	0.01	1	807.7	1.44
09:00-13:45	27/10/2016	458.1	75	0.38	0.91	300.7	0.66	0.02	1	457.5	1
07:00-11:00 12:00-16:00	29/10/2016	1356.1	66	0.64	0.88	581.2	0.43	0.03	1	996.3	0.73
07:00-11:00 12:00-16:00	31/10/2016	553.6	83	0.59	0.84	317.4	0.57	0.02	1	710.1	1.28
08:00-12:00 13:00-17:00	02/11/2016	973.2	75	0.74	0.79	373.5	0.38	0.02	1	633.4	0.66
16:00-20:00	04/11/2016	1796.8	10	0.99	0.85	410.5	0.23	0.07	1	488.0	0.28
08:00-12:00 13:00-17:00	05/11/2016	908.7	77	0.68	0.79	377.7	0.42	0.02	1	692.4	0.76
09:00-13:00 15:00-18:00	07/11/2016	2273.7	44	0.70	0.92	834.5	0.37	0.05	1	997.9	0.44
09:00-13:00 15:00-18:00	11/11/2016	1462.6	63	0.40	0.86	603.2	0.41	0.03	1	773.2	0.53
07:00-11:00 12:00-16:00	13/11/2016	653.3	83	0.37	0.98	520.5	0.80	0.02	1	797.6	1.22
07:00-11:00 12:00-16:00	14/11/2016	1969.3	51	0.64	0.98	804.7	0.41	0.04	1	1157.5	0.59
09:00-13:00 15:00-18:00	15/11/2016	1615.0	60	0.64	0.92	661.7	0.41	0.04	1	926.7	0.58
09:00-13:00 15:00-18:00	17/11/2016	2536.9	37	0.81	0.92	779.6	0.31	0.05	1	1013.1	0.40
10:30-15:30	18/11/2016	1057.5	59	0.58	0.91	482.0	0.46	0.03	1	650.7	0.62
08:00-12:00 13:00-17:00	28/11/2016	1150.6	71	0.49	1	653.9	0.57	0.03	1	872.3	0.76
07:00-11:00 12:00-16:00	29/11/2016	2973.0	27	0.74	1	977.7	0.33	0.06	1	1006.5	0.34
07:00-11:00 12:00-16:00	30/11/2016	936.2	76	0.24	0.96	840.6	0.90	0.02	1	996.3	1.06
10:30-18:00	01/12/2016	1569.2	52	0.64	0.94	618.2	0.39	0.04	1	813.3	0.52
08:00-12:00 13:00-17:00	02/12/2016	951.2	76	0.50	0.67	478.2	0.50	0.02	0.99	788.9	0.83
08:00-12:00 13:00-17:01	03/12/2016	1138.0	71	0.71	0.85	458.1	0.40	0.04	1	668.0	0.59
09:00-13:00 15:00-18:00	04/12/2016	1480.6	63	0.83	0.85	493.2	0.33	0.04	1	745.7	0.50

Schedules	Date	ALD [lx·h]	Cda [%]	Dimmer				ON-OFF			
				OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]	OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]
08:00-12:00 13:00-17:00	05/12/2016	1300.0	67	0.66	0.87	527.4	0.41	0.03	1	799.1	0.62
09:00-13:00 15:00-18:00	06/02/2016	2661.2	34	0.90	0.88	792.5	0.30	0.05	0.98	955.8	0.37
06:00-21:00	29/03/2017	2790.3	42	0.69	0.81	873.8	0.31	0.44	0.97	1501.9	0.55
06:00-21:00	30/03/2017	5733.6	16	0.98	0.65	909.5	0.16	0.74	0.99	1831.5	0.32
06:00-21:00	31/03/2017	3414.8	57	0.62	0.97	1225.1	0.36	0.42	0.98	1822.9	0.56
06:00-21:00	01/04/2017	3155.7	61	0.38	0.98	1806.7	0.57	0.38	0.97	1822.9	0.62
06:00-21:00	02/04/2017	5587.1	26	0.73	0.99	1831.5	0.33	0.73	0.99	1831.5	0.33
06:00-21:00	03/04/2017	4666.5	38	0.85	0.64	911.6	0.20	0.61	0.99	1831.5	0.39
06:00-21:00	06/04/2017	2479.2	67	0.56	0.63	911.5	0.37	0.32	0.98	1831.5	0.74
06:00-21:00	08/04/2017	2982.3	61	0.55	0.79	1120.8	0.38	0.38	0.97	1822.9	0.62
06:00-21:00	10/04/2017	3138.0	60	0.42	0.96	1602.8	0.51	0.39	0.98	1831.5	0.60
06:00-21:00	13/04/2017	2981.4	63	0.54	1	1230.4	0.41	0.50	1	1406.8	0.50
06:00-21:00	16/04/2017	3158.2	59	0.91	0.91	828.8	0.26	0.73	0.93	1086.4	0.35
06:00-21:00	17/04/2017	3198.7	60	0.56	1	1266.5	0.39	0.44	1	1666.8	0.55
06:00-21:00	19/04/2017	3719.8	52	0.56	0.96	1407.8	0.38	0.47	1	1840.2	0.51
06:00-21:00	20/04/2017	3175.8	59	0.50	0.94	1376.9	0.43	0.40	1	1840.2	0.59
06:00-21:00	21/04/2017	4767.6	38	0.77	0.93	1297.5	0.27	0.61	1	1840.2	0.39
06:00-21:00	22/04/2017	4240.2	45	0.71	0.93	1276.0	0.30	0.54	1	1840.2	0.44
06:00-21:00	23/04/2017	4351.3	43	0.76	0.94	1224.0	0.28	0.56	1	1840.2	0.43

Table 39. The indices calculated for the office in dimming control and ON/OFF control for the Bticino system

Looking at Table 39, it can be noted that in days with dimming control in continuous operation (from 6:00 to 21:00), ALD ranged between 2,479 and 5,733 lx·h while ERI ranged from 0.14 to 0.57 Wh/lx·h. In these days, these minimum values of ERI correspond to the lowest values of UAR (0.54 or 0.65) also coupled with high values of OAR (from 0.85 to 0.98). This highlights a situation where the low specific consumption is almost due to the inability of the system to fulfil the minimum target illuminance but only occasionally performing over illumination. A better tuning of the system would be addressed to enhance visual task fulfilment, although this will increase its consumption.

As well, looking at ON/OFF control from 6:00 to 21:00, we can observe that ERI ranged from 0.32 to 0.62 Wh/lx·h, OAR is generally lower than in dimming operation (from 0.32 to 0.74) and UAR is always (except in one case) equal to 1. Indeed, the ON/OFF control is not able to limit the luminous flux and avoid over illumination, resulting also in a general absence of under illumination. Also, in these cases there is coherence between low values of ERI and high values of OAR (low consumption is associated with moderate over illumination). Regarding the indices calculated for the scheduled office scenarios, the ALD values ranged between 269 and 2,973 lx·h and ERI ranged from 0.23 to 2.36 Wh/lx·h for dimming case and from 0.28 to 2.94 for the ON-OFF case. The OAR values of OAR for dimmer case are sometime very low (e.g. 0.16), but the OAR calculated for the ON-OFF case are lower. UAR are always and except in some cases, they are equal to 1 or close to 1. It must be underlined that ALD values characterize the days when the systems worked. It ranges according to the season, the hours of the occupancy schedules and of the daily time.

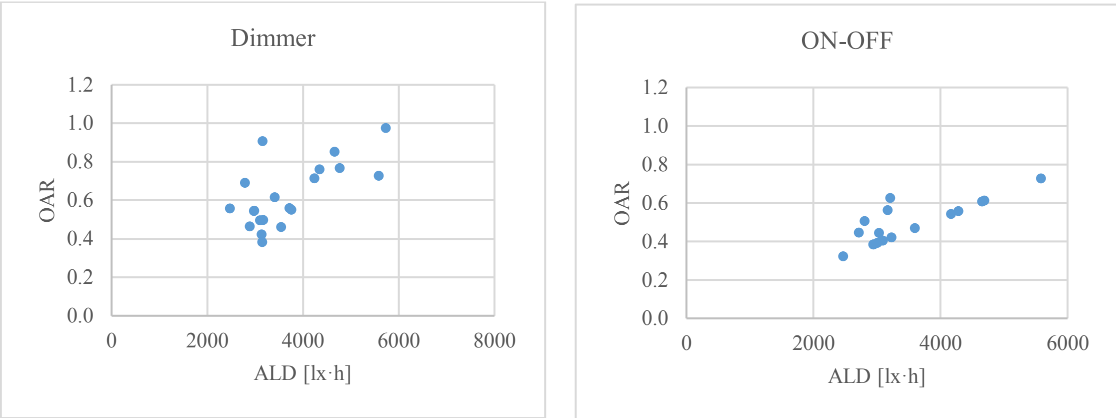


Figure 154. Relationship between OAR and ALD indices calculated for the office in continuous operation in dimming control (a) and ON/OFF control (b) for the Bticino system

Figures 154 shows the relationship of OAR and ALD. The graph confirms what has been already observed: in general, the greater the ALD, the lower the possibility of having over-lighting problems and, therefore, higher values of OAR occur.

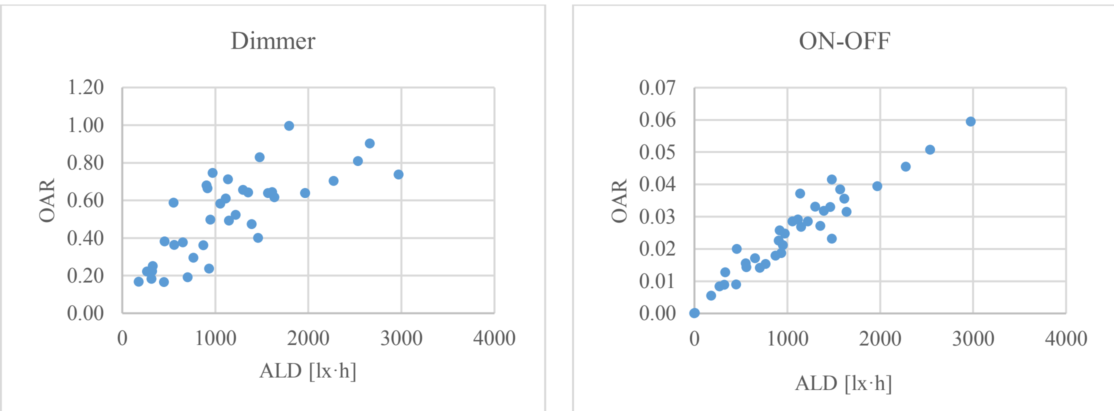


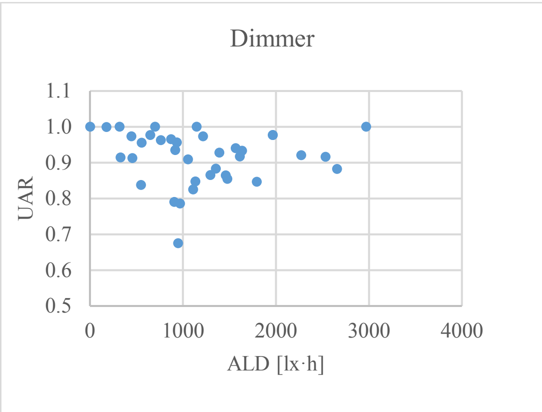
Figure 155. Relationship between OAR and ALD indices calculated for the office in dimming control (a) and ON/OFF control (b) for the Bticino system

On the contrary, looking at Figure 156, there is not a linear relationship between the UAR values and the ALD. In general, and mainly in ON-OFF cases, the UAR values are great irrespective of the ALD values. Indeed, in dimmer operation cases, the UAR values are always greater than 0.8, except in a case.

In ON-OFF cases, they are always greater than 0.99. It can be noted for all the cases, that low values of energy consumption could be related to a lack of achievement of the task illuminance.

Moreover, the analysis of OAR and UAR values compared to actual specific consumption data can be useful, to know if there is some over or under-illuminance problem affecting the latter ones.

Anyway, looking at OAR and UAR indices, it can be observed that the highest ERI values are associated to the lowest OAR values (this means that the system often over-illuminates the room) and low ERI values are coupled to very variables values of UAR. This means that low specific consumption can be caused by an excessive under-lighting, but still fairly good, values of UAR.



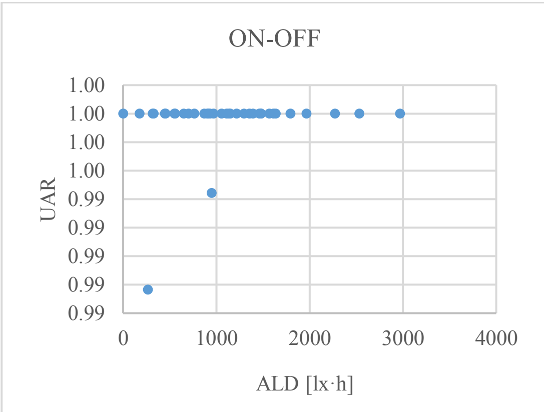


Figure 156. Relationship between UAR and ALD indices calculated for the office in dimming control (a) and ON/OFF control (b) for the Bticino system

Given that, the higher contributions to ALD are referred to the afternoon time, and so when the daylight contribution is lower, the indices have been calculated as well only considering only the afternoon time.

Table 40 shows the indices calculated only for this part of the day.

Date	ALD [lx·h]	Dimmer				ON-OFF			
		OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]	OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]
04/10/2016	874.0	0.58	0.97	404.2	0.46	0.03	1	509.9	0.58
05/10/2016	693.4	0.34	1	484.4	0.70	0.03	1	508.3	0.73
10/10/2016	1388.1	0.99	0.93	356.3	0.26	0.07	1	386.3	0.28
12/10/2016	314.9	0.50	0.01	455.7	1.45	0.04	1	508.3	0.35
13/10/2016	436.1	0.24	0.97	472.3	1.08	0.02	1	508.3	1.17

Date	ALD [lx·h]	Dimmer				ON-OFF			
		OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]	OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]
17/10/2016	114.8	0.12	1	271.6	2.36	0.01	1	499.7	4.35
20/10/2016	263.9	0.22	0.95	339.2	1.29	0.06	1	508.3	1.93
21/10/2016	1111.2	0.97	0.80	272.2	0.24	0.05	1	386.3	0.35
23/10/2016	1260.7	0.85	0.92	377.4	0.30	0.04	1	508.33	0.40
25/10/2016	919.2	0.72	0.97	333.7	0.36	0.02	1	508.33	0.55
26/10/2016	560.8	0.50	0.96	309.4	0.55	0.02	1	508.33	0.91
29/10/2016	458.5	0.49	0.93	276.0	0.60	0.03	1	508.33	1.11
31/10/2016	553.6	0.73	0.84	213.6	0.39	0.03	1	386.33	0.70
05/11/2016	908.7	0.78	0.79	283.0	0.31	0.07	0.98	508.33	0.56
07/11/2016	1812.7	0.98	0.91	464.2	0.26	0.07	0.98	509.86	0.28
11/11/2016	1426.7	0.40	0.86	409.9	0.29	0.03	1	508.3	0.36
13/11/2016	653.3	0.47	0.98	388.8	0.60	0.02	1	508.3	0.78
14/11/2016	575.9	0.41	0.98	387.0	0.67	0.06	1	387.0	0.67
15/11/2016	1615.0	0.92	0.92	445.2	0.28	0.07	1	509.9	0.32
17/11/2016	1860.6	1	0.89	423.0	0.23	0.07	1.0	508.3	0.27
27/11/2016	269.8	0.47	0.00	406.3	1.51	0.05	1	404.6	1.50
28/11/2016	1150.6	0.63	1	487.5	0.42	0.06	1	488.0	0.42
29/11/2016	1585.2	0.81	1	509.4	0.32	0.03	1	508.3	0.32
30/11/2016	642.9	0.39	0.96	437.9	0.68	0.03	1	508.3	0.79
02/12/2016	951.2	0.75	0.67	283.3	0.30	0.04	0.99	473.8	0.50
03/12/2016	1138.0	0.76	0.85	371.8	0.33	0.04	1	508.3	0.45
04/12/2016	1465.8	0.86	0.86	406.3	0.28	0.06	1	508.3	0.35
05/12/2016	1296.4	0.77	0.86	399.8	0.31	0.05	0.97	10.2	0.39
06/12/2016	1662.8	0.92	0.82	394.8	0.24	0.06	0.96	491.1	0.29

Table 40. The indices calculated for the office in dimming control and ON/OFF control considering only the afternoon time for the Bticino system

Comparing the relationship between the ALD and the OAR calculated for the whole day with the relationship between the ALD and the OAR calculated only for the afternoon time (Figure 157), it is possible to see that the OAR values are greater in the second case even if, in general the relationship is the same. Indeed, e.g., the OAR calculated for the 10/10/2016 are 0.5 for the whole day and 0.98 for the afternoon. It is because the schedule started at 11:00 until 20:00, hence during the afternoon the artificial light demand is very high.

The maximum value of ALD calculated during the afternoon is 1,860 lx·h that corresponds to an OAR value of 1 and UAR of 0.98.

The UAR values, in general are lower than the ones calculated for the whole day. It is because most part of under-illuminance problems occurred during the afternoon. Anyway, they are not so low, indeed, the minimum value is 0.67. Indeed, in this case the 99% of the ALD amount is during the afternoon.

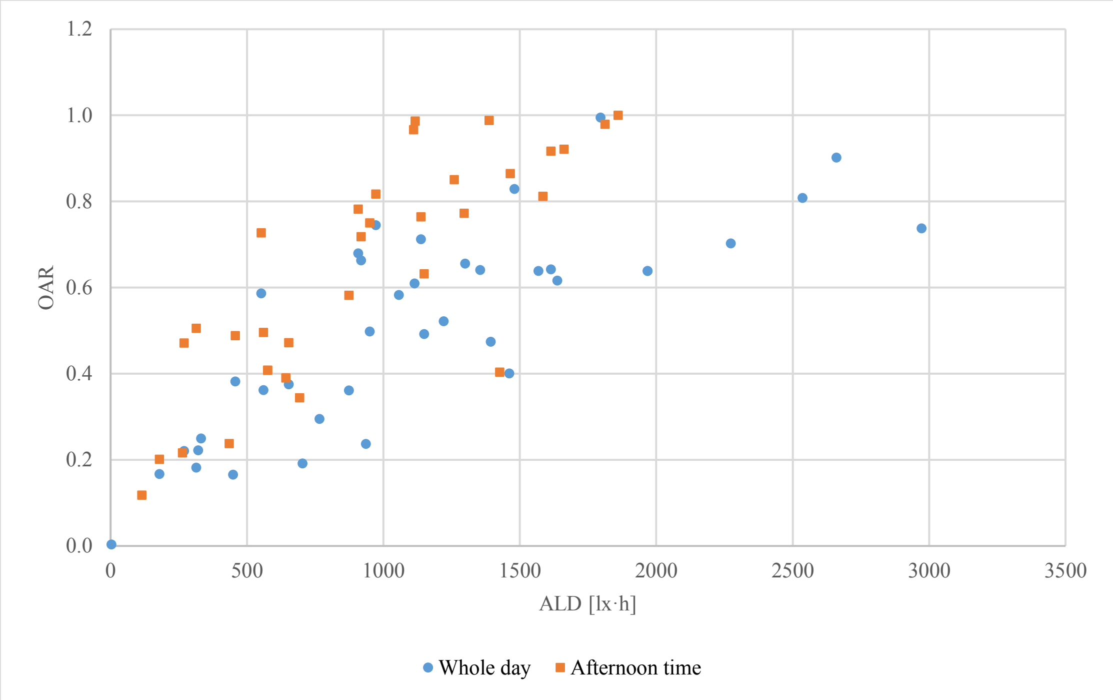


Figure 157. Comparison of the relationship between ALD index and OAR in office time scheduled operation, calculated for the whole day, and for the afternoon time for the Bticino system

In order to better understand how the ALD affects the system performance, the relationship between electrical consumption and ALD values has been studied (Figure 158).

Even if the tested systems are called "daylight-linked", they did not work perfectly as explain in their definition.

Anyway, there is a certain relationship between the consumption and the ALD. For an ideal case the consumption should be inversely proportional to the daylight contribution.

Indeed, the luminaires should be regulated having the artificial luminous flux inversely proportional to the contribution of natural light. For this reason, in case of an ideal system, the relationship between the ALD and the electrical consumption should be linear.

In the actual cases, the ALD index and the electrical consumption are only barely proportional because, as already said and observed, while calculating the UAR and the OAR, the control system did not work as expected in ideal cases.

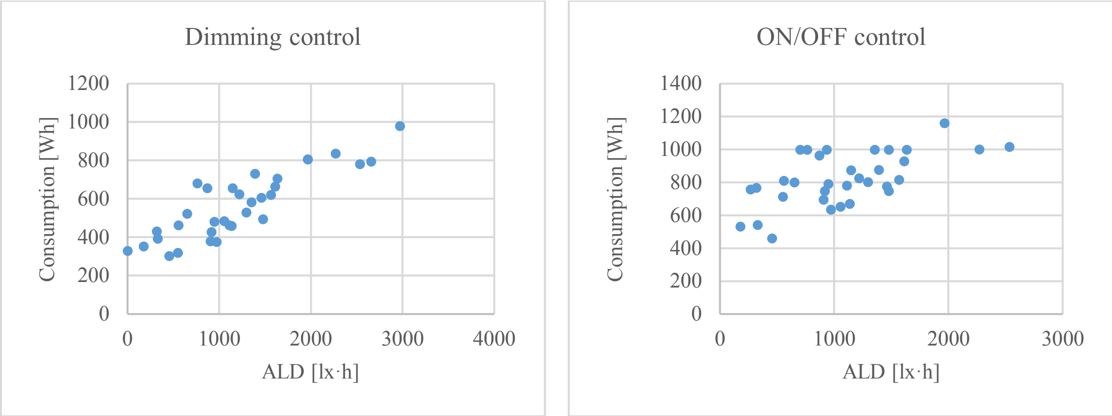


Figure 158. Relationship between ALD indices and consumption calculated for the office in dimming control (a) and ON/OFF control (b) for the Bticino system

Following graphs show the relationship of the ERI with the other indices. Regarding the relationship with the ALD the higher is the ERI the lower is the ALD. This is because, as observed in Figure 157 the system had some over-illuminance problem with low values of ALD. This trend is more evident (higher derivatives) with low values of ALD. For ALD higher than a threshold the ERI goes to an almost stable value.

The same observation can be made looking at the relationship between ERI and the OA.R. Low values of OAR (significant over illuminance provided by the system) corresponds to higher specific consumption (ERI).

On the contrary, ERI falls very fast with OAR below 0.3 and became more stable after the limit of 0.4.

Obviously, the graph with the relationship between ERI and UAR is opposite of it for the dimmer cases. As already said, in ON-OFF case the UAR values are very great and not precise relationship can be find with the other indices.

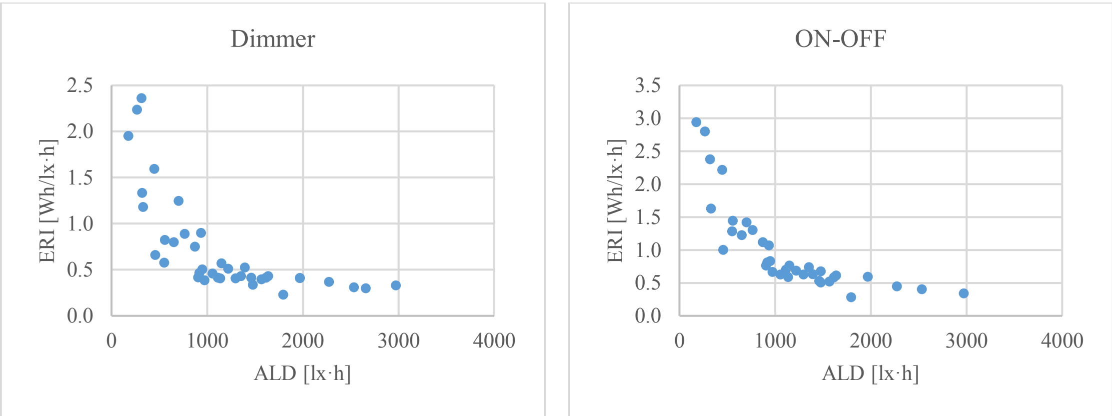


Figure 159. Relationship between ERI and ALD indices calculated for the office in dimming control (a) and ON/OFF control (b) for the Bticino system

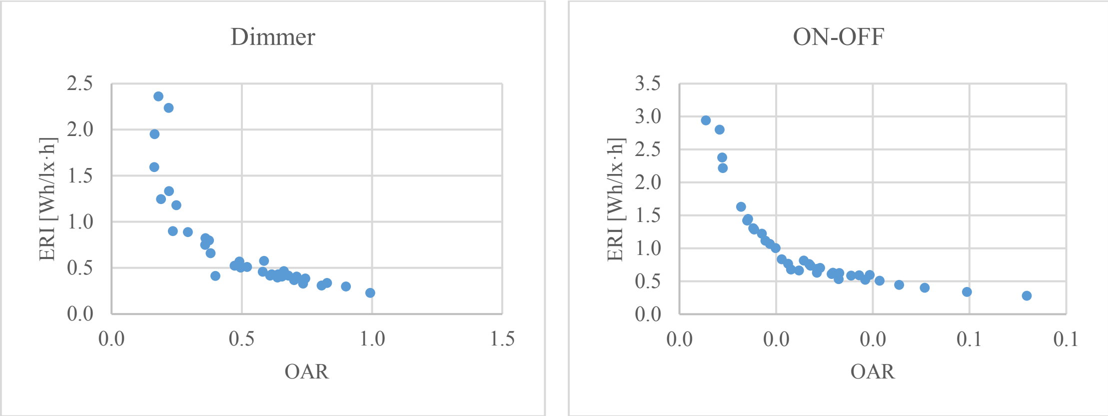


Figure 160. Relationship between ERI and OAR indices calculated for the office in dimming control (a) and ON/OFF control (b) for the Bticino system

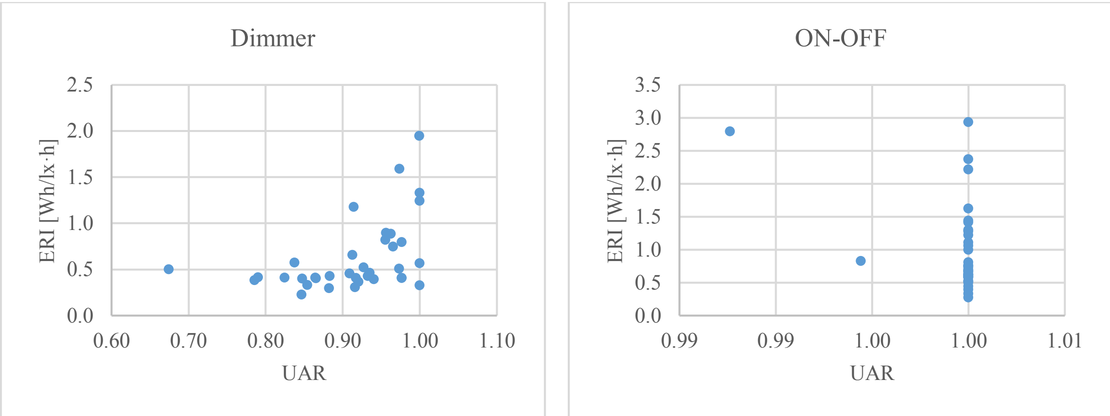


Figure 161. Relationship between ERI and UAR indices calculated for the office in dimming control (a) and ON/OFF control (b) for the Bticino system

9.2.1.2. Zumtobel I system

As well for the other systems the same indices and have been calculated and the same relationships between them have been plotted.

The following analyses are referred to the Zumtobel system with the sensor placed in the first position (I).

In Figure 162 an example of measures taken during a day is shown.

From the illuminance measures, referred to this day, it must be noted that there were some problems of under-lighting between 12:00 and 15:30 and some over-lighting problems during the whole day.

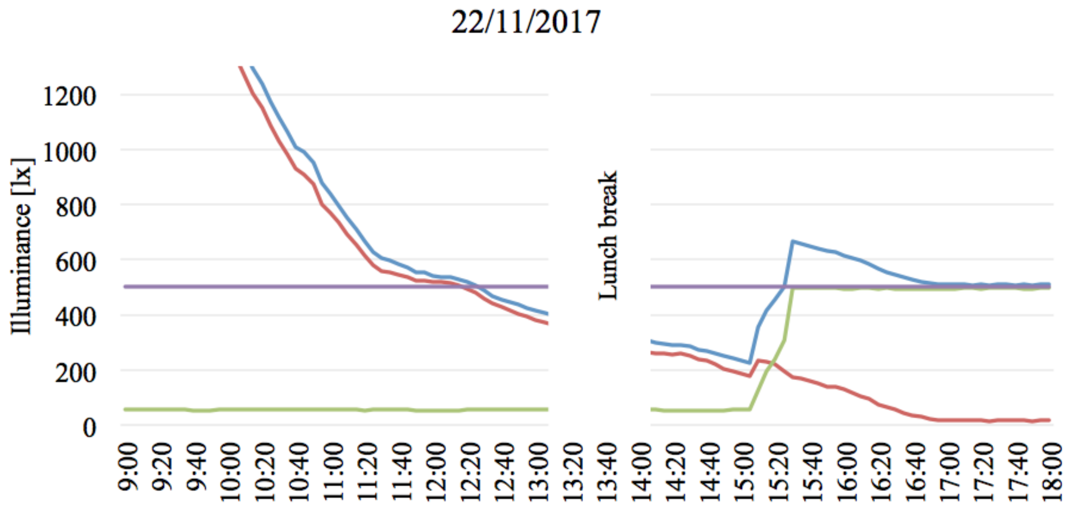


Figure 162. Example of illuminance values measured on 22/11/2017 in dimming and in ON/OFF operation for the Zumtobel I system

Schedules	Date	ALD [lx·h]	Cda [%]	Dimmer				ON-OFF			
				OAR	UAR	ELEC [Wh]	ERI [Wh/ lx·h]	OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]
09:00-13:00 15:00-18:00	31/05/2017	568.6	38	0.65	0.70	222.8	0.39	0.16	0.80	817.4	1.437
09:00-13:00 15:00-18:00	01/06/2017	733.5	43	0.87	0.68	207.5	0.28	0.51	0.65	280.7	0.383
09:00-13:00 15:00-18:00	02/06/2017	725.9	58	0.84	0.87	245.3	0.34	0.33	0.99	514.8	0.709
11:00-15:00 16:00-20:00	03/06/2017	1,613.1	15	0.73	0.82	465.2	0.29	0.39	0.95	780.9	0.484
08:00-12:00 13:00-17:00	04/06/2017	854.2	50	0.89	0.42	127.3	0.21	0.67	0.40	792.7	0.215
08:00-12:00 13:00-17:01	05/06/2017	469.5	68	0.62	0.97	195.6	0.42	0.21	1	792.7	1.095
10:30-13:30 14:30-18:00	07/06/2017	1,468.1	13	0.90	0.76	348.0	0.24	0.48	0.85	677.0	0.461
07:00-11:00 12:00-16:00	06/06/2017	852.4	59	0.77	0.95	299.0	0.34	0.33	0.96	612.6	0.719
07:00-11:00 12:00-16:00	08/06/2017	928.9	32	0.92	0.30	148.7	0.16	0.79	0.23	115.5	0.124
07:30-11:30 12:30-16:30	09/06/2017	703.1	40	0.99	0.23	109.7	0.16	0.77	0.18	87.4	0.124
07:00-11:00 12:00-16:00	10/06/2017	493.1	51	1	0.20	106.1	0.22	0.60	0.28	116.4	0.236

Schedules	Date	ALD [lx·h]	Cda [%]	Dimmer				ON-OFF			
				OAR	UAR	ELEC [Wh]	ERI [Wh/ lx·h]	OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]
07:00-11:00 12:00-16:00	11/06/2017	1,430.9	72	0.71	0.61	317.5	0.22	0.58	0.73	457.3	0.284
10:00-14:00 15:00-19:00	15/07/2017	456.9	35	0.71	0.58	187.7	0.41	0.51	0.53	320.5	0.435
09:00-13:45	13/06/2017	1,072.0	28	0.80	0.57	274.6	0.26	0.61	0.56	300.0	0.280
07:00-11:00 12:00-16:00	05/07/2017	444.6	39	1	0.10	142.4	0.22	0.87	0.10	126.1	0.182
08:00-12:00 13:00-17:00	06/07/2017	444.5	69	0.55	1	246.1	0.55	0.26	1	792.7	0.997
08:00-12:00 13:00-17:01	12/07/2017	387.2	58	0.78	0.46	150.9	0.39	0.51	0.47	792.7	0.529
09:00-13:00 15:00-18:00	13/07/2017	575.8	12	0.66	0.58	227.1	0.39	0.55	0.54	338.2	0.388
07:00-11:00 12:00-16:00	17/07/2017	437.8	39	0.47	0.44	140.4	0.51	0.11	0.86	850.5	1.943
09:00-13:00 15:00-18:00	18/07/2017	322.7	52	0.52	0.88	215.0	0.67	0.26	0.77	320.5	0.993
09:00-13:00 15:00-18:00	21/07/2017	644.7	45	0.70	0.57	233.4	0.36	0.16	0.96	947.7	1.470
09:00-13:00 15:00-18:00	15/11/2017	1,028.0	78	0.90	0.72	284.9	0.28	0.59	0.77	417.7	0.406
09:00-13:00 15:00-18:00	22/11/2017	1,743.1	62	0.84	0.73	431.5	0.25	0.41	0.90	947.7	0.544
09:00-13:00 15:00-18:00	23/11/2017	1,705.8	62	0.84	0.76	435.2	0.26	0.40	0.91	947.7	0.556
08:00-12:00 13:00-17:00	24/11/2017	1,014.6	78	0.89	0.67	262.7	0.26	0.78	0.73	792.7	0.298
10:30-13:30 14:30-18:00	25/11/2017	2,419.1	47	0.95	0.93	547.6	0.23	0.82	0.96	718.0	0.297
07:00-11:00 12:00-16:00	26/11/2017	3,207.5	38	0.87	0.92	749.8	0.23	0.74	0.92	912.3	0.284

Table 41. The indices calculated for the office in dimming control and ON/OFF control for the Zumtobel I system

Scenarios reported in Table 41 are characterized by ALD values that range between 322 and 1,613 lx·h. Looking at the ON-OFF cases, the ERI indices reached values close to 2 [Wh/lx·h], while, for dimming cases, the maximum value of ERI was 0.98. Also in this case, in general lower values of ERI correspond to low values of UAR and high values of OAR (Figures 163 and 164).

Furthermore, in dimming operation there is a general trend of OAR to rise according to ALD. An exception can be noted for the scenarios tested during the summer months, when the ALD was very low, but the OAR was in general high.

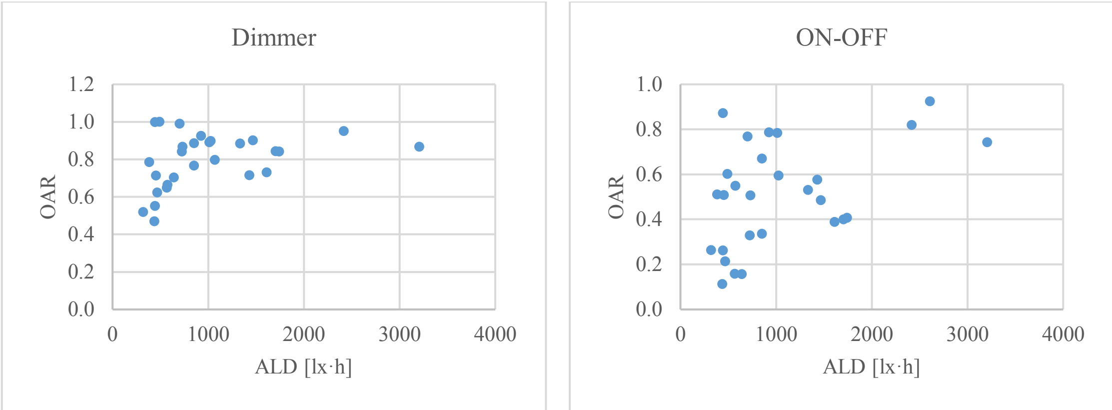


Figure 163. Relationship between OAR and ALD indices calculated for the office in dimming control (a) and ON/OFF control (b) for the Zumtobel I system

The graph confirms what has been already observed: in general, the greater the ALD, the lower the possibility of having over-lighting problems and, therefore, higher values of OAR.

Looking at the following graphs, it can be noted that there is not a good relationship between the ALD values and the UAR, mainly in dimmer cases. For ALD higher than 1000 lx·h the UAR are always higher than 0.6. In ON-OFF operation the UAR Figures are more spread when ALD is lower than 1000 lx·h. This can be caused by the fact that in days with a good contribution of daylight the intervention of fixed power lights can result not always effective.

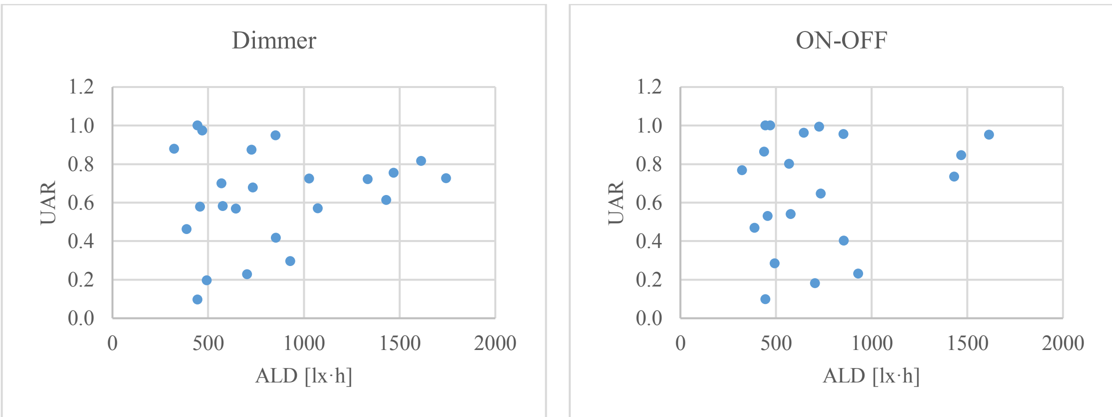


Figure 164. Relationship between UAR and ALD indices calculated for the office in dimming control (a) and ON/OFF control (b) for the Zumtobel I system

The same observations made for the system Bticino, can be replicated for the Zumtobel I. In Figure 165 the ALD and the electric consumption have been plotted. As well in this case, although a trend of common rising can be noted, the relationships are not perfectly linear as it should be because the over and under-lighting effects. Also in this case such "noise" is more evident for the ON-OFF scenarios.

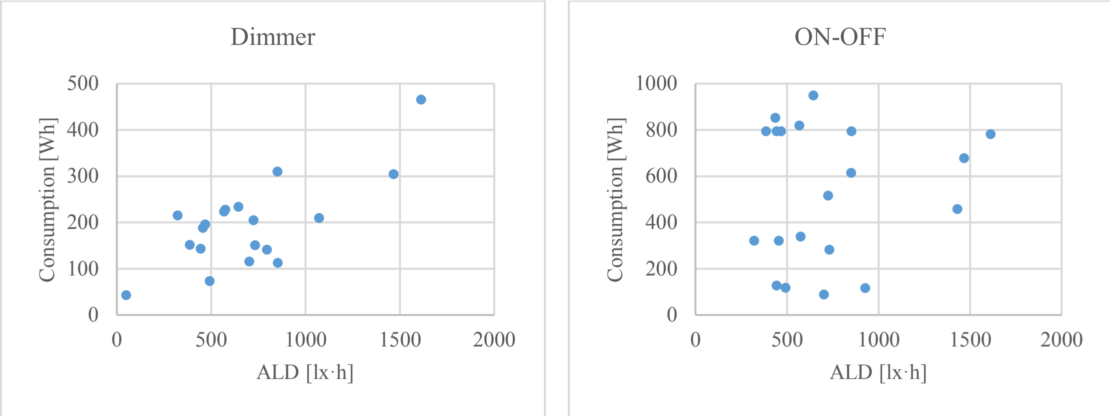


Figure 165. Relationship between ALD and consumption calculated for the office in dimming control (a) and ON/OFF control (b) for the Zumtobel I system

Following graphs show the relationship of the ERI with the other indices. The relationship with the ALD for both control strategies is clear. As well as for the Bticino system the higher is the ERI the lower is the ALD. This trend is more evident (higher derivatives) with low values of ALD. For ALD higher than a threshold the ERI goes to an almost stable value.

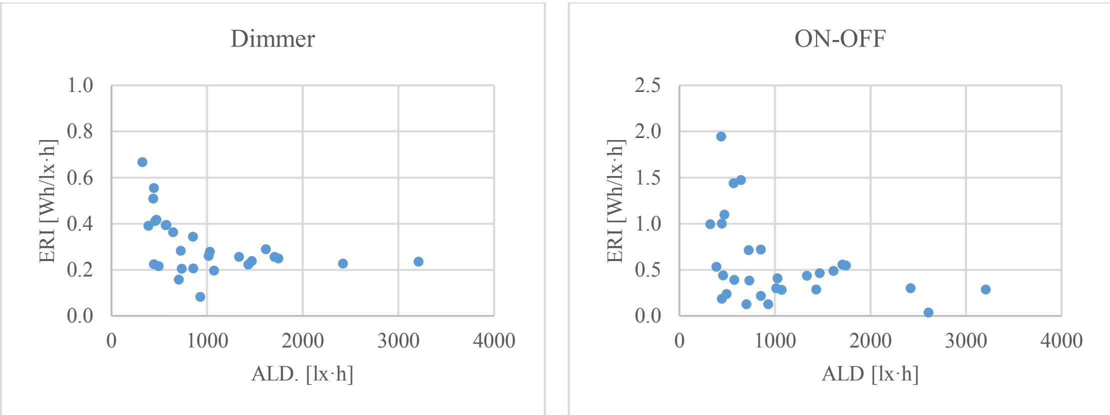


Figure 166. Relationship between ERI and ALD indices calculated for the office in dimming control (a) and ON/OFF control (b) for the Zumtobel I system

The same relationship can be observed between ALD and OAR.
On the contrary, looking at the Figures 167 and 168, the higher the ERI the higher the UAR and the lower OAR.
As shown in Table 41, the OAR calculated for this day is 0.84 and the UAR is 0.73 for the dimmer case. Even if, mainly in the first part of the day, the over-illuminance is constant, but not so high, calculating the over-lighting for the ON-OFF (as explained in section 5) case, it appears very high. Indeed, the OAR calculated for the ON-OFF is 0.41 and the UAR is 0.90. Of course, the values collected during the lunch break, have not been taken into account in the indices calculation.

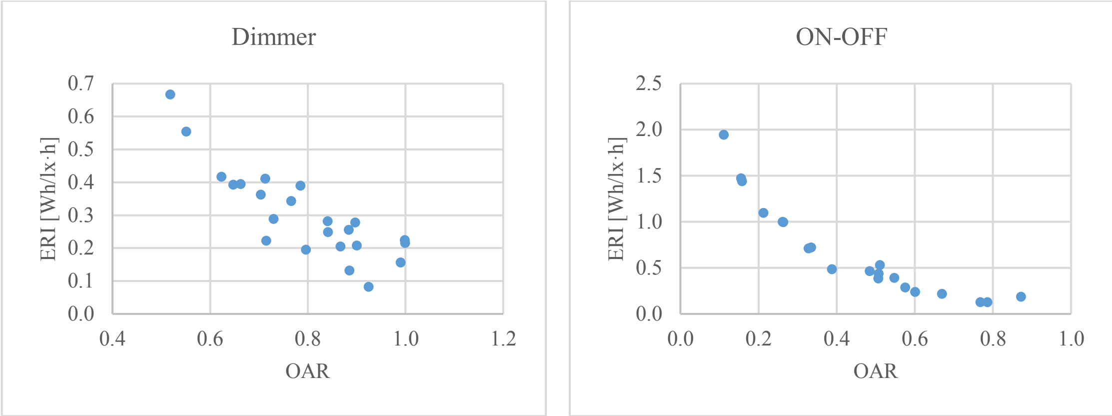


Figure 167. Relationship between ERI and OAR indices calculated for the office in dimming control (a) and ON/OFF control (b) for the Zumtobel I system

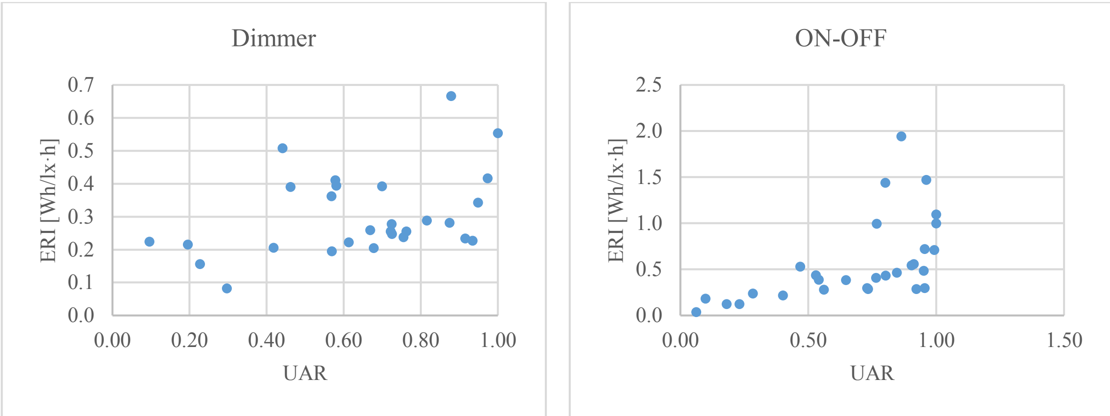


Figure 168. Relationship between ERI and UAR indices calculated for the office in dimming control (a) and ON/OFF control (b) for the Zumtobel I system

As well for this system, the indices have been calculated considering the operation only in the afternoon time (Table 42).

Schedules	Date	ALD [lx·h]	Dimmer				ON-OFF			
			OAR	UAR	ELEC [Wh]	ERI [Wh/ lx·h]	OAR	UAR	ELEC [Wh]	ERI [Wh/ lx·h]
09:00-13:00 15:00-18:00	31/05/2017	493.6	0.65	0.79	163.0	163.0	0.26	0.91	421.6	0.85
09:00-13:00 15:00-18:00	01/06/2017	675.2	0.86	0.73	140.0	157.5	0.49	0.70	270.7	0.40
09:00-13:00 15:00-18:00	02/06/2017	703.9	0.90	0.87	168.8	172.9	0.39	0.99	407.1	0.58
11:00-15:00 16:00-20:00	03/06/2017	1209.8	0.68	1	405.2	405.2	0.58	1	473.7	0.39

Schedules	Date	ALD [lx·h]	Dimmer				ON-OFF			
			OAR	UAR	ELEC [Wh]	ERI [Wh/ lx·h]	OAR	UAR	ELEC [Wh]	ERI [Wh/ lx·h]
08:00-12:00 13:00-17:00	04/06/2017	748.5	0.87	0.44	127.2	102.3	0.64	0.46	174.0	0.23
08:00-12:00 13:00-17:01	05/06/2017	449.3	0.70	0.97	151.2	151.2	0.28	1	367.3	0.82
10:30-13:30 14:30-18:00	07/06/2017	1007.5	0.86	0.96	273.3	273.3	0.48	1	473.7	0.47
07:00-11:00 12:00-16:00	06/06/2017	605.0	0.81	0.93	187.4	187.4	0.41	0.94	367.7	0.61
07:30-11:30 12:30-16:30	08/06/2017	780.8	0.92	0.30	66.2	97.8	0.75	0.27	106.3	0.14
07:00-11:00 12:00-16:00	09/06/2017	637.8	0.99	0.21	61.3	61.3	0.75	0.20	87.3	0.14
07:00-11:00 12:00-16:00	10/06/2017	486.3	1	0.19	56.9	56.9	0.60	0.29	116.3	0.24
10:00-14:00 15:00-19:00	11/06/2017	986.6	0.69	0.87	307.5	307.5	0.54	0.97	447.3	0.42
09:00-13:00 15:00-18:00	15/07/2017	426.2	0.70	0.62	137.7	137.7	0.47	0.62	270.5	0.43
07:00-11:00 12:00-16:00	05/07/2017	439.4	1	0.10	49.4	49.4	0.86	0.11	76.2	0.12
08:00-12:00 13:00-17:00	06/07/2017	444.5	0.57	1	191.2	191.2	0.28	1	375.7	0.85
08:00-12:00 13:00-17:01	12/07/2017	387.2	0.78	0.46	100.9	100.9	0.51	0.47	154.8	0.40
09:00-13:00 15:00-18:00	13/07/2017	518.1	0.64	0.64	177.1	177.1	0.50	0.65	288.2	0.40
07:00-11:00 12:00-16:00	17/07/2017	423.0	0.78	0.48	67.2	67.2	0.23	0.86	367.7	0.87
09:00-13:00 15:00-18:00	18/07/2017	322.7	0.52	0.88	165.0	165.0	0.26	0.77	270.5	0.84
09:00-13:00 15:00-18:00	21/07/2017	619.8	0.90	0.59	141.8	141.8	0.30	1	473.7	0.76
09:00-13:00 15:00-18:00	15/11/2017	957.27	0.93	0.72	214.1	214.1	0.62	0.77	332.3	0.35
09:00-13:00 15:00-18:00	22/11/2017	1534.63	0.92	0.81	334.9	214.1	0.74	1	473.7	0.31
09:00-13:00 15:00-18:00	23/11/2017	1534.17	0.92	0.84	339.5	334.9	0.74	1	473.7	0.31
08:00-12:00 13:00-17:00	24/11/2017	1007.58	0.89	0.68	212.7	339.5	0.78	0.73	252.0	0.25
08:00-12:00 13:00-17:01	25/11/2017	1890.82	0.94	1	460.7	212.7	0.91	1	473.7	0.25

Schedules	Date	ALD [lx·h]	Dimmer				ON-OFF			
			OAR	UAR	ELEC [Wh]	ERI [Wh/ lx·h]	OAR	UAR	ELEC [Wh]	ERI [Wh/ lx·h]
10:30-13:30 14:30-18:00	26/11/2017	1212.21	0.87	0.78	301.0	460.7	0.68	0.80	332.3	0.27

Table 42. The indices calculated for the office in dimming control and ON/OFF control considering only the afternoon time for the Zumtobel I system

As seen in previous graphs, the OAR values are not so low. Comparing the relationship between the ALD and the OAR calculated for the whole day with the relationship between the ALD and the OAR calculated only for the afternoon time (Figure 169), it is possible to see that the OAR values are not always greater in the second case. In some cases, considering the OAR only for the afternoon time, the OAR are lower than the OAR calculated for the whole day. Obviously, for the afternoon case the ALD values are low because they are the calculated for less hours, but in general the most part of demand of artificial light is concentrated during the afternoon. For this reason, the ALD values calculated for the afternoon and for the whole day are in the same range.

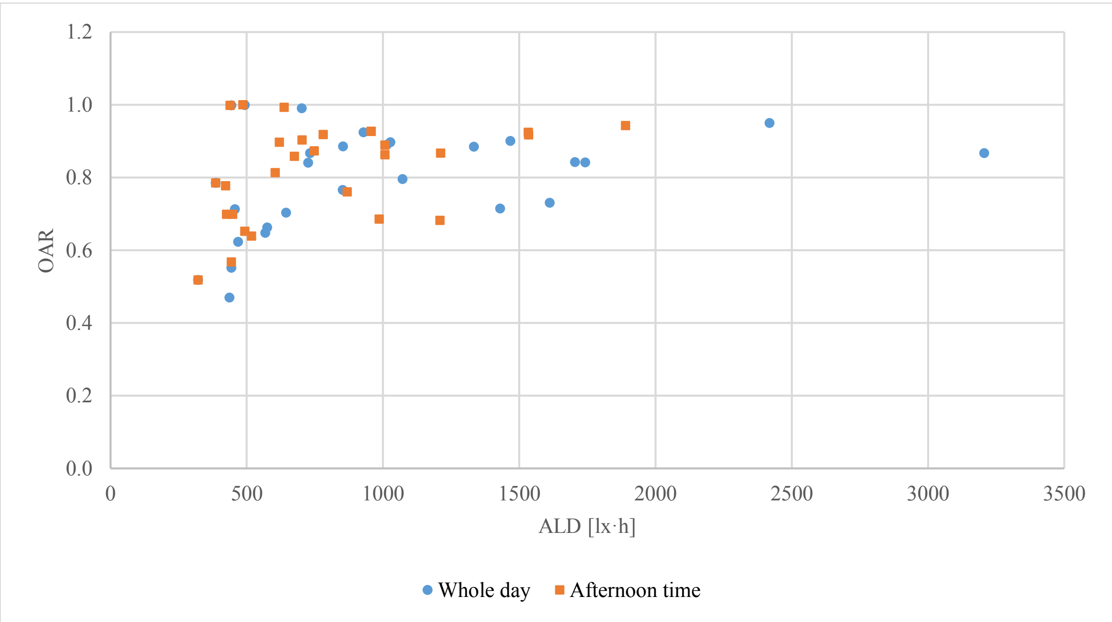


Figure 169. Comparison of the relationships between ALD index and OAR in office time scheduled operation, calculated for the whole day, and of the relationship between ALD index and OAR in office time scheduled operation calculated for the afternoon time for dimmer cases for the Zumtobel I system

It could be interesting to remind that the OAR calculated for the afternoon time shown in Figure 162 (22/11/2017) is 0.92 for the dimmer case and 0.74 for the ON-

OFF case while it was 0.84 in dimmer condition and 0.41 for the whole day in ON-OFF condition; the UAR is 0.81 in the first case and 1 in the second one for the afternoon time and 0.73 and 0.90 for the ON-OFF case for the whole day.

9.2.1.3. Zumtobel II system

It has been said that one of the parameters that can influence the performances of the DLCs is the location of the photosensor. In order to investigate this issue, the photosensor of the Zumtobel system has been placed in another point of the ceiling.

In following table, the indices calculated with the sensor placed in position II are reported.

Schedules	Date	ALD [lx·h]	Cda [%]	Dimmer				ON-OFF			
				OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]	OAR	UAR	ELEC [Wh]	ERI [Wh/ lx·h]
08:00-12:00 13:00-17:00	22/10/2017	405.2	87	0.92	0.89	169.9	0.42	0.33	0.88	792.7	0.81
08:00-12:00 13:00-17:01	21/10/2017	377.2	88	0.71	0.87	190.4	0.50	0.28	0.81	792.7	0.92
10:30-13:30 14:30-18:00	23/10/2017	2,062.9	54	0.85	0.89	462.0	0.22	0.59	0.92	806.4	0.39
07:00-11:00 12:00-16:00	24/10/2017	707.7	84	0.79	0.82	247.3	0.24	0.37	0.90	448.4	0.63
07:00-11:00 12:00-16:00	25/10/2017	785.2	82	0.78	0.90	284.9	0.26	0.35	0.97	503.6	0.64
07:30-11:30 12:30-16:30	26/10/2017	612.5	86	0.85	0.45	92.5	0.15	0.55	0.48	192.8	0.31
09:00-13:00 15:00-18:00	27/10/2017	1,252.4	72	0.78	0.74	363.7	0.29	0.30	0.92	947.7	0.76
10:00-14:00 15:00-19:00	28/10/2017	2,191.8	63	0.86	0.86	531.4	0.24	0.60	0.90	772.8	0.34
09:00-13:00 15:00-18:00	29/10/2017	1,161.7	74	0.84	0.66	299.9	0.26	0.28	0.95	947.7	0.82
09:00-13:00 15:00-18:01	30/10/2017	2,058.9	54	0.91	0.87	502.4	0.24	0.49	0.94	947.7	0.46
09:00-13:00 15:00-18:02	31/10/2017	2,069.4	54	0.82	0.88	563.7	0.27	0.48	0.90	947.7	0.46
11:00-15:00 16:00-20:00	01/11/2017	3,093.9	31	0.96	0.87	569.4	0.18	0.72	0.91	841.7	0.27
08:00-12:00 13:00-17:00	02/11/2017	1,031.6	77	0.98	0.82	193.4	0.19	0.63	0.93	792.7	0.38
08:00-12:00 13:00-17:01	03/11/2017	998.6	77	0.98	0.79	177.6	0.18	0.62	0.93	792.7	0.36

Schedules	Date	ALD [lx·h]	Cda [%]	Dimmer				ON-OFF			
				OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]	OAR	UAR	ELEC [Wh]	ERI [Wh/ lx·h]
11:00-15:00 16:00-20:00	04/11/2017	2,761.1	39	0.94	0.85	630.6	0.24	0.87	0.82	544.5	0.20
10:30-13:30 14:30-18:00	05/11/2017	2,303.5	49	0.99	0.92	439.8	0.19	0.77	0.95	764.1	0.33
07:00-11:00 12:00-16:00	06/11/2017	1,383.9	69	0.89	0.81	339.2	0.22	0.56	0.85	581.1	0.42
07:00-11:00 12:00-16:00	07/11/2017	1,273.7	72	0.74	0.87	448.6	0.35	0.47	0.86	700.4	0.55
07:00-11:00 12:00-16:00	09/11/2017	659.3	85	0.84	0.81	243.2	0.37	0.49	0.90	444.2	0.67
07:00-11:00 12:00-16:00	10/11/2017	2,075.6	55	0.88	0.79	526.1	0.25	0.56	0.84	797.5	0.38
10:00-14:00 15:00-19:00	11/11/2017	2,115.1	57	0.84	0.87	482.9	0.23	0.76	0.88	636.8	0.28
09:00-13:00 15:00-18:00	12/11/2017	1,927.3	57	0.87	0.88	504.7	0.26	0.45	0.91	947.7	0.49

Table 43. The indices calculated for the office in dimming control and ON/OFF control for the Zumtobel II system

These schedules have been tested from 22/10/2017 until 12/11/2017.
For this reason, the ALD values are in general high, even if most part has been calculated not during winter time. ALD values ranged between 377.2 and 2,761.1 lx·h. It must be underlined that the 29/10/2017 the clock time changed from UTC+1 to +2. The OAR values were between 0.71 and 0.98 while the UAR between 0.44 and 0.91. Finally, the ERI values were very similar to the ones of Zumtobel I and change very little as it can be possible to see as well in following graphs.
For this reason, it is difficult to find a relationship with the ALD similar to the one observed previously (Figure 170).

Regarding the relationship with the OAR values, it can be seen in the graph in Figure 171, that also in this case the higher is the OAR the lower is the ERI especially in ON-OFF case. A very weak relationship is observed UAR and the ERI. In ON-OFF cases the ERI were more variable. Indeed, they ranged from 0.31 to 0.92.

Regarding the OAR, also for this system, in general they are higher in dimmer case. In ON-OFF cases they assumed low values until 0.27, while in dimmer cases the minor OAR value was 0.74.

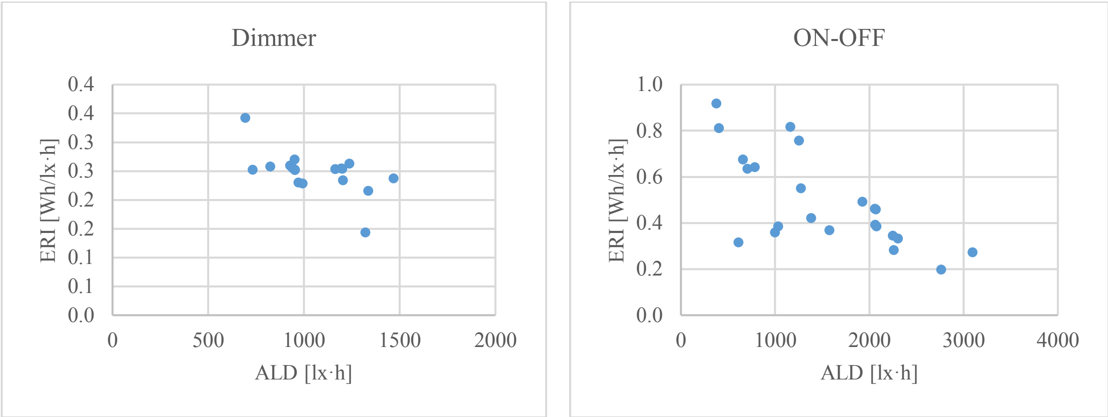


Figure 170. Relationship between ERI and ALD indices calculated for the office in dimming control (a) and ON/OFF control (b) for the Zumtobel II system

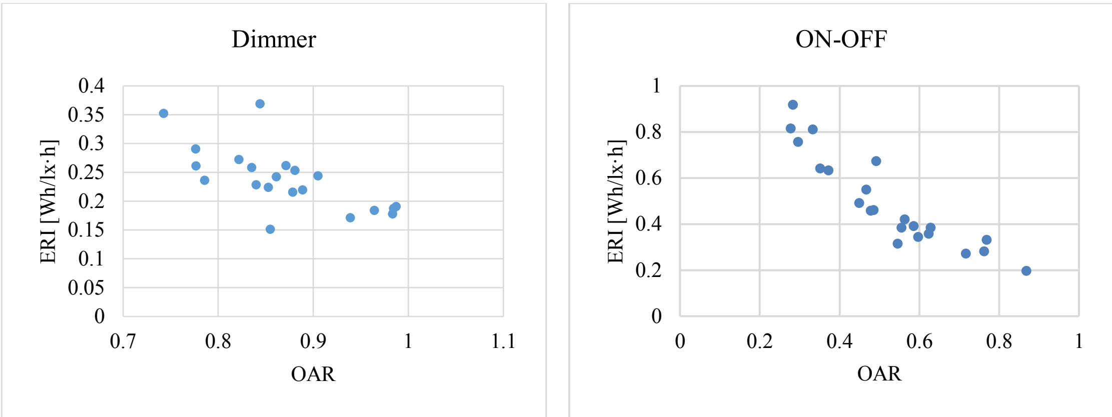


Figure 171. Relationship between ERI and OAR indices calculated for the office in dimming control (a) and ON/OFF control (b) for the Zumtobel II system

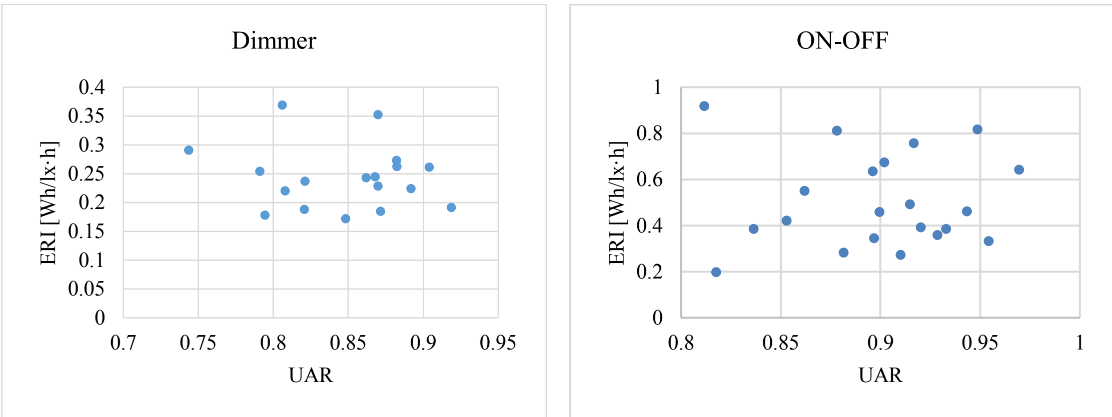


Figure 172. Relationship between ERI and UAR indices calculated for the office in dimming control (a) and ON/OFF control (b) for the Zumtobel II system

Same observations about the relationship between OAR and ALD can be made in this case. The ALD the UAR values have not a strong relationship, especially in the ON-OFF cases. In this last case the UAR, except a case, is always greater than 0.7.

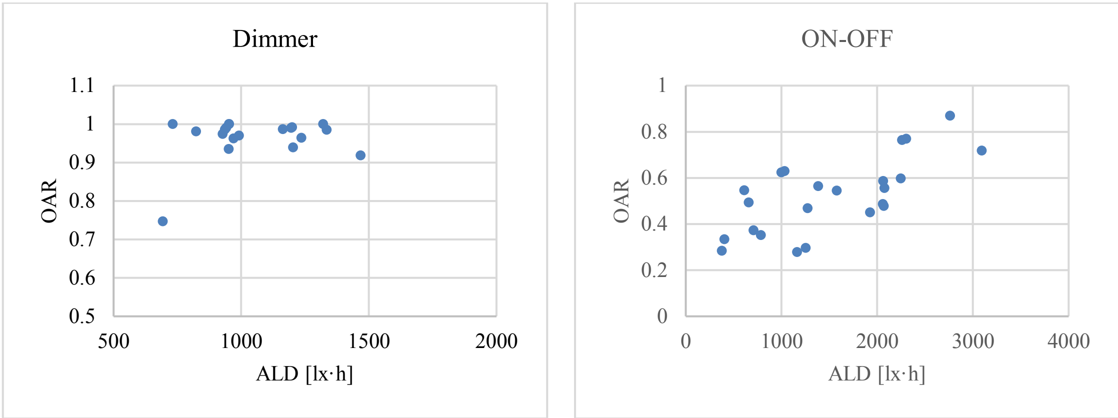


Figure 173. Relationship between ALD and OAR indices calculated for the office in dimming control (a) and ON/OFF control (b) for the Zumtobel II system

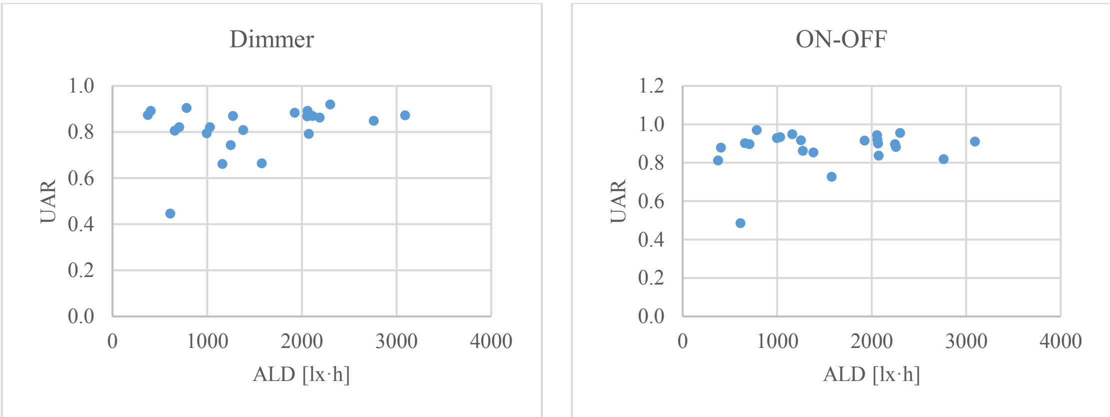


Figure 174. Relationship between ALD and UAR indices calculated for the office in dimming control (a) and ON/OFF control (b) for the Zumtobel II system

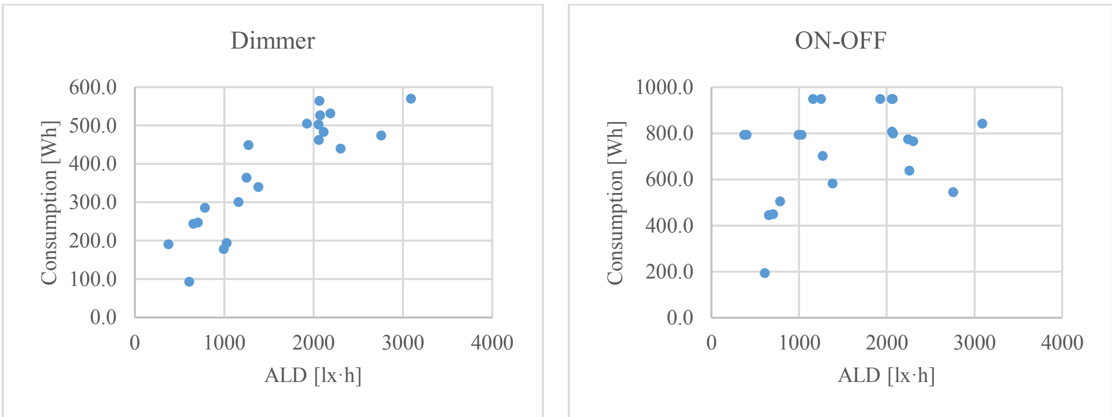


Figure 175. Relationship between ALD and consumption calculated for the office in dimming control (a) and ON/OFF control (b) for the Zumtobel II system

Also in this case, looking at the dimmer cases in Figure 175, the measured consumption has a relationship with the ALD values, but the over-lighting and the under-lighting problems make it not-perfectly linear. Indeed, in ON-OFF cases, where there were most of over-lighting and under-lighting problems, it cannot be possible to find a relationship between ALD and consumption. Following table reports the indices considering the afternoon time. Comparing the OAR with the ones in Table 44, they are greater in the afternoon when most part of the ALD amount is concentrated. While, the UAR values in some cases are greater in some case not, e.g. looking at the case of 10/11/2017. For this day, when the ALD were 2,075 lx·h for the whole day and 1,403 lx·h for the afternoon, a large part of UAR values calculated for the afternoon is lower, even if during the afternoon, the UAR achieved values greater than 0.90.

Date	ALD [lx·h]	Dimmer				ON-OFF			
		OAR	UAR	ELCE [Wh]	ERI [Wh/lx·h]	OAR	UAR	ELCE [Wh]	ERI [Wh/lx·h]
21/10/2017	377.2	0.78	0.87	131.3	0.50	0.34	0.81	252.0	0.67
22/10/2017	405.2	0.92	0.89	119.9	0.41	0.33	0.88	278.5	0.69
23/10/2017	1,533.9	0.87	0.99	363.6	0.22	0.74	1	473.7	0.31
24/10/2017	314.6	0.97	0.62	48.2	0.24	0.42	0.80	186.7	0.59
25/10/2017	251.9	0.93	0.72	44.8	0.26	0.27	0.91	204.0	0.81
26/10/2017	510.0	0.97	0.33	42.2	0.15	0.73	0.38	87.0	0.17
27/10/2017	1,110.2	0.87	0.81	268.3	0.29	0.53	1	473.7	0.43
28/10/2017	1,419.7	0.97	0.97	337.6	0.24	0.78	0.99	456.8	0.29
29/10/2017	1,097.1	0.99	0.70	203.7	0.19	0.53	1	473.7	0.43
30/10/2017	1,557.3	0.99	0.92	340.3	0.22	0.75	1	473.7	0.30
31/10/2017	1,435.6	0.90	0.98	368.6	0.26	0.69	1	473.7	0.33
01/11/2017	1,958.0	0.99	0.99	411.7	0.21	0.94	1	473.7	0.24
02/11/2017	1,020.6	0.99	0.82	183.4	0.18	0.64	0.93	386.7	0.38
03/11/2017	998.3	0.98	0.79	167.6	0.17	0.62	0.93	348.0	0.35
04/11/2017	1,913.1	0.96	1	415.0	0.24	0.92	1	473.7	0.25
05/11/2017	1,866.9	0.99	0.98	386.5	0.21	0.90	1	473.7	0.25
06/11/2017	1,045.7	0.96	0.75	199.4	0.19	0.69	0.81	367.7	0.35
07/11/2017	837.0	0.82	0.81	255.4	0.31	0.63	0.79	358.9	0.43
09/11/2017	554.2	0.86	0.77	166.1	0.30	0.49	0.88	350.0	0.63
10/11/2017	1,403.2	0.99	0.71	296.8	0.21	0.73	0.76	367.7	0.26
11/11/2017	1,723.5	0.98	0.98	399.3	0.23	0.90	0.99	456.8	0.25
12/11/2017	1,755.3	0.98	0.96	401.8	0.23	0.84	1	473.7	0.27

Table 44. The indices calculated for the office in dimming control and ON/OFF control considering only afternoon time for the Zumtobel II system

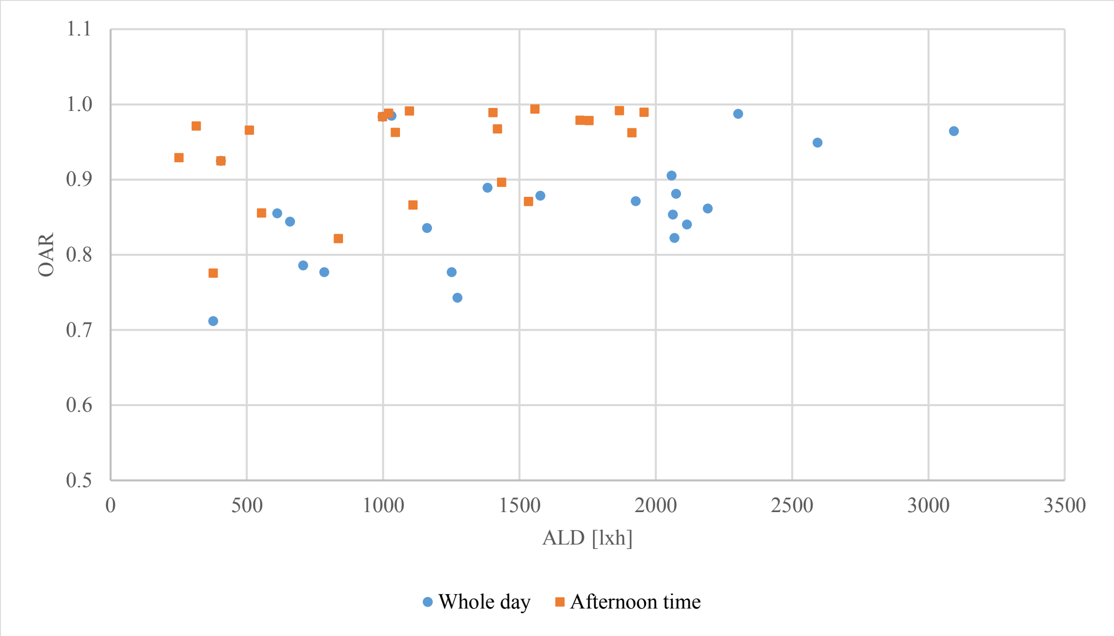


Figure 176. Comparison of the relationship between OAR index and ALD in office time scheduled operation, calculated for the whole day, and of the relationship between OAR index and ALD in office time scheduled operation calculated for the afternoon time for the Zumtobel II system

The same observation made for the other systems, regarding the relationship between consumption and ALD can be replicated for Zumbtobel II. As well in this case, the relationship is not perfectly linear as it should be because of the over and under-lighting “noise”.

9.2.2. Residential scenarios

In this section, the same analyses, but for the residential end-use are presented. Obviously, the ALD values are lower than the one calculated for office schedules, but only because of the smaller number of hours respect to the number of hours considered for office end-use.

9.2.2.1. Bticino system

Looking at the Table 45, it is possible to see that ALD range between 280 and 584 lx·h.

It must be noted that the scheduled time considered in these scenarios included the hours when the most percentage of ALD are concentrated. The same consideration can be done for the consumption. Since the indices values are very similar values, the relationship is not so appreciable as for the office cases.

Scheduled	Date	ALD [lx·h]	Cda [%]	Dimmer				ON-OFF			
				OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]	OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]
18:00-22:15	14/07/2016	373.3	55	0.53	0.90	240.4	0.64	0.05	0.95	241.1	0.65
18:00-21:45	15/07/2016	341.9	52	0.42	0.91	244.8	0.72	0.03	0.95	261.7	0.77
18:45-22:00	19/07/2016	321.9	47	0.46	0.86	194.8	0.61	0.02	1	222.8	0.71
17:30-22:00	20/07/2016	331.6	62	0.80	0.84	158.7	0.47	0.06	0.88	195.3	0.59
18:00-22:30	22/07/2016	405.2	53	0.82	0.89	180.2	0.44	0.04	0.91	230.9	0.57
17:45-22:30	23/07/2016	425.1	54	0.89	0.71	163.7	0.68	0.03	0.88	216.1	0.90
18:15-21:45	25/07/2016	353.9	48	0.81	0.81	172.9	0.49	0.03	0.64	237.9	0.72
18:15-21:45	26/07/2016	316.8	53	0.47	0.85	143.1	0.43	0.03	0.88	202.2	0.62
18:15-22:30	29/07/2016	421.3	49	0.48	0.86	187.4	0.43	0.04	0.94	229.2	0.53
18:15-22:30	01/08/2016	442.3	47	0.84	0.88	145.1	0.33	0.04	0.96	221.9	0.51
17:45-22:00	03/08/2016	361.4	56	0.81	0.88	170.4	0.47	0.04	0.83	182.9	0.51
17:45-22:00	04/08/2016	408.2	12	0.82	0.84	173.7	0.43	0.04	0.94	244.1	0.60
17:15-22:15	05/08/2016	390.4	60	0.80	0.63	173.1	0.44	0.04	0.82	178.6	0.62
17:15-22:15	06/08/2016	359.9	62	0.79	0.67	173.7	0.48	0.04	0.85	241.4	0.67
17:17-21:00	12/08/2016	281.0	66	0.84	0.85	115.9	0.41	0.05	0.80	156.3	0.57
17:00-23:00	13/08/2016	584.1	34	0.84	0.92	250.6	0.43	0.04	0.98	305.8	0.53
17:00-21:45	16/08/2016	289.5	68	0.51	0.41	182.6	0.68	0.02	0.94	222.1	0.79
17:00-21:00	18/08/2016	266.5	65	0.71	0.88	143.7	0.48	0.03	0.44	172.7	0.81
18:45-23:00	20/08/2016	583.8	29	0.97	0.91	192.7	0.33	0.04	0.99	299.0	0.52
18:45-23:00	21/08/2016	581.9	29	0.85	0.94	218.9	0.38	0.04	1	305.0	0.53

Table 45. The indices calculated for the residential cases in dimming control and ON/OFF control for the Bticino system

In Figure 177, an example of measurement taken during the 21/08/2016 are shown. It is possible to see that there were not big problems of over-lighting or under-lighting.

As it is possible to see in Table 45, all the control systems in residential use have been tested only during summer time. The illuminance measures plotted in the graph in Figure 177, demonstrate that the luminaires worked for most of the time at 100% of the power during all the occupancy time. It means that the luminaires were not dimmed during the winter time, when, with the same occupancy time, the ALD would be higher. Therefore, in these case the system behaviour would be very close to the ideal one and, therefore the calculation of the indices would not make sense. It is visible in Figure 192, where some last measures taken during the Zumtobel II system test are plotted.

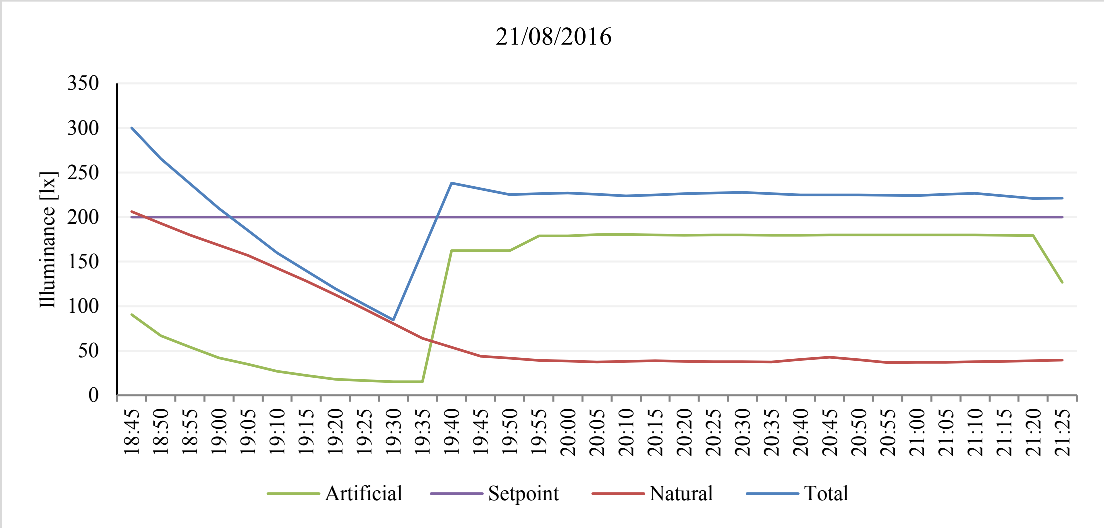


Figure 177. Example of illuminance values measured on 21/08/2016 in dimming operation for the Bticino system

In general, it is possible to see that, being generally the ALD high (related to the number of hours), the systems worked well. ERI have assumed values from 0.33 to 0.74 Wh/lx·h. In general, for this system, in office use, the occurrences of the over illumination are higher than in residential mode. This is due to the fact that, in these latter cases, dimming control is well actuated mainly in the late afternoon, because of the low daylight level. Similar considerations can be made while comparing ON/OFF control operation for office and residential uses. As well in this case, plotting all the calculated values of OAR and ERI (Figure 180), it is possible to note that there is a good relationship between the two indices and, as expected, the higher OAR the lower ERI. Moreover, the graphs show that as the ERI index decreases and as OAR tends to 1, the slope of the line decreases. Bearing in mind that ERI is a specific consumption index, this means that the influence of over-lighting on energy consumption is higher when low OAR occurs.

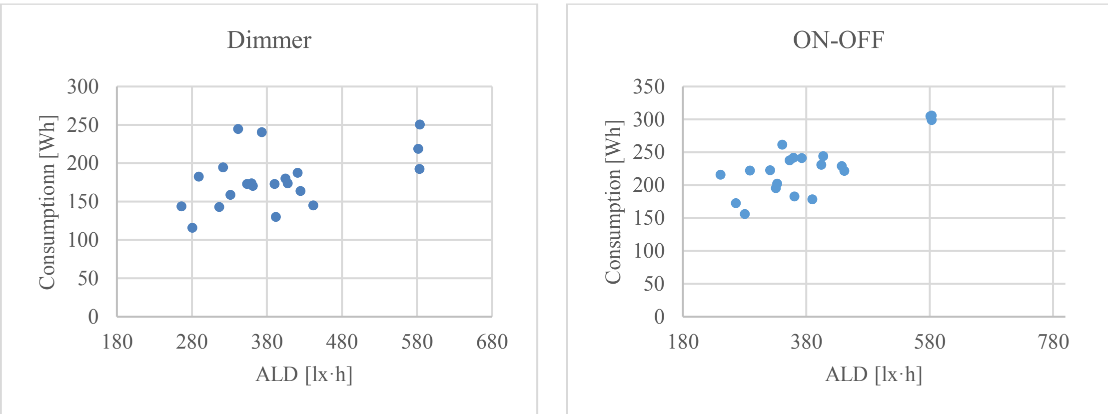


Figure 178. Relationship between ALD and consumption calculated for the residential in dimming control (a) and ON/OFF control (b) for the Bticino system

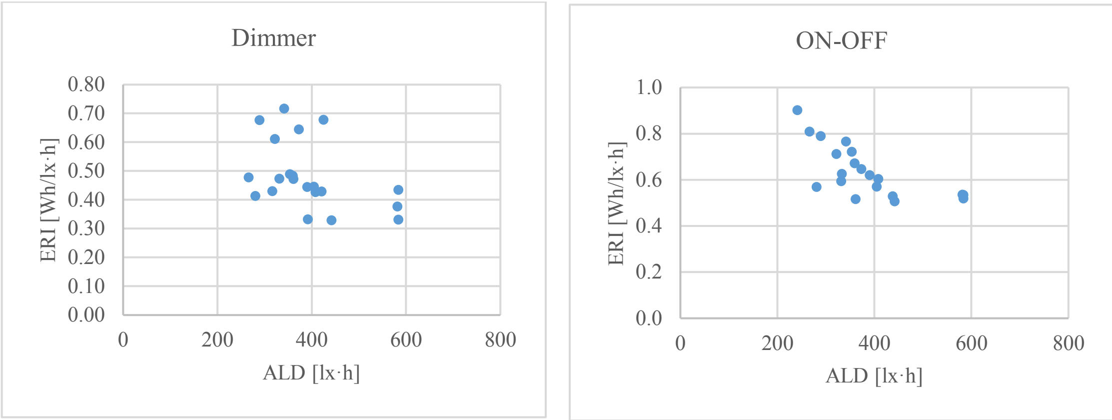


Figure 179. Relationship between ERI and ALD indices calculated for the residential in dimming control (a) and ON/OFF control (b) for the Bticino system

Looking at the relationship between OAR and ERI, the higher is the ERI the lower is the OAR both in dimmer and ON-OFF cases.

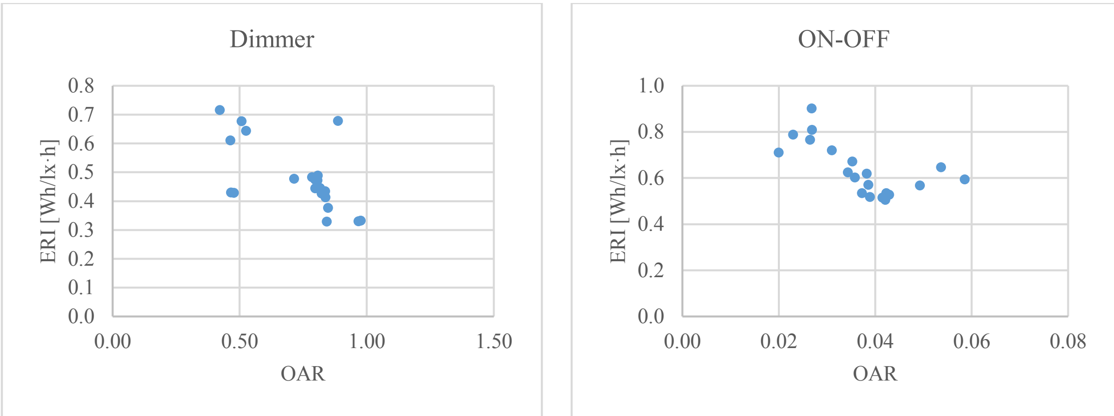


Figure 180. Relationship between ERI and OAR indices calculated for the residential in dimming control (a) and ON/OFF control (b) for the Bticino system

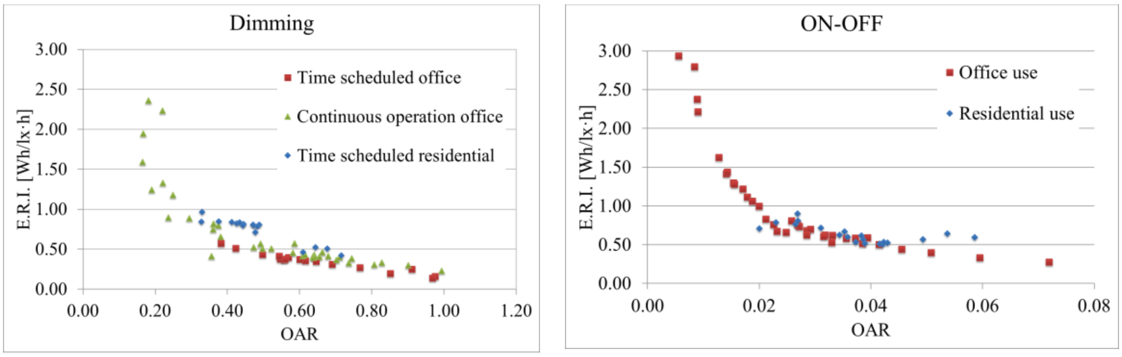


Figure 181. Relationship between ERI index and OAR index calculated in dimming control (a) and ON/OFF control (b) for the Bticino system

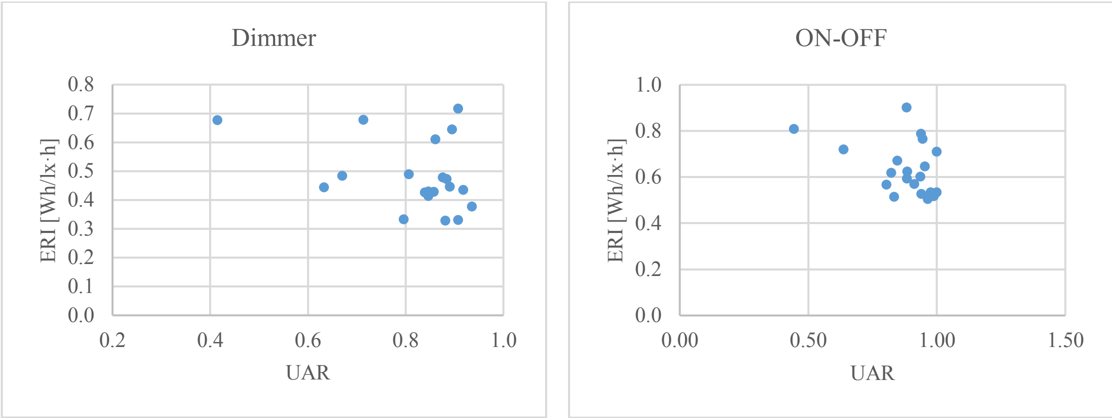


Figure 182. Relationship between ERI and UAR indices calculated for the residential in dimming control (a) and ON/OFF control (b) for the Bticino system

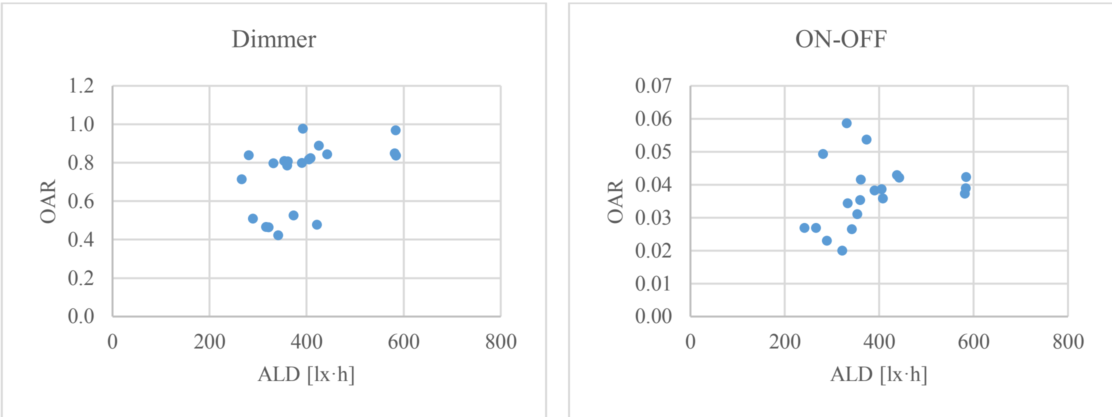


Figure 183. Relationship between OAR and ALD indices calculated for the residential in dimming control (a) and ON/OFF control (b) for the Bticino system

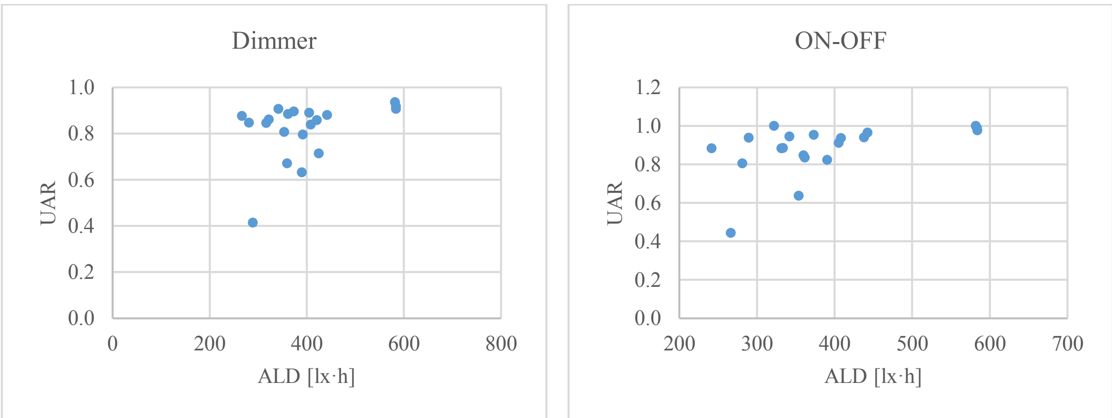


Figure 184. Relationship between UAR and ALD indices calculated for the residential in dimming control (a) and ON/OFF control (b) for the Bticino system

9.2.2.2. Zumtobel I system

Better relationships have been found plotting the indices calculated for the Zumtobel system. As well, in this case, the higher is the ERI the lower is the ALD and the higher is the OAR the lower is the ERI.

For the Bticino system, there is a good relationship between OAR and ALD. On the contrary, it is weaker between ALD and UAR. Except for some cases, these last indices are very high for same reasons explained for the other system.

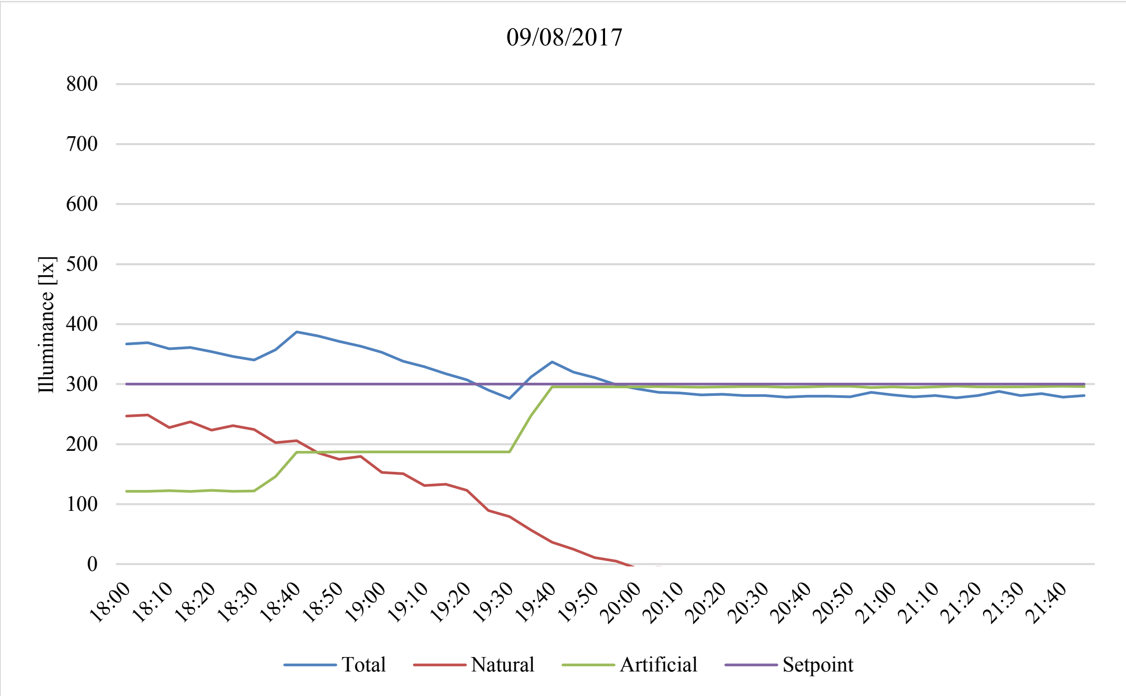


Figure 185. Example of illuminance values measured on 09/08/2017 in dimming operation for the Zumtobel I system

In Figure 185 it is possible to see that for almost half of the time the luminaires are switched on at 100%. It is because the scenarios started at 18:00 of a day of August when the daylight contribution is higher than the winter time. As well in this, in residential use the control system was not tested during winter time.

Scheduled	Date	ALD [lx· h]	Cda	Dimmer				ON-OFF			
				OAR	UAR	ELEC [Wh]	ERI [Wh/lx· h]	OAR	UAR	ELEC [Wh]	ERI [Wh/lx· h]
18:00:00-22:15	06/08/2017	977.7	23	0.93	0.98	270.7	0.28	0.72	1	320.7	0.34
18:00-21:45	09/08/2017	775.2	28	0.86	1	233.6	0.30	0.67	1	283.7	0.37
18:45-22:00	08/08/2017	818.8	12	0.94	1	223.9	0.27	0.82	1	246.7	0.30

Scheduled	Date	ALD [lx· h]	Cda	Dimmer				ON-OFF			
				OAR	UAR	ELEC [Wh]	ERI [Wh/lx· h]	OAR	UAR	ELEC [Wh]	ERI [Wh/lx· h]
17:30-22:00	07/08/2017	822.3	36	0.81	1	269.1	0.33	0.60	1	339.2	0.41
18:00-22:30	10/08/2017	807.6	10	0.89	1	234.7	0.29	0.70	1	283.7	0.35
17:45-22:30	11/08/2017	976.0	19	0.94	1	289.0	0.37	0.77	1	315.3	0.32
18:15-21:45	12/08/2017	733.9	27	0.86	0.30	216.8	0.29	0.68	1	265.2	0.36
18:15-21:45	01/09/2017	892.7	12	0.96	0.98	231.9	0.17	0.82	1	262.9	0.30
18:15-22:30	18/08/2017	1,015.2	16	0.92	1	286.3	0.28	0.78	1	320.7	0.32
17:45-22:00	16/08/2017	820.6	27	0.82	1	259.5	0.32	0.64	1	314.5	0.38
17:45-22:00	17/08/2017	864.4	29	0.84	1	267.3	0.31	0.66	1	318.0	0.37
17:15-22:15	19/08/2017	977.6	7	0.84	1	253.5	0.26	0.64	1	376.2	0.38
17:15-22:15	02/09/2017	1,278.0	11	1	0.69	231.4	0.18	0.83	1	376.2	0.30
17:15-21:00	28/08/2017	636.0	30	0.80	0.94	208.4	0.33	0.65	1	376.2	0.38
17:00-21:45	29/08/2017	867.9	36	0.91	0.96	244.0	0.28	0.76	0.98	288.3	0.32
18:45-23:00	30/08/2017	1,145.6	8	0.96	1	303.0	0.27	0.88	1	320.7	0.28
18:45-23:00	31/08/2017	1,179.3	5	0.97	1	269.5	0.26	0.91	1	318.0	0.27
18:00-22:15	03/09/2017	1,044.9	3	0.98	0.95	257.3	0.24	0.80	1	320.7	0.31
18:00-21:45	04/09/2017	895.9	2	0.90	1	253.6	0.28	0.78	1	283.7	0.32
18:45-22:00	05/09/2017	880.3	3	0.98	0.98	223.1	0.25	0.88	1	246.7	0.28
17:30-22:00	06/09/2017	978.7	6	0.90	0.97	275.6	0.28	0.74	0.99	328.5	0.34
18:00-22:30	07/09/2017	953.4	24	0.93	1	261.6	0.27	0.83	1	283.7	0.30
17:45-22:00	13/09/2017	1,154.4	11	0.99	0.97	288.6	0.25	0.89	1	318.0	0.28
17:00-23:00	14/09/2017	1,322.1	21	0.93	0.97	362.1	0.27	0.78	0.99	417.3	0.32
17:00-21:45	15/09/2017	1,006.7	26	0.86	1	305.3	0.30	0.69	1	357.7	0.36
17:00-21:00	16/09/2017	942.3	20	0.95	0.97	250.4	0.27	0.74	1	302.2	0.34
18:45-23:00	17/09/2017	1,256.0	0.5	1	0.99	319.2	0.25	0.93	1	318.0	0.26

Table 46. The indices calculated for the residential in dimming control and ON/OFF control for the Zumtobel I system

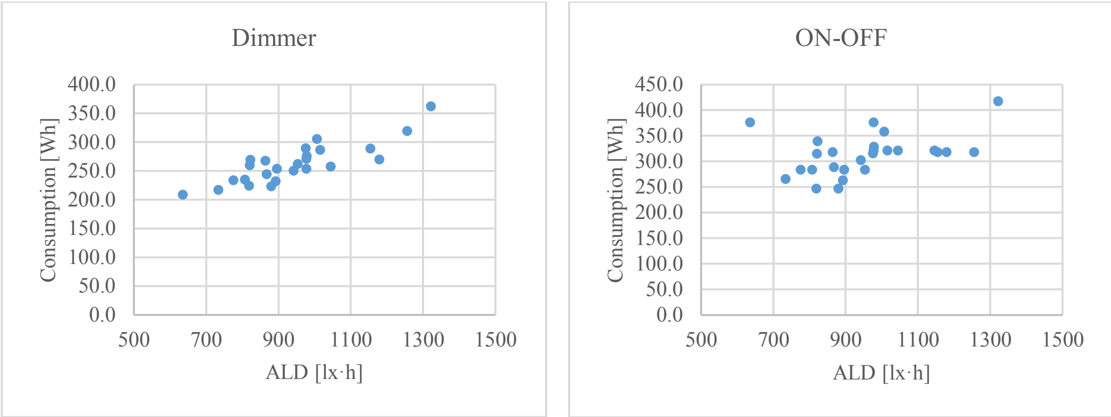


Figure 186. Relationship between ALD and consumption calculated for the residential in dimming control (a) and ON/OFF control (b) for the Zumtobel I system

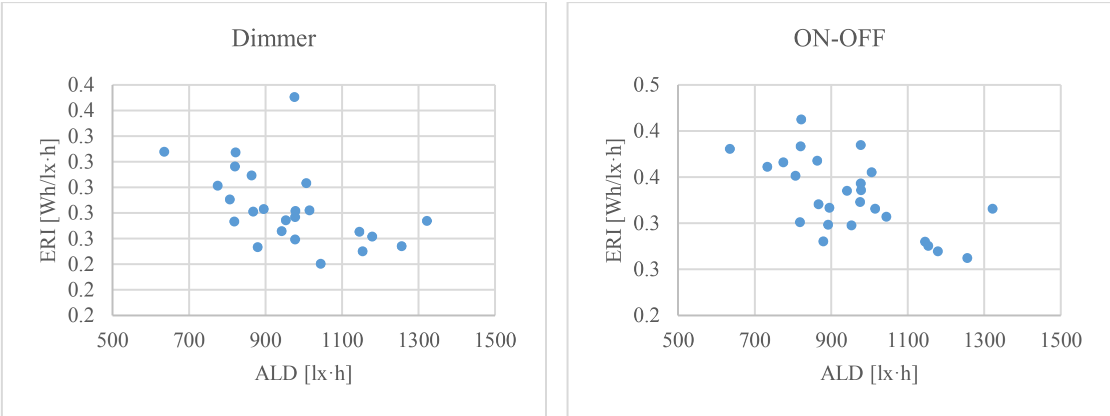


Figure 187. Relationship between ERI and ALD indices calculated for the residential in dimming control (a) and ON/OFF control (b) for the Zumtobel I system

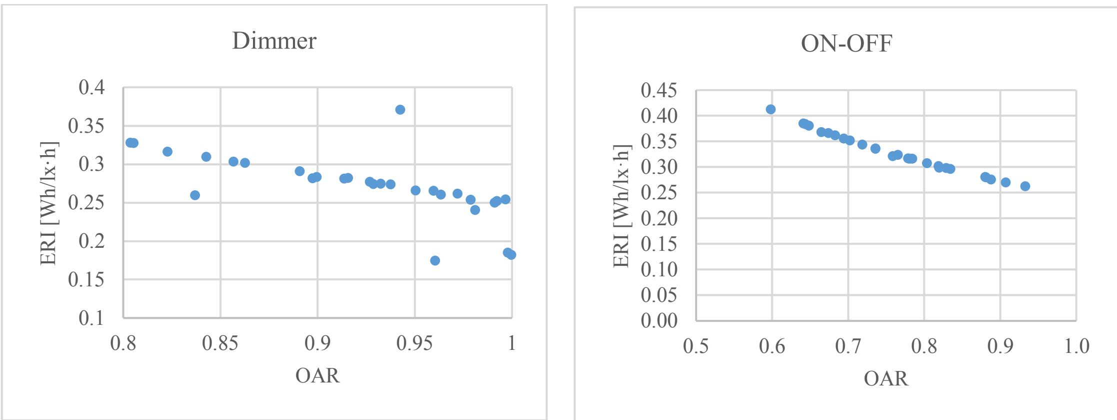


Figure 188. Relationship between ERI and OAR indices calculated for the residential in dimming control (a) and ON/OFF control (b) for the Zumtobel I system

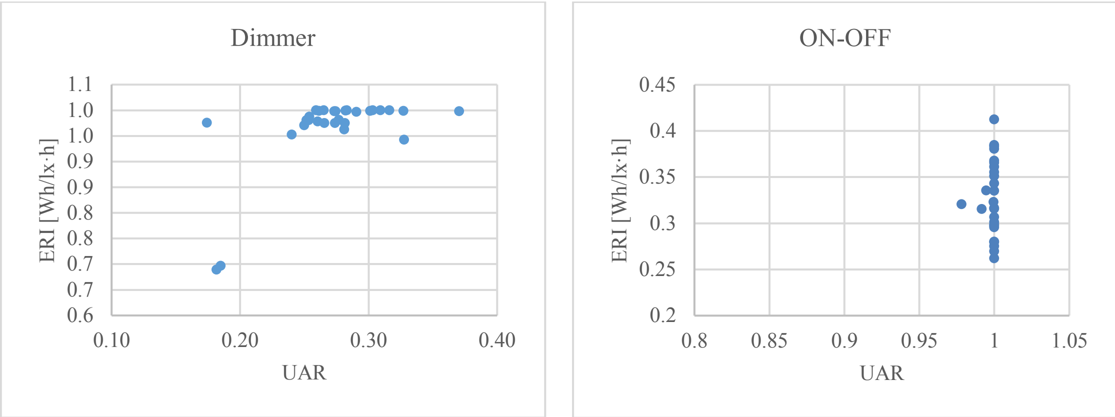


Figure 189. Relationship between ERI and UAR indices calculated for the residential in dimming control (a) and ON/OFF control (b) for the Zumtobel I system

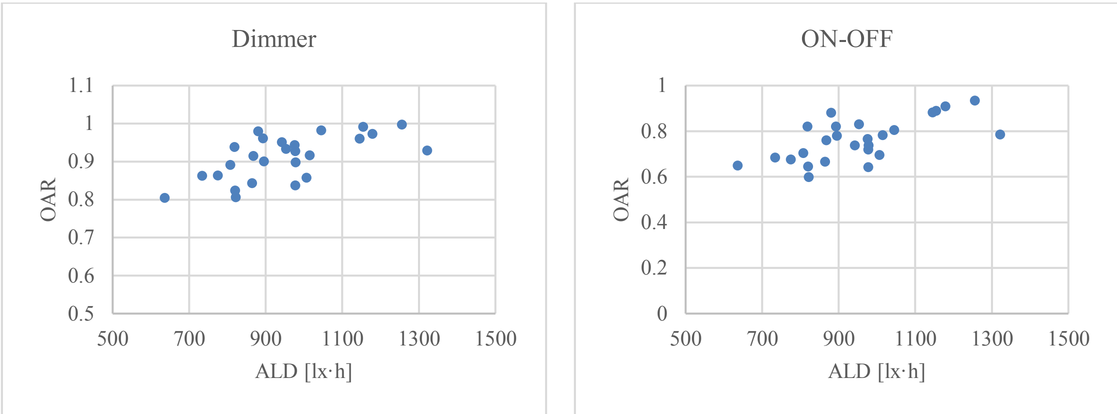


Figure 190. Relationship between OAR and ALD indices calculated for the residential in dimming control (a) and ON/OFF control (b) for the Zumtobel I system

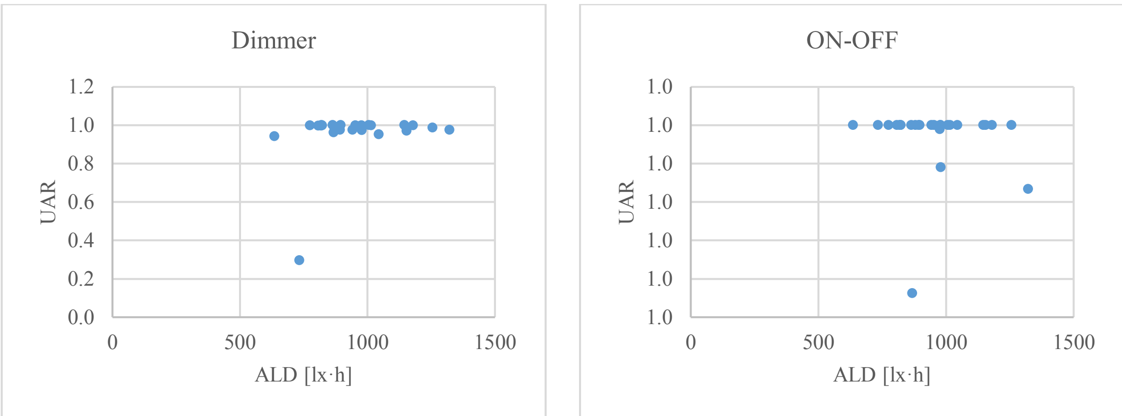


Figure 191. Relationship between UAR and ALD indices calculated for the residential in dimming control (a) and ON/OFF control (b) for the Zumtobel I system

9.2.2.3. Zumtobel II system

Finally, as well for the residential end use, the indices have been calculated with the photosensor placed in the position II. They are shown in Table 47.

Schedules	Date	ALD [lx·h]	Cda [%]	Dimmer				ON-OFF			
				OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]	OAR	UAR	ELEC [Wh]	ERI [Wh/lx·h]
18:00-22:15	18/09/2017	1,109.0	9	0.96	0.98	288.8	0.26	0.85	1	320.7	0.29
18:00-21:45	19/09/2017	955.0	11	1	0.70	176.7	0.18	0.83	1	283.7	0.30
18:45-22:00	20/09/2017	927.1	0.6	0.99	0.98	233.5	0.25	0.93	1	246.7	0.27
17:45-22:30	24/09/2017	1,237.0	9	0.96	0.98	324.6	0.26	0.85	1	357.7	0.29
18:15-21:45	25/09/2017	970.7	0.5	0.96	1	222.9	0.23	0.90	1	265.2	0.27
18:15-21:45	26/09/2017	992.3	0.2	0.97	1	226.2	0.23	0.92	1	317.7	0.27
18:15-22:30	27/09/2017	1,196.0	0.3	0.99	0.98	304.3	0.25	0.92	1	320.7	0.27
18:15-22:30	28/09/2017	1,200.7	0.2	0.99	0.98	304.5	0.25	0.92	1	320.7	0.27
17:45-22:00	29/09/2017	1,164.3	0.7	0.99	0.97	294.5	0.25	0.90	1	318.0	0.27
17:15-22:15	03/10/2017	1,335.7	1.3	0.98	0.98	287.9	0.22	0.88	1	376.2	0.28
17:15-22:15	04/10/2017	1,321.5	1.5	1	0.69	188.9	0.14	0.87	1	188.8	0.28
17:15-21:00	05/10/2017	714.4	6.5	0.95	0.95	217.3	0.30	0.87	1	376.2	0.28
17:00-23:00	06/10/2017	1,468.8	13	0.92	0.84	347.8	0.24	0.82	1	444.0	0.30
17:00-21:45	07/10/2017	1,203.6	11	0.94	0.85	281.0	0.23	0.83	1	357.7	0.24
17:00-21:00	08/10/2017	693.7	23	0.75	1	237.4	0.34	0.57	1	302.2	0.44
18:45-23:00	09/10/2017	953.1	0	1	0.98	239.8	0.25	0.93	1	320.7	0.26
18:45-23:00	10/10/2017	952.8	0	1	0.98	240.3	0.25	0.73	1	320.7	0.34
18:00-22:15	11/10/2017	927.6	3	0.97	0.98	240.4	0.26	0.71	1	320.7	0.35
18:00-21:45	12/10/2017	941.7	1.2	0.99	0.98	240.0	0.25	0.72	1	320.7	0.34
18:45-22:00	13/10/2017	732.4	0.1	1	0.98	184.7	0.25	0.73	1	246.7	0.34
17:30-22:00	14/10/2017	952.0	5.6	0.94	0.98	256.9	0.27	0.69	1	339.2	0.36
18:00-22:30	15/10/2017	824.5	2	0.98	0.98	212.4	0.26	0.72	1	283.7	0.34
17:45-22:30	16/10/2017	937.3	1.7	0.99	0.98	240.2	0.26	0.72	1	320.7	0.34

Table 47. The indices calculated for the residential in dimming control and ON/OFF control for the Zumtobel II system

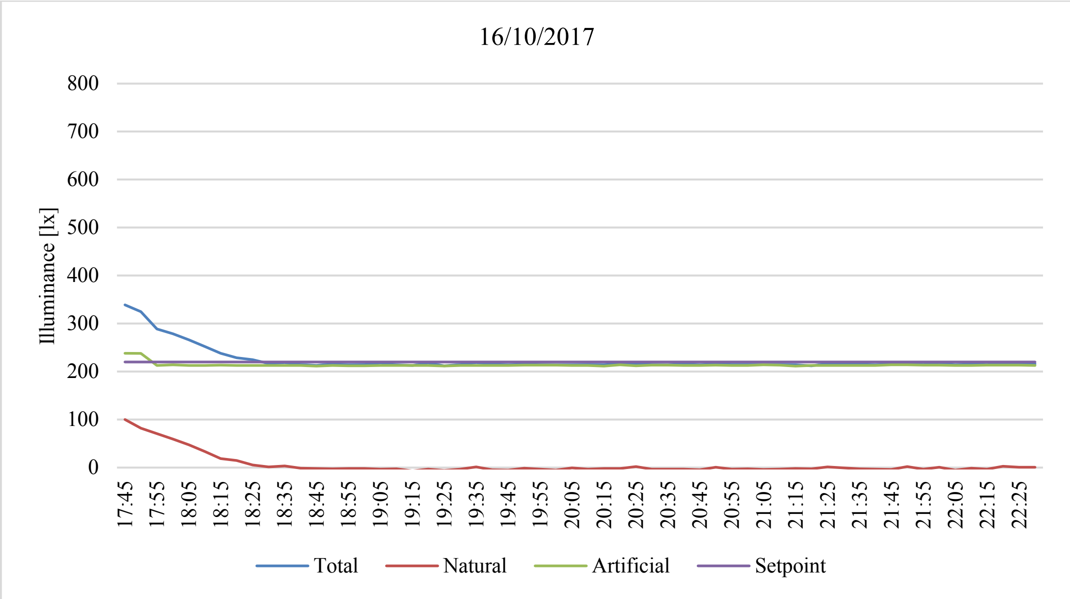


Figure 192. Example of illuminance values measured on 16/10/2017 in dimming operation for the Zumtobel II system

As already said commenting the Bticino system behaviour, during the winter time in residential use, the indices calculation would not have sense because the behaviour of the system would be very close to the ideal one, since the luminaires would not be dimmed, as shown it Figure 192.

The relationships between the indices are the same of the other system.

The comparison between the indices calculated with the data will be shown in next paragraph, as well with the comparison of them with the system Bticino

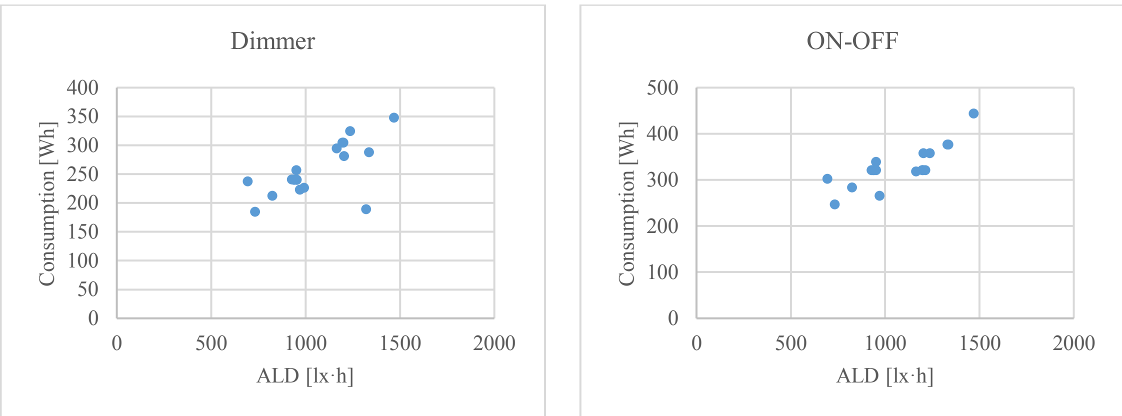


Figure 193. Relationship between ALD and consumption calculated for the residential in dimming control (a) and ON/OFF control (b) for the Zumtobel II system

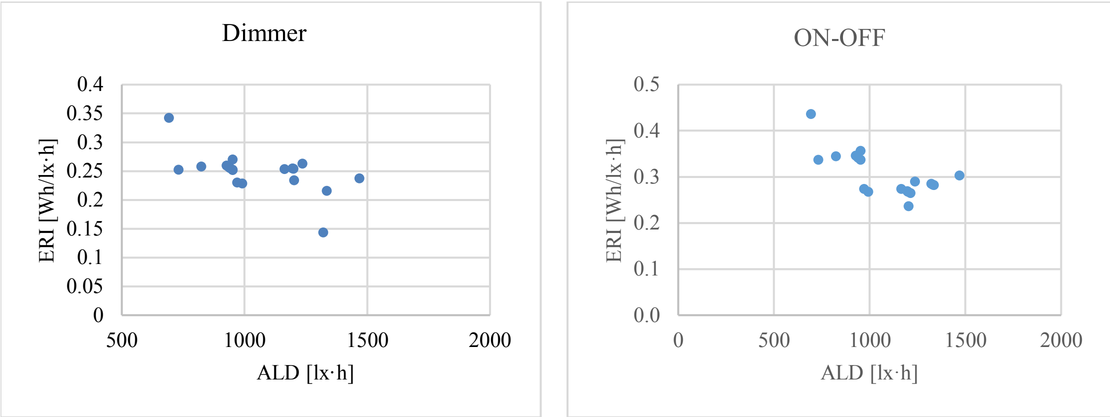


Figure 194. Relationship between ERI and ALD indices calculated for the residential in dimming control (a) and ON/OFF control (b) for the Zumtobel II system

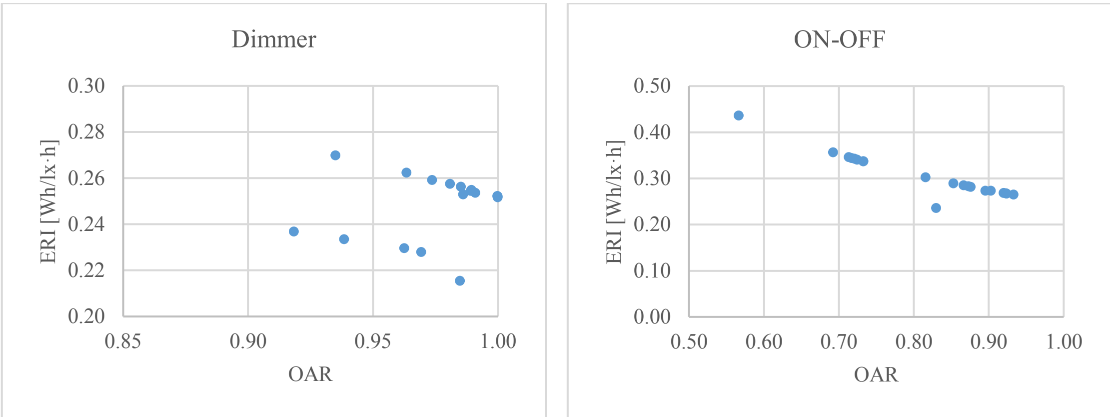


Figure 195. Relationship between ERI and OAR indices calculated for the residential in dimming control (a) and ON/OFF control (b) for the Zumtobel II system

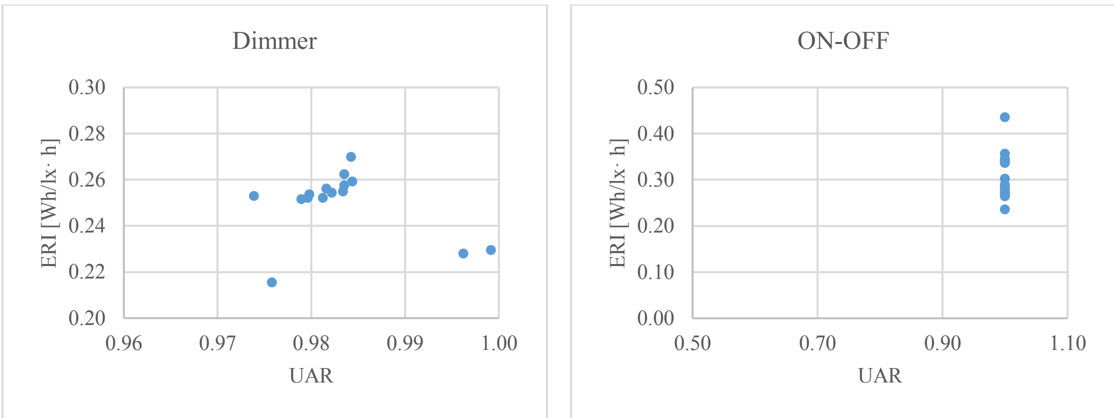


Figure 196. Relationship between ERI and UAR indices calculated for the residential in dimming control (a) and ON/OFF control (b) for the Zumtobel II system

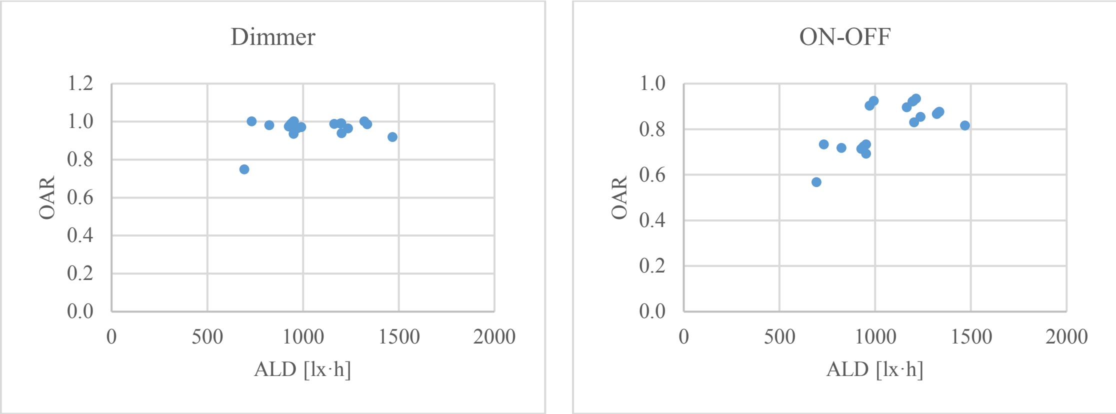


Figure 197. Relationship between OAR and ALD indices calculated for the residential in dimming control (a) and ON/OFF control (b) for the Zumtobel II system

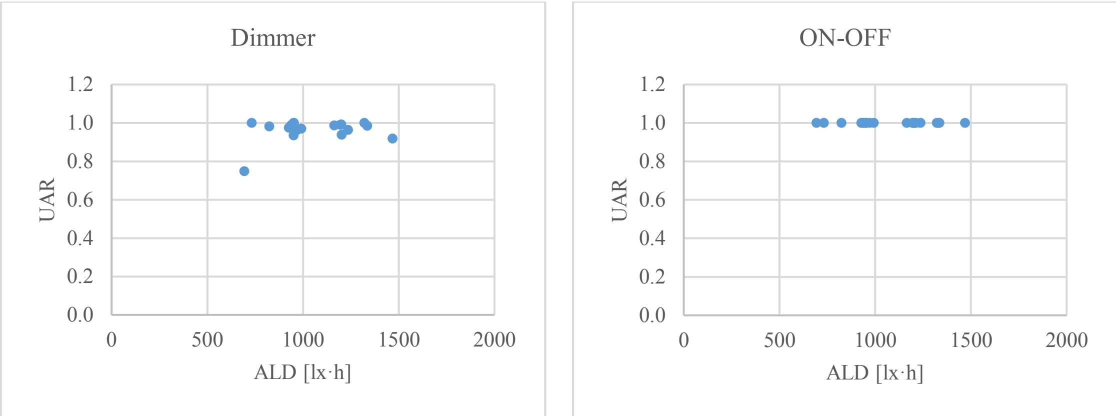


Figure 198. Relationship between UAR and ALD indices calculated for the residential in dimming control (a) and ON/OFF control (b) for the Zumtobel II system

9.2.3. Comparison between the systems

One of the aim of the calculation and analysis of this set of indices is to make a comparison of actual performances of different systems under the same or different conditions.
Following chapters presents this kind of analysis for the cases of office and residential end-uses.

9.2.3.1. Comparison of systems in office end-use

In Figure 199, the comparison between ALD and OAR in office time scheduled operation, calculated for the system Zumtobel with the sensor in the position I and in position II is shown. It can be noted that the OAR of the system with the photosensor placed in the position II are more homogeneous. While, in the other case, there is a wide range of values. So, the photosensor in the position II had higher performances in most cases in terms of high values of OAR manly for operations in ON/OFF mode. Similar considerations can be made for the UAR.

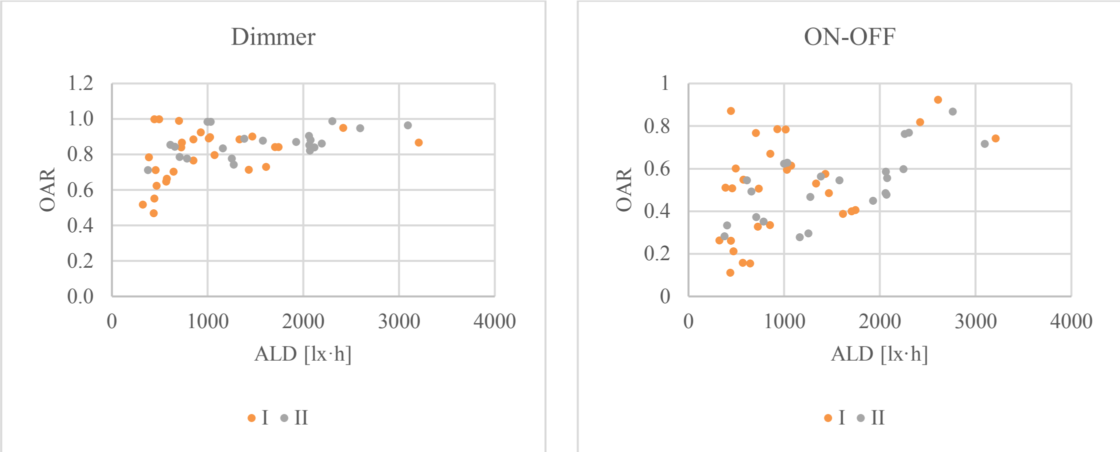


Figure 199. Comparison of the relationship between ALD index and OAR in office time scheduled operation, calculated for the system Zumtobel with the sensor the position I, and II

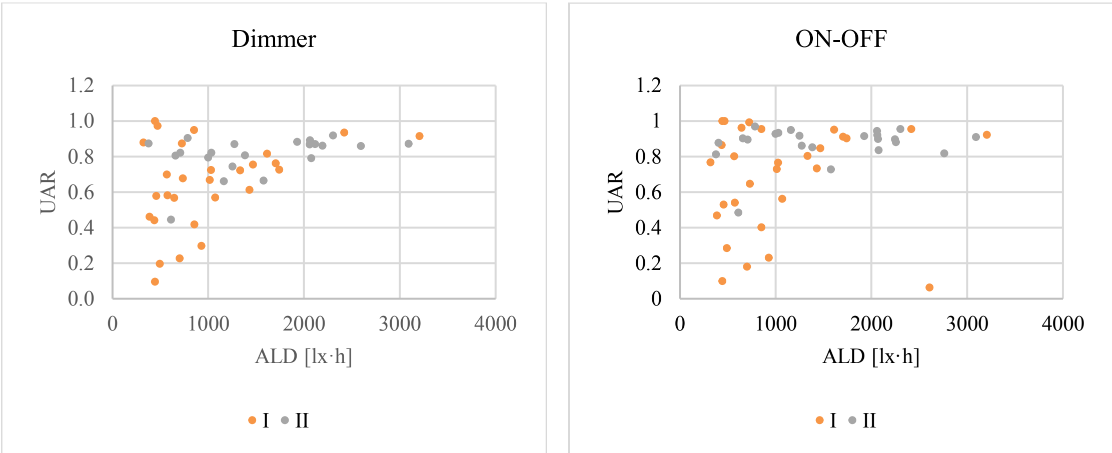


Figure 200. Comparison of the relationship between ALD index and UAR in office time scheduled operation, calculated for the system Zumtobel with the sensor in the position I and II

Results for scenarios reported in Tables 41 and 43 are characterized by ALD values that ranges between 315 lx·h and 1,797, for the Biticino, and from 322 and 3207 lx·h, for the Zumtobel I and between 377 and 2,303 lx·h for the Zumtobel II.

Starting to compare how the systems worked, it can be noted that in some cases, they worked in different way in scenarios with ALD very similar. For instance, for the scenarios with ALD of about 322 lx·h an OAR of 0.22 and an UAR of 1 have been calculated for the Biticino system and an OAR of 0.52 and an UAR of 0.88 for Zumtobel I. Also, for scenarios with ALD of about 703 lx·h an OAR of 0.19 and an UAR of 1 have been calculated for the Bticino, an OAR of even 0.99 an UAR of 0.23 for Zumtobel I.

The graphs in Figure 201 show the relationship between OAR and ALD indices for the systems operated by the two control strategies. In general, high values of OAR corresponded high values of ALD. It means that the systems worked better when there was low contribution of daylight. So, in general, the greater the ALD, the lower the possibility of having over-lighting problems. The same is for the ON-OFF control case.

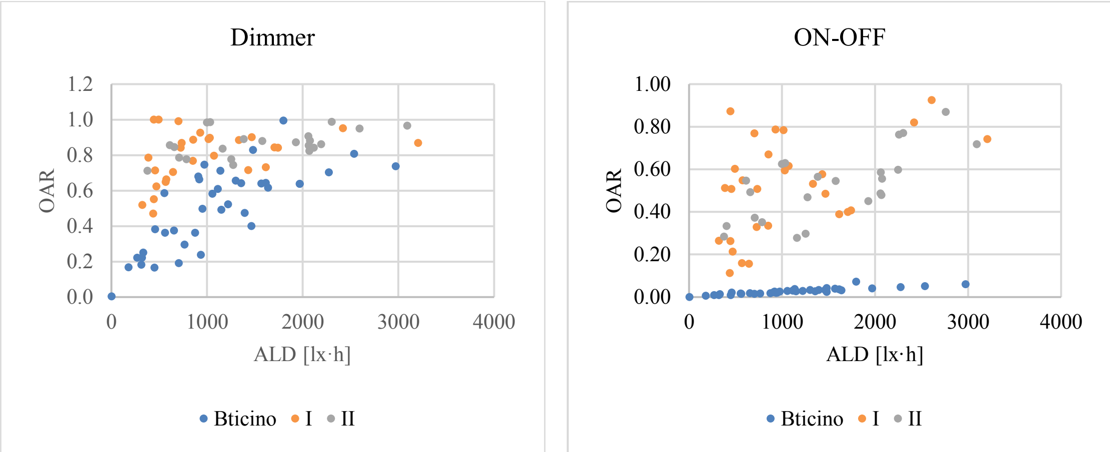


Figure 201. Relationship between ALD index and OAR index calculated in dimming control and ON/OFF control for the systems

More in detail, in dimming operation system Bticino had OAR lower than both Zumtobel systems. For all the systems a certain linear relationship with ALD can be observed. In ON-OFF operation (Figure 201) Bticino system had a maximum of OAR equal to 0.07 (very poor result), while Figures of Zumtobel system are generally better, even if not well correlated with ALD.

Also, observing Figure 202i and 202ii, it can be noted that the higher ERI the lower OAR values. It means that the system wastes energy over-lighting the room. On the other hand, low ERI values are coupled to low values of UAR (Figures 201iii and 202iv), because such energy "saving" is affected by an excessive under-lighting. The reason why relationships OAR vs ERI and UAR vs ERI are not very robust lays on the fact that the system can perform in under and over-lighting in the same day of operation.

It can be noted that the Bticino system in ON-OFF case had not problems of under-lighting (Figure 202iv), but it had serious problems of over-lighting (Figure 202ii).

As already noted looking at the calculated values, the Zumtobel system had higher performances than the Bticino system. Comparing the two control strategies, it can be observed that both systems had higher performances with dimmer control. Anyway, the gap between the performances of the two control strategies is larger for Bticino system. Indeed, the cloud of points calculated for the Bticino system with dimmer control shifted slightly to higher values of OAR (Figure 202i). In the case of ON-OFF control, it is much more evident (Figure 202ii).

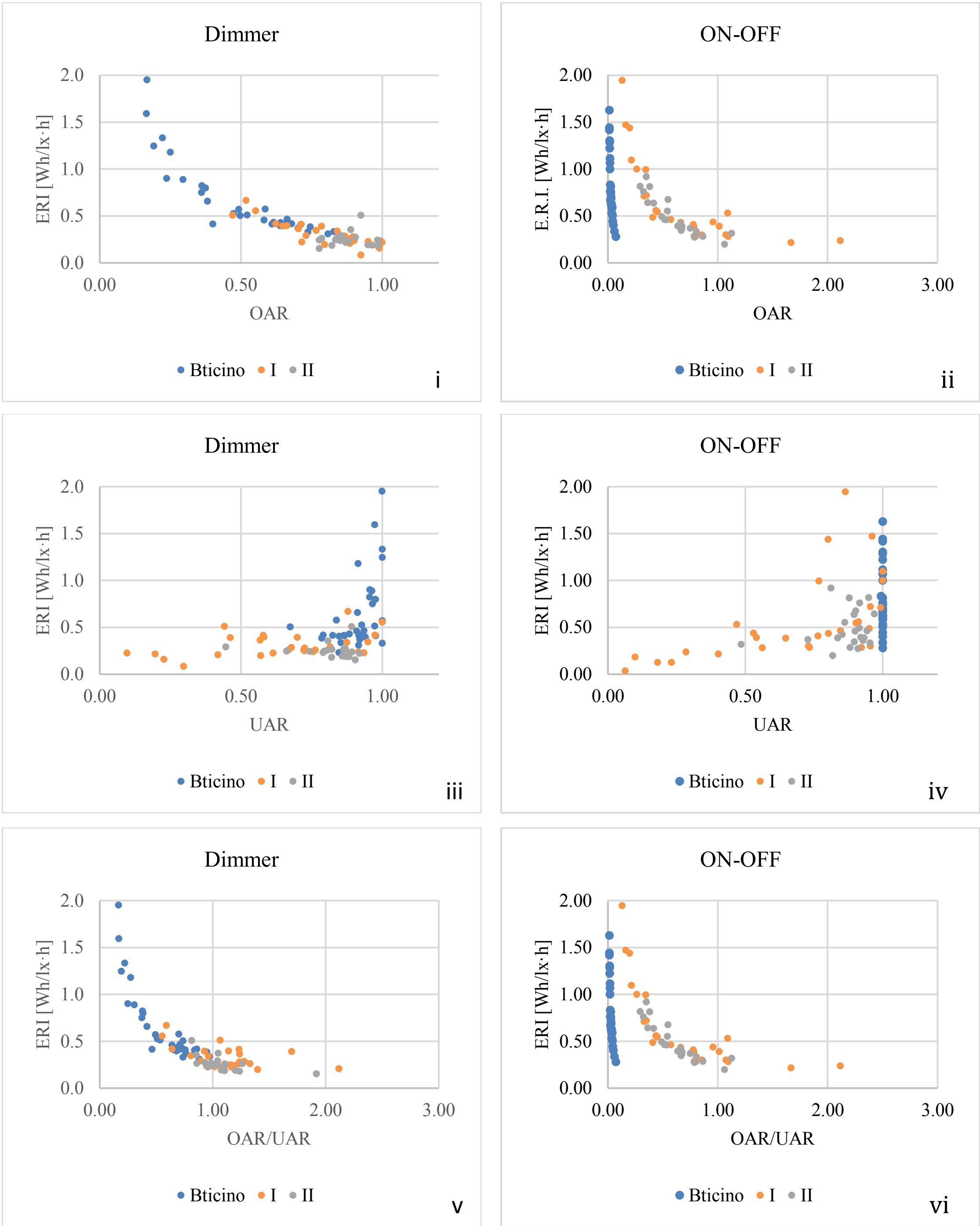


Figure 202. Relationships between ERI index, UAR and OAR index calculated in dimming control and ON/OFF control for the two systems

The OAR values are very low for the Bticino system (the highest value is 0.07). On the contrary, in the case of Zumtobel system they are higher reaching value of 0.99 in dimming case and 0.92 in ON-OFF case, while, UAR are almost every time equal 1 in ON-OFF case and in dimming case a value of UAR of 0.93 has been reached. In such a light it is useful to observe a new graph, representing the ratio OAR/UAR vs ERI.

The higher such ratio the higher is the influence of the under-lighting during the system operation.

All the considerations related to the best performance of Zumtobel system and of the dimming control for both the systems are confirmed also in graph 202iii and 202iv. Also, the predominant “overlighting” behaviour of Bticino system (with OAR/UAR generally very low) is confirmed.

It has been highlighted that the relationship between electrical consumption and ALD values (Figure 203) is useful for analysing the ALD influence on the system performance.

An “ideal consumption” for each system and scenarios has been calculated proportionally to the ALD. For this reason, the relationship is linear. On the contrary, looking at the actual consumption lines (both of Bticino system and II), the relationship is not linear. It is because, as already observed, the control system did not work as expected in ideal cases and, in some cases, low values of UAR and the OAR have been found. In general, it can be noted that the more the points are closer to such ideal consumption line, the more the system worked well. In addition, the actual consumption lines shifted from the ideal one because the absorbed power of the control systems (around 18.3 W for the Bticino system and around 10 W for the Zumtobel system).

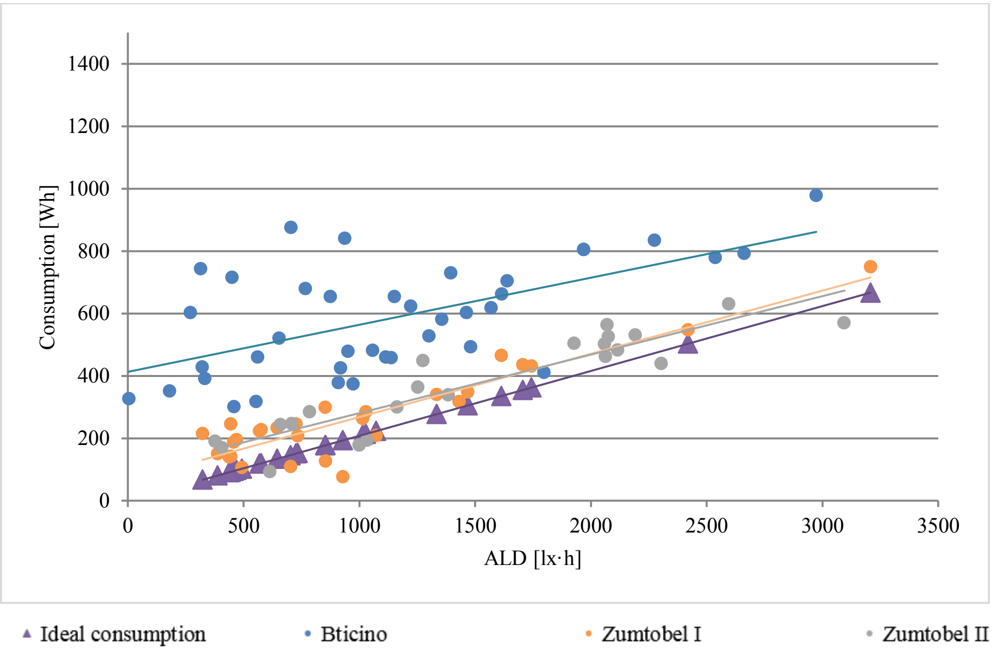


Figure 203. Comparison between the relationship of ALD index and electrical consumption for the two systems and calculated for an ideal case

9.2.3.2. *Comparison of systems performance in residential end-use*

As well for the residential cases, it is interesting to compare the indices calculated for the different systems. As an example, in the following graph (Figure 204) the OAR and the ALD of the system Zumtobel, with the photosensor placed in the two different positions are plotted. Looking at the ALD values, it is possible to have an idea of the daylight condition and of the daylight contribution. For the residential case it is not possible to see large difference of ALD and, therefore, of the daylight contribution of the two positions given that the residential scenarios have been run during the second part of the afternoon and the indoor illuminance values were low in any case as well as diffuse.

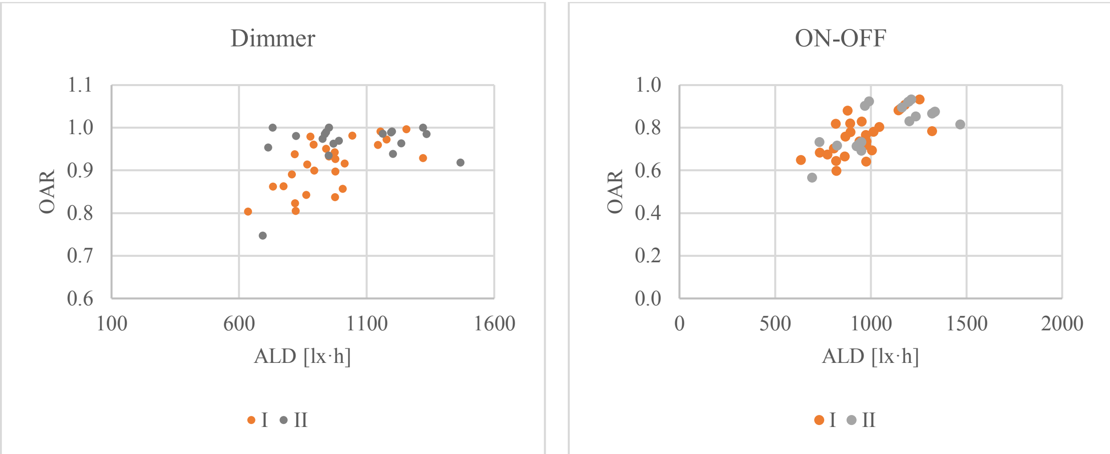


Figure 204. Comparison of the relationship between ALD index and OAR in residential time scheduled operation, calculated with the sensor in the position I, and of the relationship between ALD index and OAR in residential time scheduled operation calculated with the photosensor in the position II

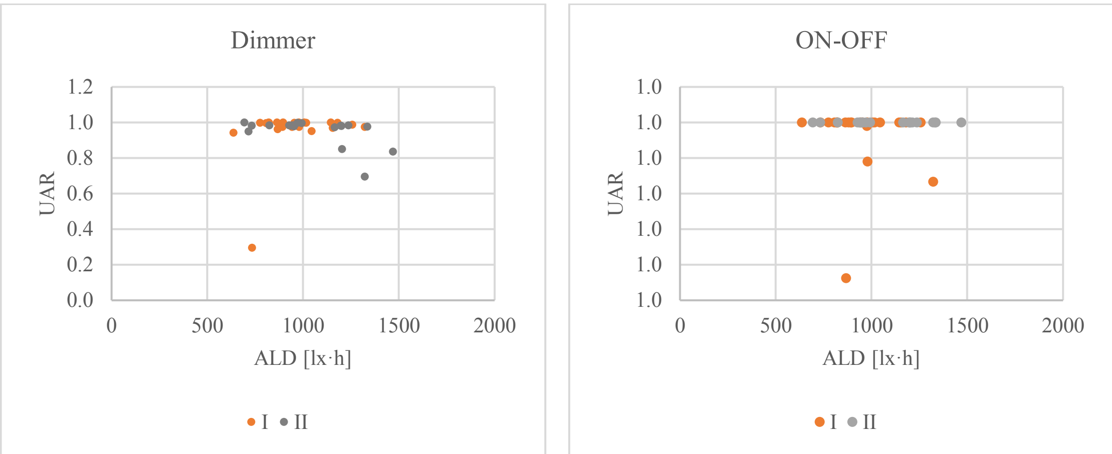


Figure 205. Comparison of the relationship between ALD index and UAR in residential time scheduled operation, calculated with the sensor in the position I, and of the relationship between ALD index and UAR in residential time scheduled operation calculated with the photosensor in the position II

Also in terms of UAR, in general, the system worked better with the photosensor in the second position, as it is possible to see in Figure 205, especially in dimmer operation. In ON-OFF operation, as see in almost all the cases, the UAR is very high and in most part of the cases equal to 1. This means that the system had not under-lighting problems.

The following graphs show the comparison between the system Bticino and the system Zumtobel with the photosensor placed in the two positions. In terms of OAR, as well for the office cases, the system Bticino had lower performances in some cases. Anyway, in general, the Bticino system the system performed better in the residential case. This is more noticeable for the ON-OFF case. For all the cases, in general, high values of OAR corresponded to high values of ALD. As well as for office case, it is possible to say that the systems worked better when there was low contribution of daylight because the higher is the ALD, the lower the possibility of having over-lighting problems. The same observation can be done for the ON-OFF control case.

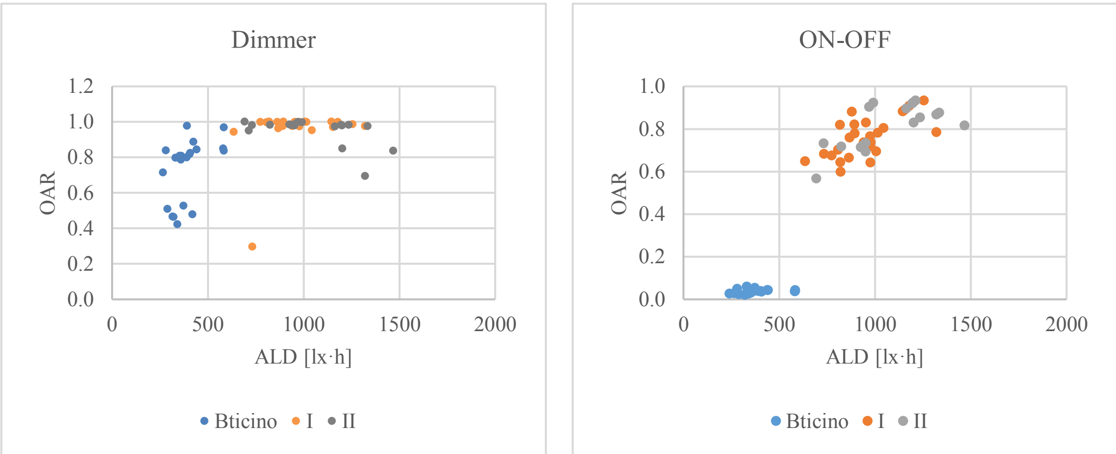


Figure 206. Relationships between ALD index and OAR index calculated in dimming control and ON/OFF control for residential scenarios

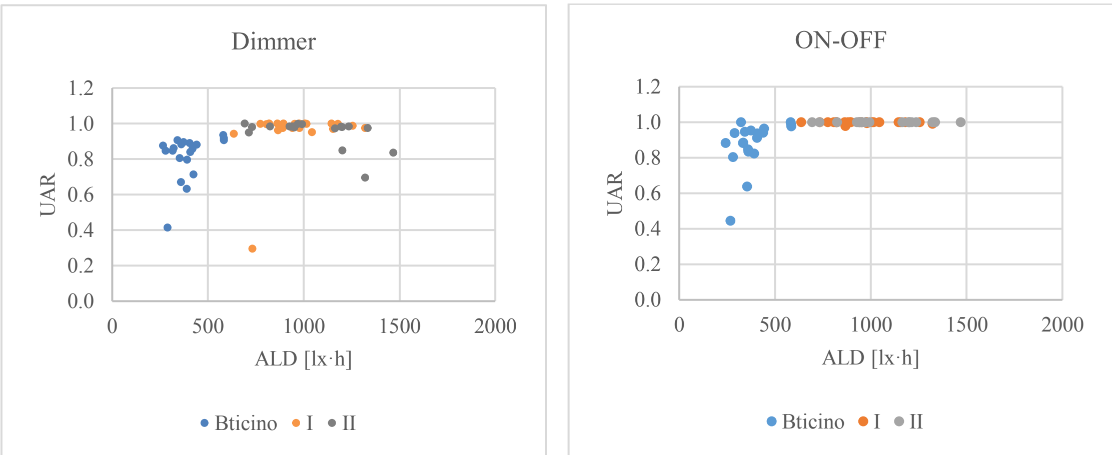


Figure 207. Relationship between ALD index and UAR index calculated in dimming control and ON/OFF control for all the systems for residential scenarios

It is possible to see that the ALD values are, in general, for the residential case lower. But, as already said, it is necessary to consider that the number of occupancy hours of the residential scenarios is lower than the office ones. Furthermore, the task-illuminance selected for the office end-use is higher than the one selected for the residential case. It means that, if the system would be tested for the residential scenarios, but using the same task illuminance selected for the office use (500 lx), the ALD values would be higher.

Even if the difference is not so high as for the office case, in dimming operation the OAR calculated for the system Bticino are lower than Zumtobel system.

In Figure 208, the relationships between the electrical consumption and the ALD values for each system are shown. As well in this case, the relationships are not perfectly linear because, of the variable occurrence of over and under lighting. Reminding the observation done for the office case, the comparison between the three relationships shows that for the Zumtobel II is more linear. It confirms that its performances were the highest.

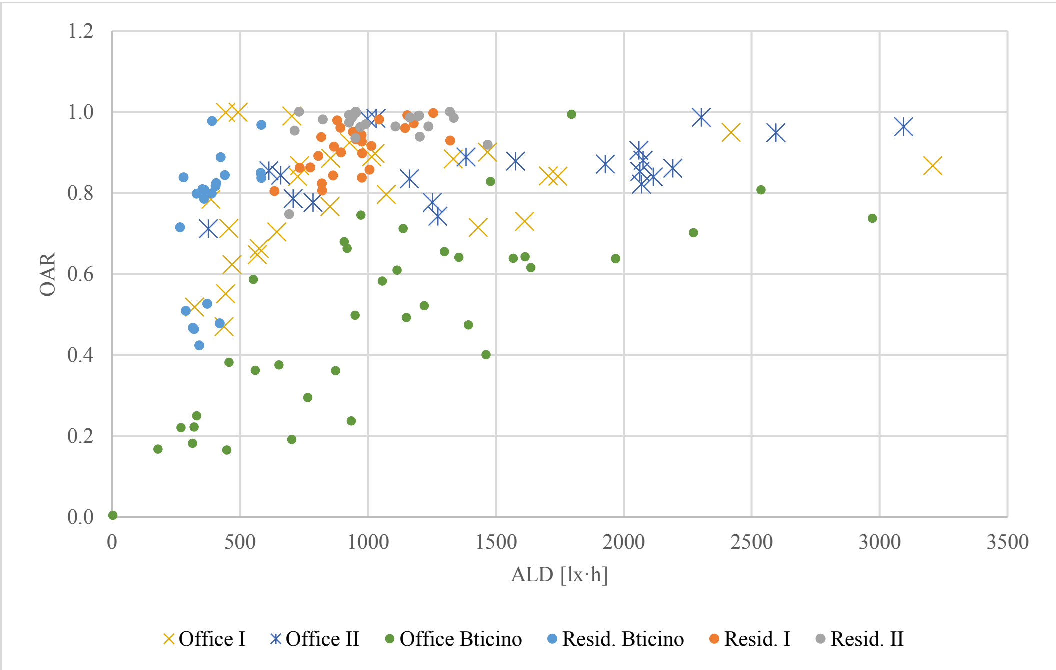


Figure 208. Relationship between ALD index and OAR index calculated in dimming control and ON/OFF control for all the systems in Office and Residential operations

Also, observing Figure 209i and 209ii, it can be noted that the higher ERI the lower OAR values. In order to evaluate the relationship between ERI and UAR it is better to see each graph for each system. Anyway, the relationship between UAR and ERI is not so linear. Looking at the graphs in Figures 209iii and 209iv, it can be said that in terms of UAR that in general the Zumtobel II system worked better, both in dimmer case and in ON-OFF case. Also in the residential case, comparing the two control strategies, it can be observed that all system had higher performances with dimmer control.

The relationship between the ratio OAR/UAR and the ERI, calculated for the residential case, has been plotted in Figures 209v and 209vi. Indeed, the higher the ratio the higher is the influence of the under-lighting during the system operation. On the contrary the lower is the ratio the higher is the influence of the over-lighting during the system operation. Because, as already noted, in the residential case the system worked better than in the office one, this ratio was never too high or too low.

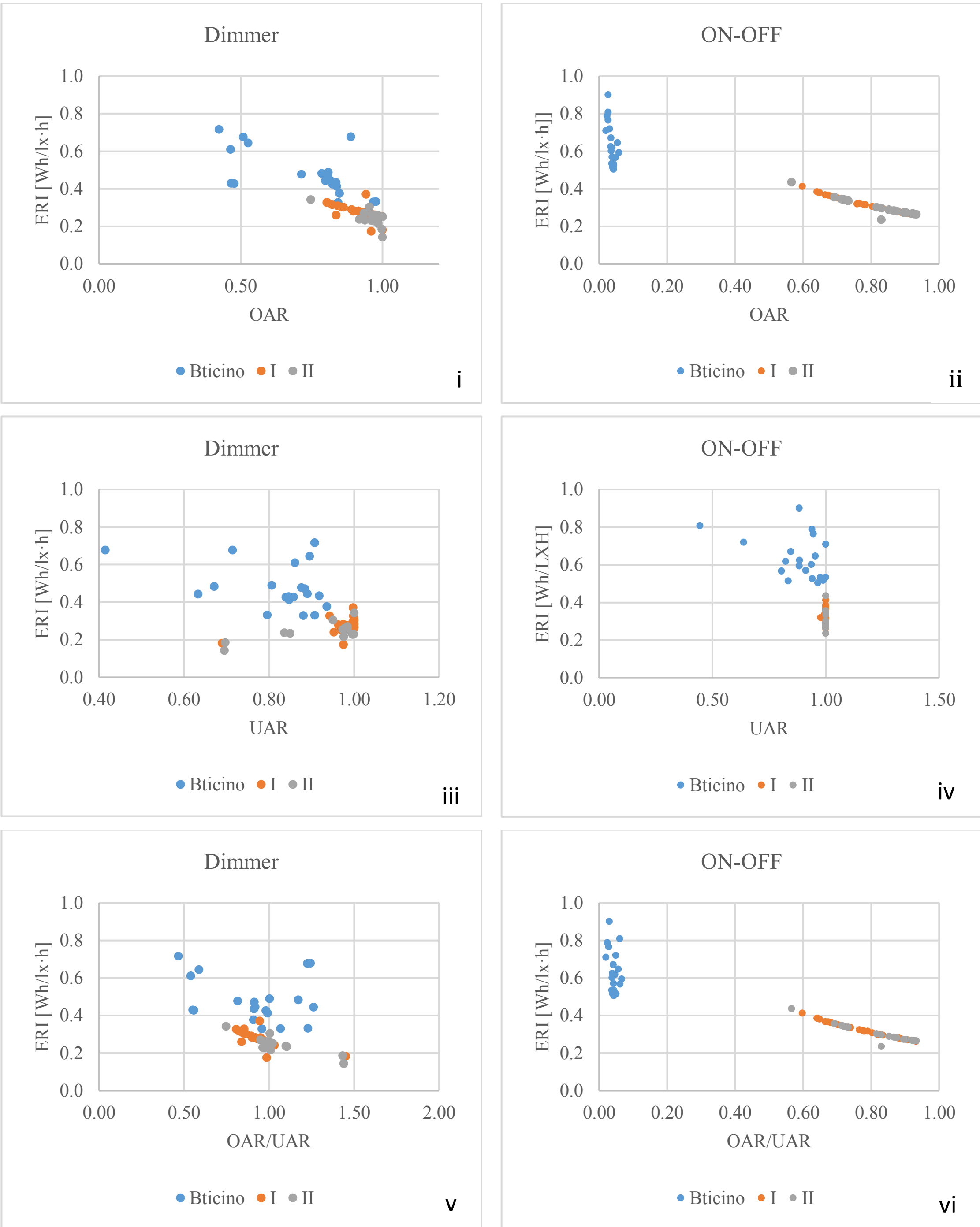


Figure 209. Relationships between ERI index, UAR and OAR indices calculated in dimming control and ON/OFF control for the two systems

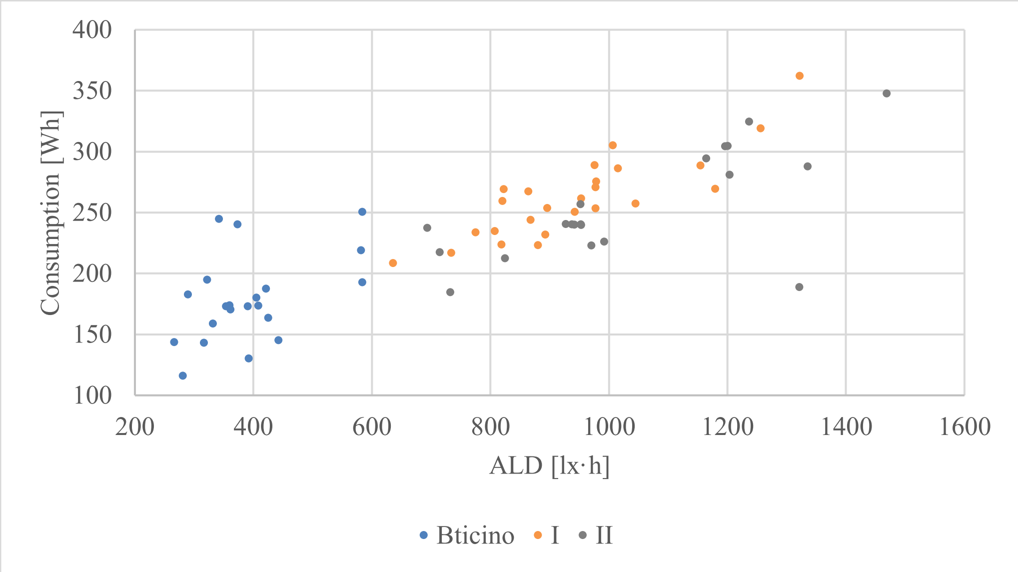


Figure 210. Comparison between the relationship of ALD index and electrical consumption for the two systems

9.3. Comparison between ideal consumption and actual ones

In previous sections (e.g. 4, 6 and 8) some methods used to predict the electricity consumption have been described and analysed. Some of these are already presented in literature, other have been developed and proposed in this thesis.

These methods can be useful for a good design of lighting control systems and the lack of their use can cause the decrease of the systems performances, topic of this thesis. On the other hand, they can be not always precise methods and the results can be more or less different from the actual ones.

In this section, a comparison between the actual energy consumption measured for all the presented scenarios and predicted consumption calculated with three methods based on DA, cDA and ALD is presented. The Daylight Autonomy and the Continuous Daylight Autonomy have been largely described in section 1 and in this section as well as the ALD. These methods can be applied only knowing the daylight contribution that, as already said can be predicted using many described methods or, as in this case, measured.

For the first method the luminaires have been considered switched on at 100% every time the daylight did not achieve the task illuminance and completely switched off every time the daylight achieved the task illuminance.

In the second case, the luminaires have been considered switched on, but at a certain percentage proportional to the supplementary of the continuous daylight illuminance contribution. E.g. if the cDA, at a certain time step was 40%, the luminaires have been considered switched on at 60%.

The consumption based on the ALD index has been calculated as:

$$ELEC_{ALD} = \left(\left(\frac{P_{100\%}}{E_{100\%}} \right) \cdot ALD \right) + P_{SYS} \cdot t_s \; [Wh] \tag{45}$$

Where $ELEC_{ALD}$ is the electrical consumption, $P_{100\%}$ is the absorbed power by the lamps at 100%, $E_{100\%}$ is the illuminance that the lamps can provide turned on at 100% and P_{sys} is the power absorbed by the control system and t_s is the timestep.
The consumption based on the cDA index has been calculated as:

$$ELEC_{cDA} = \left(\left(1 - \frac{E_{nat}}{E_{set}} \cdot P_{100\%} \right) + P_{SYS} \right) \cdot t_s \, if \, E_{nat} < E_{set} \, [Wh] \tag{46}$$

If $E_{nat}>E_{set}$, then E_{nat}/E_{set} can be considered equal to 1 because it means that the luminaires can be switched off.
The consumption based on the DA index has been calculated as:

$$\begin{aligned} &ELEC_{DA} = (P_{100\%} + P_{SYS}) \cdot t_s \\ &if \, E_{nat} < E_{set} \, [Wh] \end{aligned} \tag{48}$$

If $E_{nat}>E_{set}$, then E_{nat}/E_{set} can be considered equal to 1 because it means that the luminaires can be switched off.
It can be interesting to compare the results of the first method with the consumption calculated in ON-OFF strategy and the other two ones with the dimmer one.

The following graphs show for each system the comparison between the results of the three methods above described, the actual consumption (with dimming strategy) and the consumption calculated for the ON-OFF strategy.

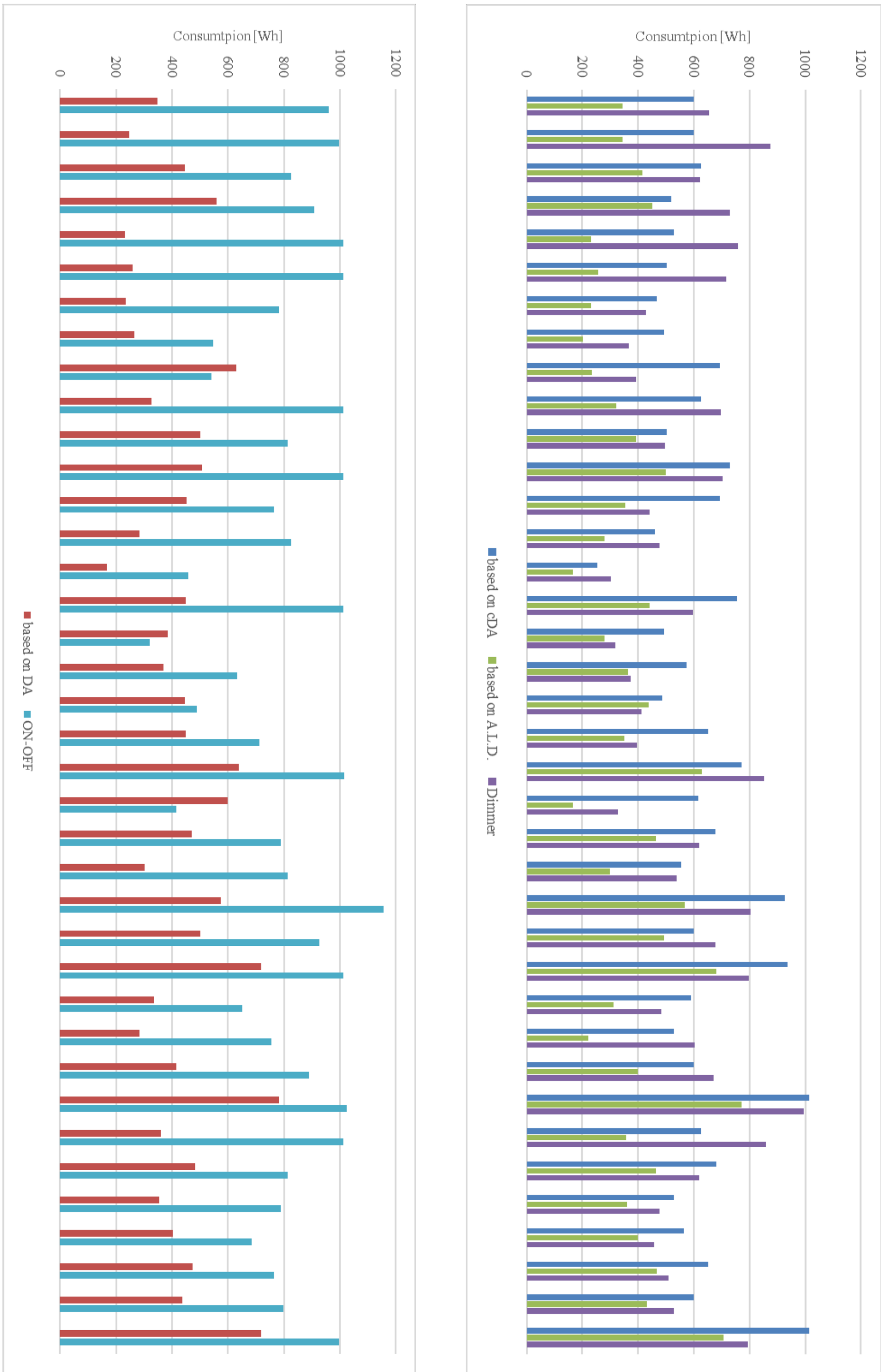


Figure 211. Comparison between the consumption measured and calculated on the basis of the three indices for the office end-use for the Bticino system

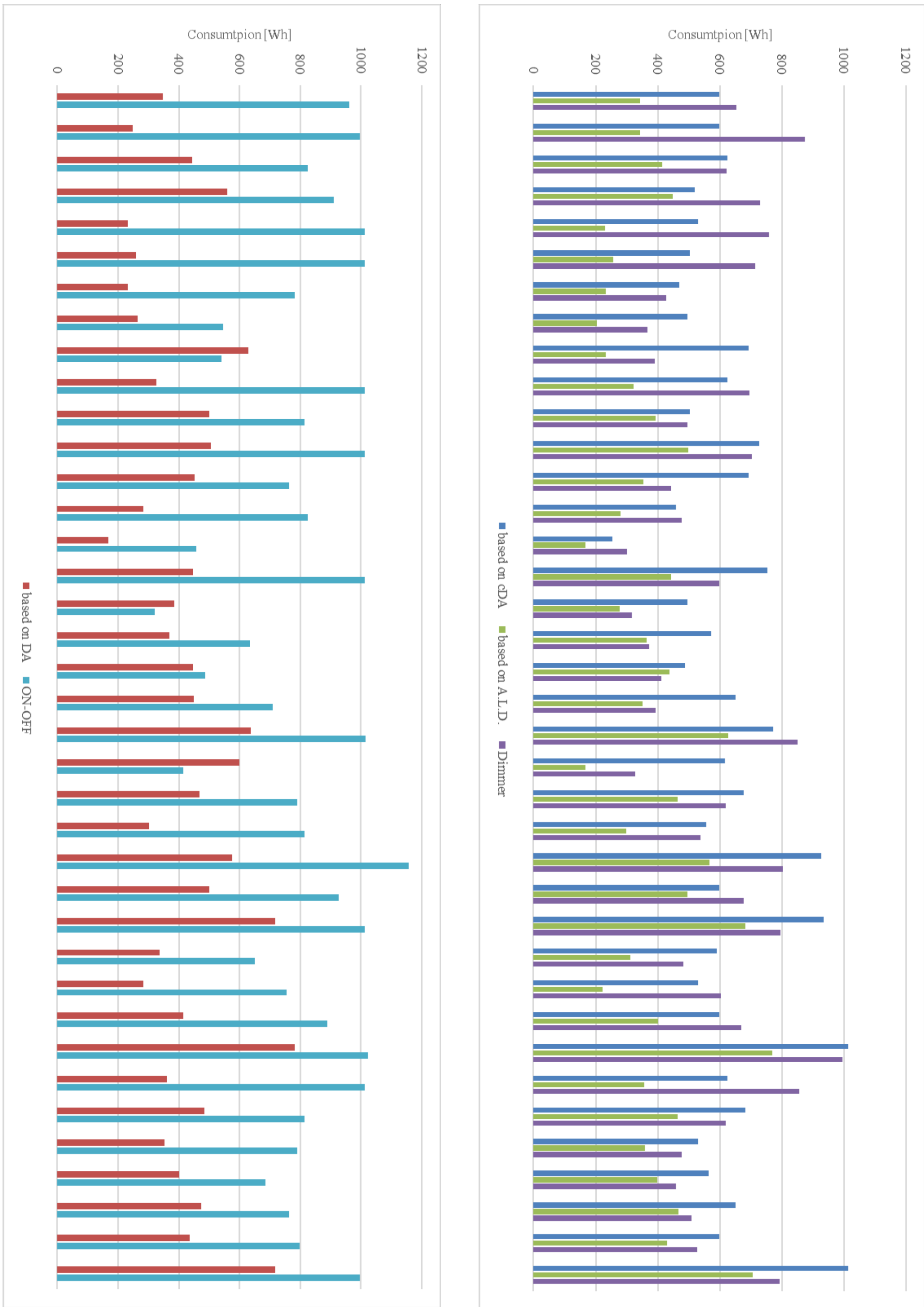


Figure 212. Comparison between the consumption measured and calculated on the basis of the three indices for the office end-use for the Zumtobel I system

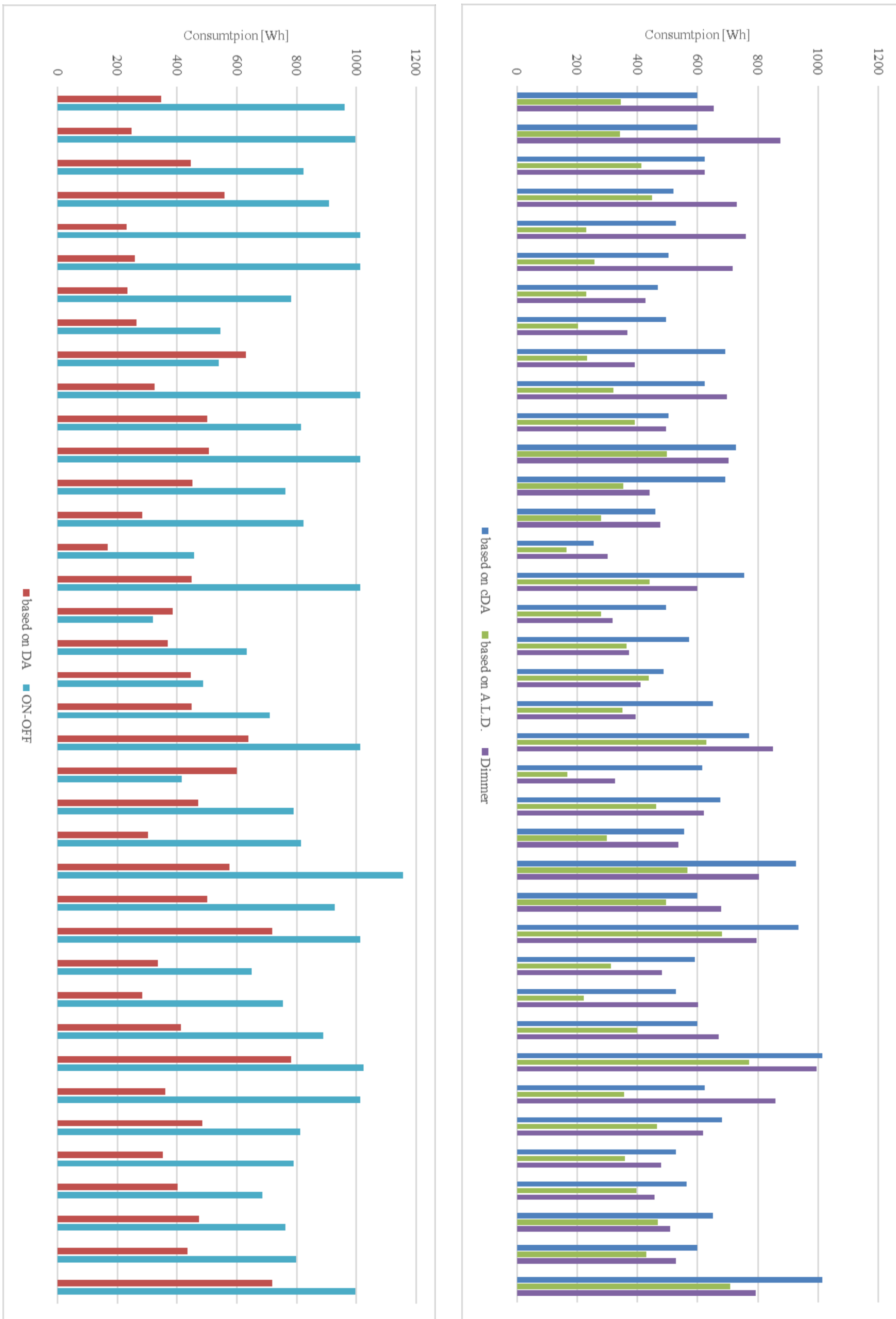


Figure 213. Comparison between the consumption measured and calculated on the basis of the three indices for the office end-use for the Zumtobel II system

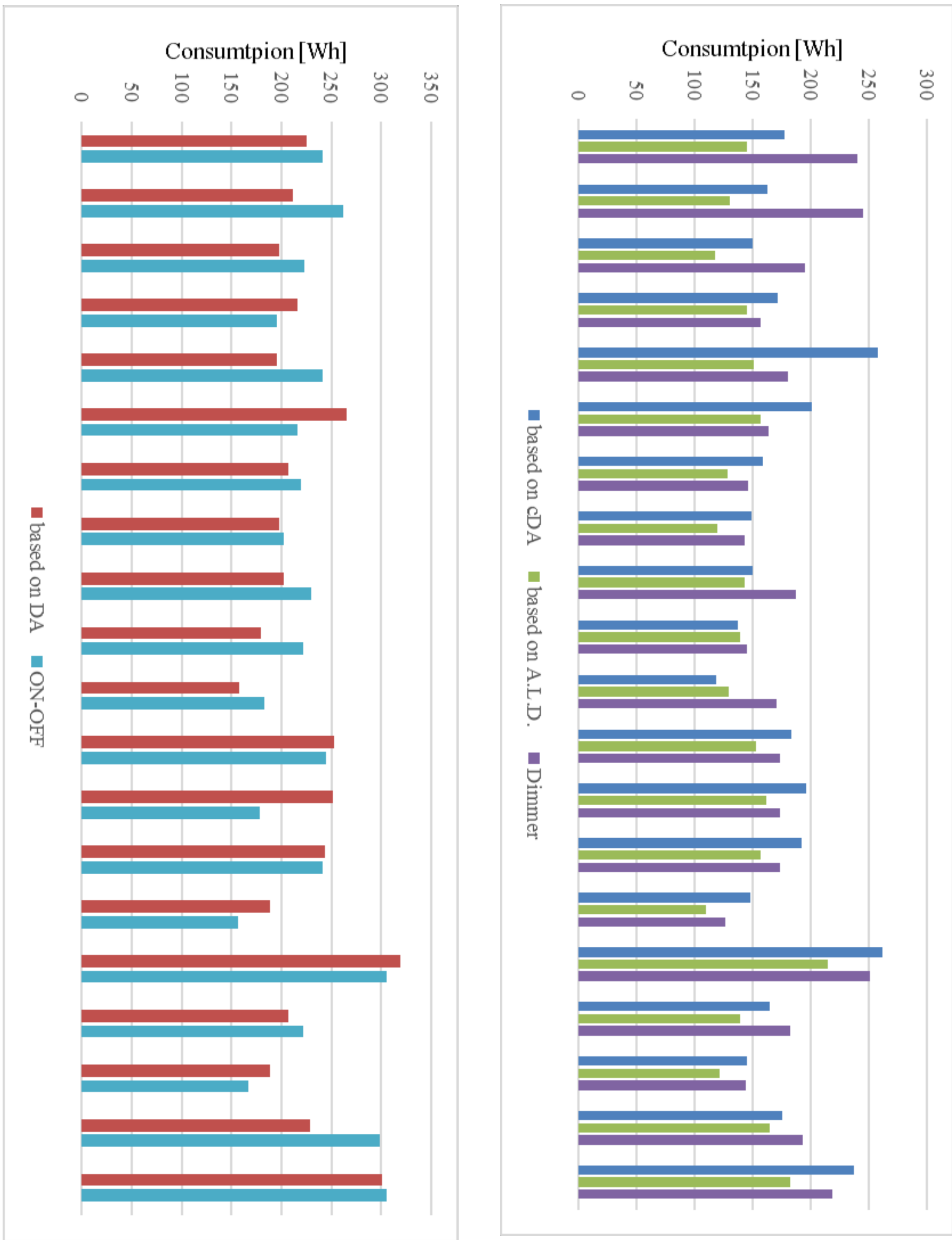


Figure 214. Comparison between the consumption measured and calculated on the basis of the three indices for the residential end-use for the Bticino system

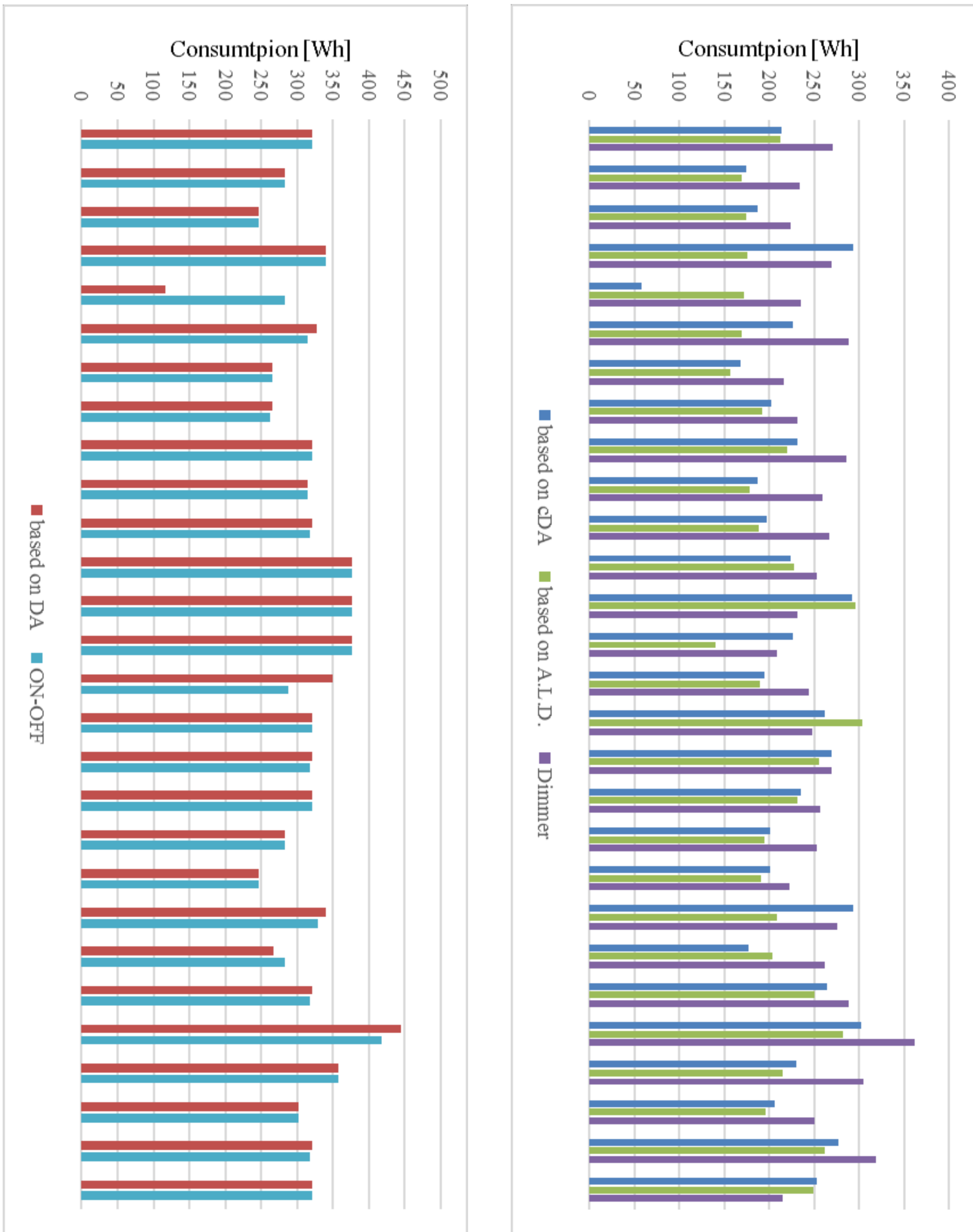


Figure 215. Comparison between the consumption measured and calculated on the basis of the three indices for the residential end-use for the Zumtobel I system

Figure 217. Comparison between the consumption measured and calculated on the basis of the three indices for the residential end-use for the Zumtobel II system

It can be noted that in all the scenarios, and for all the systems, the consumption achieved with the ON-OFF control is the highest. While, in most case the consumption calculated based on ALD are the lowest for the residential case. In office case the lowest is for some cases the consumption calculated based on ALD and in other cases, the one derived from the cDA. In some case the ideal consumption calculated by the ALD are higher than the actual consumption (with dimmer). But for these cases have been calculated a low UAR value. In most part of the residential case the ON-OFF consumption is the same. The same is for the consumption calculated using the DA. This is because, during the hours of the schedules considered for all the residential scenarios the luminaires are never completely switched off. Even if for these cases the absorbed power has been considered at 100% for all the time, the consumption is not always the same for the scenarios because the hours are different. For the office case the consumption calculated according to the ALD are in most part of the case lower than the consumption calculated using the cDA, except some case of Zumtobel II in residential case. As well in this case, by comparing the results with the actual measured data, the error has been calculated. Regarding the consumption calculated on the ALD basis the average relative error is the 23%. In the case of the consumption calculated on the cDA basis the error is 26.29% and on the DA basis the error is the 40%. By considering only the consumption measured during the Bticino system test, the consumption calculated on the ALD has an error of the 29.5%, the one calculated on cDA of the 23.8% and on DA of the 44.4%. By considering only the consumption measured during the Zumtobel system, the consumption calculated on the ALD has an error of the 18.6%, the calculated on cDA on of the 28.3% and on DA of the 36.65%.

9.4.Final remarks

In this section a method, based on the calculation of a set of indices, has been developed to evaluate the actual performance of a DLCs and presented in this section. Furthermore, an experimental test of the method has been carried out to evaluate the actual performance of two commercial DLCs. In general, it has been proven the ability of the indices to highlight situations where e.g. a low specific consumption is almost due to the inability of the system to fulfil the minimum target illuminance but only occasionally performing over-lighting. Likewise, it can be noticed that the highest ERI values correspond to the lowest OAR values i.e. system is performing in over-lighting conditions.

Anyway, low ERI values are also coupled to very variable values of UAR. For this reason, it is useful to observe it as function of OAR/UAR ratio. In this light, the higher the ratio the more prevalent is the under- lighting condition. In almost all the observed conditions Bticino System performed worse than the Zumtobel one with a persistent behaviour characterized by frequent and relevant over-lighting.

For both the systems the relationship between ALD and electrical consumption was only barely proportional because the control system did not always work as expected in ideal cases (with UAR and OAR both equal to 1). It can be affirmed that such method can be utilised to assess the systems performance on different days and, consequently, with different daylight conditions as well as different systems operating

in similar daylight conditions. Further work will deal with the test of other commercial systems aiming also at a comparison of their performances in different seasons and with the calculation of the indices to evaluate the performance of automated shading system.
Furthermore, a comparison between the actual energy consumption measured for all the presented scenarios and predicted consumption calculated with three methods based on DA, cDA and ALD has been presented. The difference between the measured and the calculated consumption are in general high. Despite them are not so low it can be affirmed that the method based on ALD values is quite good and a little more precise than the one based on cDA values.
In addition, it must be noted that, once an ERI value for a given system has calculated (after a short period of operation), if an ALD value is assessed for a longer period, it is possible to make an assessment of the system' consumption for the same time. Indeed such value is simply the results of ERI times ALD.

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10. Conclusions

The topic of the automated control system applied to the building systems is today matter of studies and researches. Their advantages in terms of energy saving respect to the traditional systems are well demonstrated by their application.

The literature researches show that it became increasingly important to establish a realistic baseline of the actual lighting energy consumption in buildings for the different scenarios nowadays used (both manually and automatically operated), which incorporates occupant behaviour. Many methods have been developed to design them and the technologies are always more sophisticated, but accessible. Nevertheless, the more recent research is focusing on the real performance as well in terms of actual energy saving respect also related to the comfort conditions. Moreover, these systems are often commercial DLCs which are configured using very simplified methods and software provided by the manufactures companies are "closed". These facts, together with a possible not effective installation of them can sensibly decrease the performance of the system in terms of visual comfort and energy consumption. Indeed, the ex-post evaluations are becoming an important aspect and it is necessary to take them into account for a whole and complete analysis. They are using throughout the European Commission to assess whether a specific intervention was justified and whether it worked (or is working) as expected in achieving its objectives and why.

The thesis deals with the evaluation of the actual performances of the automated control systems for indoor lighting and, in particular, of the Daylight Control Systems (DLCs) by investigating methods - existing or developed within this thesis - applicable from the first steps to the ex-post evaluation.

Expected performances of DLCs are usually assessed during the design step by computer simulations, which are able to handle average meteorological data and "ideal" behaviour of systems and occupants. In this thesis, several analyses have been developed and commented, most of them supported by a large set of data coming from different cases study with different end-uses: three real education buildings and a laboratory.

To this aim, the DEIM laboratory has been equipped with an experimental set-up in order to simulate different end-uses and to test several scenarios, based on several occupancy schedules.

The research outputs have the following main implications:

- presentation of an upgraded review;
- development and presentation of new analyses that can be used during the DLCs design and for their ex-post evaluation;
- comments on the application of existing and original tools and analyses;
- a large database of measured data, available for further researches.

The application on two cases study of a method based on the cost optimisation can be a good example of the practice to predict the best retrofit actions. The method will be further implemented with the application on other cases study, but the first results show that the retrofit actions can be advantageous only in some selected cases.

Many preliminary analyses of the daylight distribution are presented and commented in the case study of HFT where monitoring of lighting environment and actual occupation have been utilised to assess the real efficacy of several design options, including control strategies.

The implementation of the existing predictive methods demonstrated that the ideal performance calculated by them are less or more far from the actual ones. In particular, application of the methods suggested by the two European standards (EN 15232 and EN 15193) demonstrated that results are different for each case and each system. Indeed, in some cases the results allow one to affirm that the BAC factor method, besides characterized by a certain degree of approximation, but also by a remarkable simplicity, can be in some case used with sufficient precision for evaluating the final energy consumption. In other cases, and in particular, for the other tested system, the error is higher. It means that the suggested factors should be based on more parameters, e.g. the characteristics of the system control. On the contrary the EN 15193, and in particular the first proposed method, considers in the calculation of the energy demand all these parameters. The procedure is very complicated and many factors must be calculated or adopted by assumptions. These could lead to an error propagation and, in addition, generate calculations that gives different results according to the analyst. Nevertheless, in general, it can be affirmed that the errors of the BAC factors are not so high even if the standard EN 15232 suggests to apply the method provided by the standard EN 15193, for which the error are higher. As it is shown largely in this thesis, one of the reasons is because this kind of systems cannot work as expected.

The development of Neural Network models and their application demonstrated that it is possible to find a reliable relation between the illuminance on the workplane and in a point of the room where the photosensor could be installed. Four of the five tested Neural Networks have been optimised and trained and the results have been compared in order to know the best correlation of the illuminance measured on the work-plane and the illuminance measured on another of the points. Comparing the error distribution graphs, it was possible to note which position should be to locate the photosensor find the best correlation. The developed model has proved to be able to predict the illuminance values on the work-plane in order to know if they fulfil the visual comfort requirements.

The review of the software that introduced the lighting control system on their consumption calculation, demonstrated that it is not easy to model the parameters that can influenced the performance of these systems and that different software have different aim and use different calculation methods. It can cause very different results from different software.

Finally, the actual performances of the tested systems have been studied and analysed by using a developed ex-post method based on a set of indices to evaluate the actual performances of the daylight linked control systems by monitored data and its application. This part is one of the main outcome of the thesis. In particular, the first index so-called

A.L.D. (Artificial Light Demand) can be defined as the sum, during the operation time, of the differences between the illuminance target value on task area (E_{set}) and illuminance due to available natural light (E_{nat}), when this one is lower than the set point itself, times the hours. The index E.R.I. (Energy Ratio of Illuminance) is the ratio between the electricity consumption (ELEC measured in Wh) and ALD (lx·h). Last two indices measure the quantity of excess or deficiency of light that a control system can cause. So, they have been used to account the system ability to maintain the target illuminance on the task area. The first is so-called O.A.R. (Over illuminance Avoidance Ratio) and is defined as the ratio, evaluated for an observed time period, between the minimum requirement of artificial light (ALD) and the sum of it plus the artificial light eventually provided in excess by the system (E_{exc}). The second one, U.A.R. (Under-illuminance Avoidance Ratio) can be considered for accounting the relative weight of the under-illuminance times.

The indices have been calculated using about 47,000 illuminance measures as many electrical measures during for 179 days during a 16 months long campaign. Two different control systems, produced by two manufactures, have been tested for a total of 359 scenarios. Furthermore, in one case, the photosensor have been tested in two different positions.

Several relationships among the indices have been investigated and have demonstrated the strong dependence of energy consumption with the real fulfilment of visual comfort tasks.

A further comparison by the actual energy consumption and ideal ones calculated using the three indices and the cDA has been carried out and the error that this further predictive method has been calculated. This analysis showed, as well in this case, that the predictive methods can provide results far from the actual ones.

The study also foresees further research developments. One of this is the implementation and the improvement of the automated control system by incorporating shading control functionality, in order to study the influence of them on the system performance and on the visual comfort.

Furthermore, the developed and tested methods can be adapted and used also for lighting control systems for outdoor environment.

Finally, with the aim to evaluate in detail the influence that this kind of systems can have on the psychological aspects of the users, a broader survey will be conducted for many other case studies.

The presented Neural Networks can be used also in other application and environment where a DLCs system is applied, contributing to a better design and, so, to the implementation of its performance. Using a kit of mobile photo-sensors for collecting the data, before the installation of the system, the implemented ANN could give a suggestion to select the best selection of the position. In a further work, other ANNs will be implemented in order to find best sensor configurations and best control strategies. Moreover, author aims to exploit ANN capabilities for building algorithms and DLL for adaptive control of DLCS able to overcome the problematic handling of weak correlations between photosensors and task area illuminances.

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