Empirical BAC factors method application to two real case studies in South Italy

Marina Bonomolo[1]*, Gaetano Zizzo[1], Simone Ferrari[2], Marco Beccali[1], Stefania Guarino[1]

[1] Engineering Department, University of Palermo, 90128, Palermo ITALY
[2] Dipartimento di Architettura, Ingegneria delle Costruzioni e Ambiente Costruito, Politecnico di Milano, 20133, Milano ITALY

e−mail: *marina.bonomolo@unipa.it, gaetano.zizzo@unipa.it, simone.ferrari@polimi.it, marco.beccali@unipa.it, stefania.guarino@unipa.it

ABSTRACT

The application of Building Automation and Control (BAC) systems has many advantages. One of these is the reduction of the end-user electricity consumption and, if applied to lighting systems, the achievement of well-acknowledged benefits from daylight, such as productivity, health, visual comfort and well-being. Concerning the first aspect, the international Standard EN 15232 proposes the so-called BAC Factors (BF) method to assess the impact of BAC systems on the final energy consumption. The method provides a simplified estimation of the energy savings due to automation in buildings and questions arise on its applicability in some situations. For this reason, the authors have carried out an experimental study aiming at comparing the energy savings calculated using the simplified BAC factor method with those evaluated with a measurement campaign on a laboratory setup. In particular, the BF are evaluated for an office and a residential environment, using sets of data measured in two cases study in South Italy by testing two lighting control systems in different end-uses (residential and office). The comparison between the sets of data shows the limits of the simplified BAC factor method.

KEYWORDS

Energy efficiency in buildings; lighting controls; BAC factors; lighting; daylight linked control systems

1. INTRODUCTION

Humans, unconsciously or consciously, are able to adapt their bodies to the conditions and solicitations of the environment. Moreover, they can use suitable control systems to achieve environmental conditions that are considered comfortable according to their dynamic and personal preferences [1] [2] [3] [4]. For this reason, the use of Building Automation Control (BAC) and Technical Building Management (TBM) systems is becoming more and more common [5] and advantageous [6] [7]. Indeed, these systems can provide many advantages in terms of safety, comfort and energy/economic savings [8] [9]. Consequently, their use is proposed in many standard methods for calculating the energy performance of buildings. As an example, the EPB Directive 2010/31/EU [10] defines a general framework for calculating the energy performance of buildings, taking into account domestic hot water production, cooling and heating demand and lighting requirements [11]. Furthermore, the Directive underlines the important role of automation, control and monitoring systems in energy-saving actions [12], supporting the use of smart control and smart metering as an important measure for reducing energy consumption and CO_2 emissions [13]. Also Directive 2012/27/EU [14] refers to automation, innovative demand response (DR) strategies, and smart meters' utilization as a way to reduce energy consumption.

Various researchers show the advantage of BAC systems mainly applied to the lighting system. Automated lighting systems, in addition to reduced energy consumption [15] compared to not-automated systems, offer the possibility of optimizing the well-acknowledged advantages from natural lighting such as health, well-being, productivity and occupant comfort [16] [17] [18] [19]. This happens, especially, when automation is combined with modern light sources such as Light Emitting Diodes (LED) that opens many perspectives in this field. Indeed, the application of these technologies can increase user comfort and energy efficiency [20]. For this reason, the replacement of the light sources with more efficient ones and the installation of the control system are very common actions in retrofitting existing buildings [21]. Furthermore, it has to be reminded that the daylight harvesting can have important advantages given that solar energy is considered a promising renewable energy resource for the sustainable development [22] [23].

Systems' automation can be based on natural light characteristics that dynamically change depending on time, season, and weather conditions. Kwon et al. [24] suggested a lighting system that provides effective lighting for health, emotion, performance, and energy savings, according to context, by reconfiguring the lighting environment in accordance with short-wavelength ratio, colour temperature, and energy.

Nevertheless, as Aghemo et al. pointed out in [25], it is necessary to focus on the correct design of the control system and, consequently, on the essential activity of commissioning, both during the start-up of the plant and also afterward, in order to correct and improve the operation of the system compared to the initial set-up. Aste et. al. [26] 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 [27]. Beccali et al. [28] developed a method based on Artificial Neural Network that can be used as tools to optimize the design and the set steps of a Daylight-linked Control System.

Many studies for assessing the effects of control systems on the final energy consumption for lighting in buildings are based on simulations or simplified methods [29][30]. Some of these use technical standards. For instance, the standard EN 15193 [31] introduces an indicator called LENI (Lighting energy numeric indicator) that can be calculated, by using three different methods (more or less simplified), to evaluate the energy requirements of lighting in buildings. In [32], an improvement of the procedure is suggested. The authors took into account other parameters, e.g. the number of control groups, the typologies of lighting sources and control, the operation time, the delay in turning off and the technique of modulation (dimming or switching). Furthermore, the authors compared the proposed method with the ones included in technical standards. Also, Aghemo et al. [25] focused their attention on the new edition of EN 15193-1 to calculate the Lighting Energy Numeric Indicator (LENI), especially focusing on the approach in order to calculate the daylight supply factor (FD,S). Doing a sensitivity analysis on these factors and calculating the LENI for a set of case-studies (simple reference rooms with a different site and architectural features), they concluded that the new version of the standard expanded the possible cases that influence the daylight availability in a room, compared to the previous version. Starting from the new Swiss standard SIA 387/4 (Elektrizität in Gebäuden - Beleuchtung: Berechnung und Anforderungen) [33], in [34] Zweifel proposed a new method that can replace the oversimplified method of the standard. The author represented six options for the daylight dependent lighting control, one option for the presence-control and three options for the control of solar protection.

Similarly, to the EN 15193, in the standard EN 15232 [35] a set of TBM and BAC fixtures that influence the performance of buildings (in terms of energy and comfort) are listed. Furthermore, the standard proposes four BAC classes and presents also a simplified BAC factor method for estimating the energy savings due to the application of BAC and TBM functions. Nevertheless, as Pellegrino et al. [36] underlined in their work, sometimes the outcomes obtained from the monitored data can show some significant differences from the expected energy saving estimated applying of the BAC method.

Ippolito et al. [37] studied how the automation functions listed in EN 15232 affect the energy performance of a single-family test house. While, López-González [38] investigated, the impact of TBM and BAC systems on the registration of certificates of energy performance in the Autonomous Community of La Rioja. Based on the results of this study, the authors expected to gain a perspective on the evolution of energy efficiency ratings in terms of both primary energy consumption and CO_2 emissions. Bonomolo et al. [39] proposed a method for the definition and the evaluation of a new BAC factor for outdoor lighting systems.as complementary to the one proposed by the Standard EN 15232.

Parise et al. [40] investigated possible advanced control systems to avoid energy waste during unoccupied and daylight hours. They used the methodology to quantify the energy performance of the lighting systems based on a statistical approach introduced by the European Standard EN15193. In order to verify and validate the reference values given by the standard, they used actual measurements in three classrooms made at the Engineering Faculty of the University of Rome "La Sapienza" testing an advanced control system adopting the Konnex protocol. It regulated light intensity according to the actual presence of activities and to the actual availability of daylight. In particular, they implemented two control strategies and solutions to associate the energy savings with the costs of installation. The first one consisted of an "on-off switching" control. It was a "cheap" solution because the existing luminaires can be maintained. The second solution is more expensive because for a "dimming" control it needed the replacement of the luminaires. The authors found that the reference values suggested by the standard are useful in a preliminary evaluation but that it is convenient to adopt specific, accurate values for the building project, if available, suitable for an advanced evaluation. Also Andrzej Ożadowicz and Jakub Grela [41] presented a study that investigates the impact of Building

Automation Control System on the energy efficiency of a university classroom. They found that the BAC efficiency factors cannot be treated arbitrarily but that they should be analysed and verified for specific kinds of buildings as well as the BACS applications.

In this context, this paper aims to investigate the limits of the simplified BAC factor method for lighting systems, using the results of experimental measurement campaigns carried out for two case studies in South Italy. The first case study is the laboratory of Thermal Solar Systems for Summer and Winter Air-conditioning of the Department of Engineering of the University of Palermo. Here two different control systems applied to the same lighting system were used. A measurement campaign (long 13 months) was performed collecting illuminance and energy data with a time step. The measured values were used for evaluating the actual yearly and seasonal consumptions for both a residential and an office environment, with the aim of assessing the accuracy of the BAC factor method for lighting systems as well as to relate the results also in terms of provided visual comfort for occupants. The present work represents a further step of the research presented in [42]. Indeed, in order to get to a more general conclusion on the real performance on the simplified BAC factor method, in the present study further analyses have been carried out by considering a second case study (an office room of the lighthouse of Lampedusa) and the effect of new parameters e.g. two different typologies of control system, the efficiency of the lighting system and the relation with the index called Artificial Light Demand (ALD). The index, defined in [43], it is useful to understand the theoretic amount of artificial lighting according to the daylight contribution.

The rest of the paper is organized as it follows: in Section 2 a brief explanation of the BAC factor method is reported; Section 3 describes the methodology applied in this work; Section 4 describes the experimental setup for the two case studies; Section 5 reports the results of the assessment and, finally, Section 6 contains the conclusions of the work.

2. THE BAC FACTOR METHOD

The standard EN 15232 ("Energy performance of buildings – Impact of Building Automation, Controls and Building Management") was designed by the Europe-wide implementation of the directive for energy efficiency in buildings (Energy Performance of Buildings Directive EPBD 2002/91/EU), and proposes methods, controls, and conventions useful to evaluate the influence of BAC and TBM systems on energy use and energy performance in buildings. In particular, three methods are described in the standard. The first method can be used to calculate the minimum energy required by the building automation system and the technical building management functions. The second method is more detailed and can be used to assess the impact of these functions on the energy performance of a given building enabling the calculation of factors and indicators utilized by the relevant standards. The last one is a simplified method and it can be used to get a first estimation of the impact of these functions on the energy performance of typical buildings. This method uses a set of pre-calculated energy efficiency factors, named BAC factors. A BAC factor is a number that expresses the ratio between the yearly energy consumption of a system in a building (HVAC system, lighting system, etc.) when BAC systems are adopted for its management and the consumption of the same system assumed with a reference (base) automation level.

According to the BAC factor method, the automation system is characterized by a so-named BAC efficiency class (four classes are defined: A, B, C, D), whose features are defined by the EN 15232 standard and applicable both to non – residential and residential buildings. Class D is used for classifying a system when non-energy efficient BACs are installed (building with such systems shall be retrofitted and new buildings shall not be built with these systems). Class C is related to the buildings with standard BAC systems and corresponds to the base level of automation. Class B is considered for buildings with advanced BACs and TBM systems and class A corresponds to high energy performance BAC and TBM systems. Although BAC factors are calculated by the Standard with reference to Class C systems, in presence of buildings without any automation it is more useful to refer the BAC factors to class D, for better evaluating the effect of automation on the final consumption.

With the BAC factor method, being know the BAC efficiency class BF_1 and the yearly energy consumption E_1 of a given system, the consumption E_2 that the same system would have if it had a different BAC class BF_2 is calculated simply by the following expression:

$$E_2 = E_1 \cdot \frac{BF_2}{BF_1} \tag{1}$$

Table 1 reports the BAC Factors (BF) given by the last edition (2017) of the EN 15232 Standard and referred to class C for a residential and an office building (the two applications that will be considered in the following). Table 2 reports the same factors calculated assuming class D as a reference for assessing the effects of automation in building with only manual control of the devices.

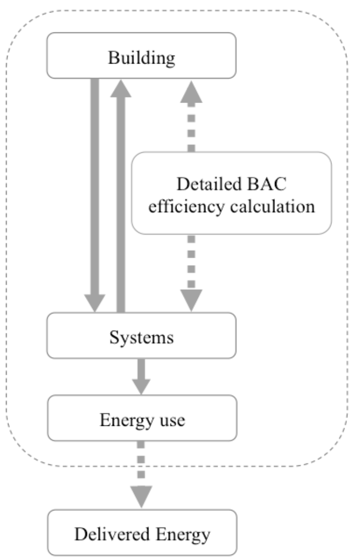
Table 1. EN 15232 BFs for electricity consumption in residential and office buildings (reference class C).

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

Table 2. Corrected BFs for electricity consumption in residential and office buildings with (reference class D).

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

In Figure 1 the difference between the detailed method and the so-called BF method to calculate the impact of the BACs is shown. In this work, only the BF method is applied and the BF proposed by the standard are compared with the factors calculated using the collected data in the two installations.



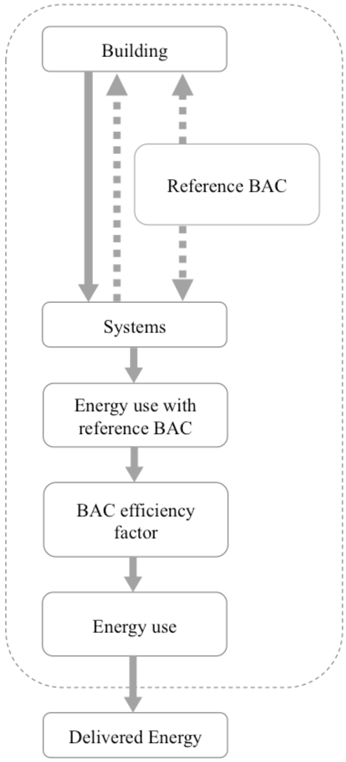


Figure 1. Difference between detailed (above) and BAC Factor methods (below).

3. METHODOLOGY

The methodology proposed in this work is based on the calculation of the BFs for two experimental setups and in a comparison with the values from the EN 15232 Standard. The experimental verification of BFs for lighting systems is carried out starting from the assumption that whichever realistic scenario includes automatic control of some lamps as well as manual control of other lamps. Therefore, in the present case study, the manual control of the mono-optic luminaires is considered as a condition consistent with the assumption of the experiments.

Two case studies related to South Italy are considered: an installation at the Engineering Department of the University of Palermo and an installation in an office at the lighthouse of Lampedusa Island. The energy consumption of the lighting system is measured for each considered scenario and for each setup:

- in the absence of automatic control of all the lamps (as in class D building);
- in presence of automatic on-off control of the pendant luminaires (installed in Z.1 and Z.2 of the first setup) as a function of the established illuminance set-points;

- in presence of dimming control of the artificial lighting.

Despite BFs are normally related to a specific scenario with a slight presence of automation (class C, see previous Table 1), for the goal of our study, the actual BAC factors for the case studies in this paper are calculated assuming as class D as a baseline. The reason lays in the choice of assuming that the baseline scenario is fully manually controlled. For this reason, the "corrected" values of the BFs listed in Table 2 were adopted for a comparison with the measured values.

In accordance with the Standard EN 15232, in absence of BAC system, the lighting system is considered as a class D system, while in the other cases it is assumed being class C or A, respectively, depending on the functions activated during the experimental campaign. In order to assign easily the class, the Standard EN 15232 provides a table with the functions list and the corresponding assignment to energy performance classes.

Therefore, the actual BF are calculated as the ratio:

$$BF = \frac{E_{AUT}}{E_D} \tag{2}$$

where E_{AUT} is the daily energy consumption of the lighting system measured in presence of automation and E_D is the theoretical consumption that the lighting system would have on the same day in the absence of automatic control. This last value was calculated as:

$$E_D = P_{100\%} * t \tag{3}$$

where $P_{100\%}$ is the power (W) of the system and t is the occupancy time (h).

Concerning the energy consumption calculated in the absence of BAC systems, it is worth noting that the power absorbed by the control system is not to be accounted for. Indeed, in some cases, it was found that the energy consumption calculated with on-off control systems was 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 are very frequently, or always, switched on.

One of the defects of the BAC factor method is that it does not consider the contribution of natural lighting in rooms for the calculation of energy consumption. Indeed, daylight can be significantly different according to the geometry of the room, the optics characteristics of the indoor surfaces, the latitude, the season, etc. For this reason, it appears a big shortcut if the considered control systems work according to the natural lighting. Therefore, in order to underline the lack of relation between the BF with the natural light contribution, the results of the energy-saving calculations have been related to an index called Artificial Light Demand (ALD), able to assess daylight by taking into account different aspects. This index has been described in detail in [43] together with other indices that were not considered in the present study because not useful for our assessment. The ALD can be defined as the sum of the differences between the illuminance target value on the workplane area (E_{set}) and the illuminance due to available natural light (E_{nat}), when this one is lower than the setpoint itself, times the hours:

$$ALD = \Sigma_{operation\ time} (E_{set} - E_{nat}) \times \Delta t \text{ if } E_{nat} < E_{set} \quad (3)$$

Figure 2 shows the meaning of ALD definition in two different patterns of daylight time series.

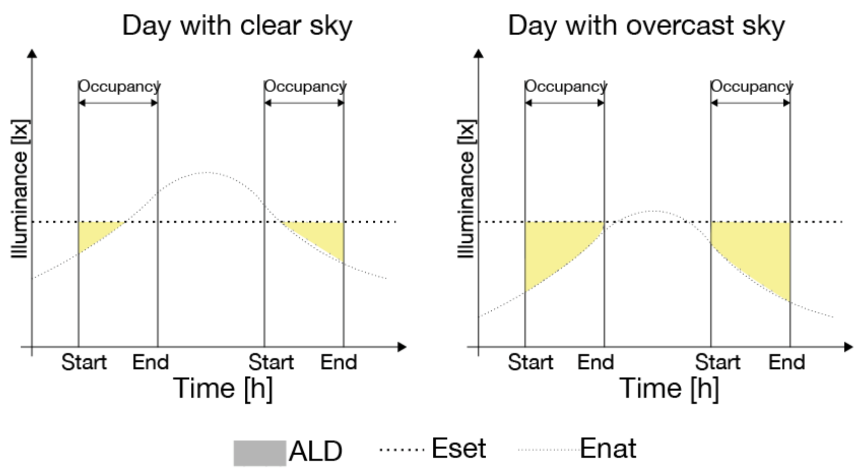


Figure 2. Conceptual scheme of ALD for two different days [43].

ALD is very well correlated to the continuous Daylight Authonomy (cDA) (Figure 3).

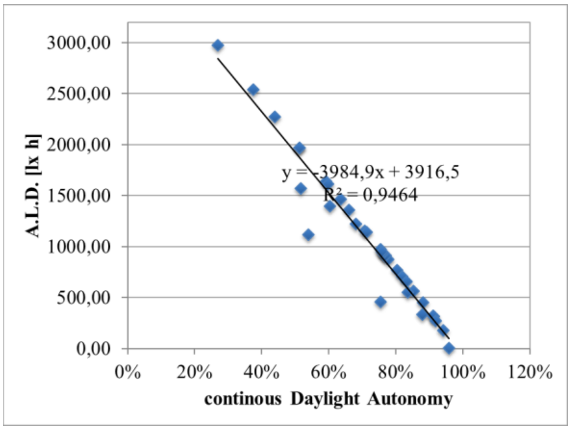


Figure 3. cDA and ALD calculated from measured data in comparison.

The Continuous Daylight Autonomy is the fraction of time in an annual simulation that an analysis point meets or exceeds a specified illuminance level, with proportional credit given for daylight contributions that partially meet this level. So, it measures the percentage of the year when a minimum illuminance level is met by daylight alone and attributing a partial weight to daylight levels below a threshold in a linear fashion [44]. In any case, ALD takes into account the area of the graph where the line of measured daylight illuminance is below the illuminance threshold for time integral.

4. THE EXPERIMENTAL SETUP DESCRIPTION

The analyses have been performed by using the sets of data measured in two cases study: the laboratory of Thermal Solar Systems for Summer and Winter Air-conditioning at the Engineering Department of the University of Palermo and a room used as an office at the lighthouse of Lampedusa Island. As well known, environmental characteristics can highly influence the distribution of the light and, consequently, the performance of the lighting system. Therefore, in this section, a short description of the characteristics of the two sites, of the surrounding environment and of the tested systems are reported.

4.1. Case study 1: the laboratory in Palermo

4.1.1. The site

The laboratory of Thermal Solar Systems for Summer and Winter Air-conditioning of the University of Palermo is located on the third floor of Building 9 of the Department of Engineering. Palermo’s weather presents yearly global radiation on the horizontal surface of 648164 Wh/m^2 and about 2500 yearly sun hours, about 228 sunny mornings and about 227 clear evenings. The lab has an area of 106 m^2 and a height of 3.40 m. The room has four windows, mounting clear double-glazing with aluminium frames (without thermal break). Furthermore, the façade is partially shaded by a solar overhang protruding 2.70 m.

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.

The basement of the building façade is covered with grey stone bricks, while the rest with yellow plaster (ρ=0.40) (Figure 4). 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. 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 aluminum 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 closet (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 (for more detail refer to [45]).

Figure 4. Pictures of the laboratory in Palermo (above) and of the windows (below).

4.1.2. The lighting system

The lighting system, installed in the laboratory (Figures 5 and 5), is composed of:

- pendant luminaires, equipped with 54 W LED lamps in all the zones;
- mono-optic indoor downlight with 15 W LED lamps in two zones.

Mono-optic luminaires　　Suspended luminaires

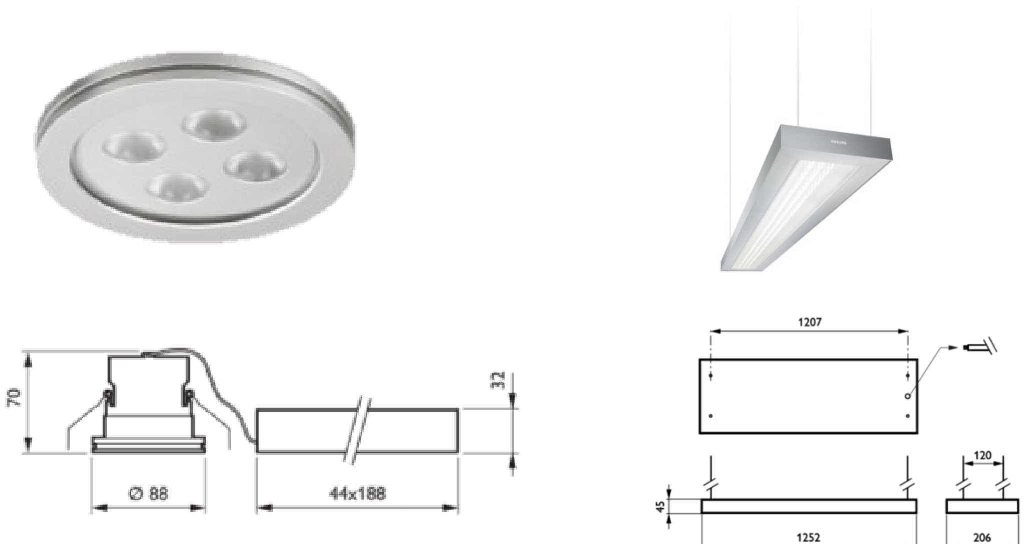


Figure 5. Mono-optic and suspended luminaires.

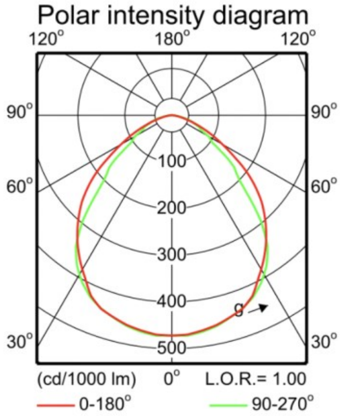


Figure 6. Light distribution for the suspended luminaire

The suspended 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) [46] standard, for the office case.

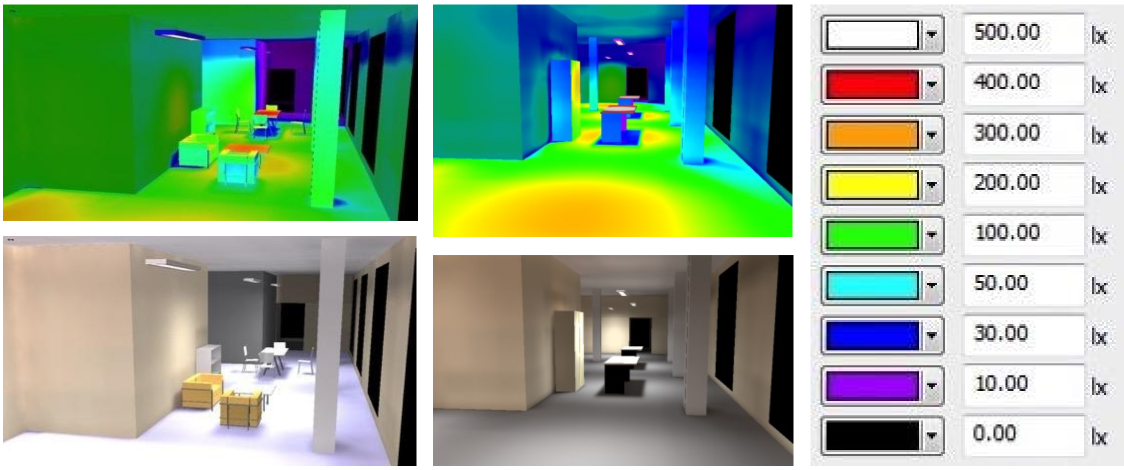


Figure 7. Real and false colour rendering of lighting simulation in residential case (left) and office (right) case.

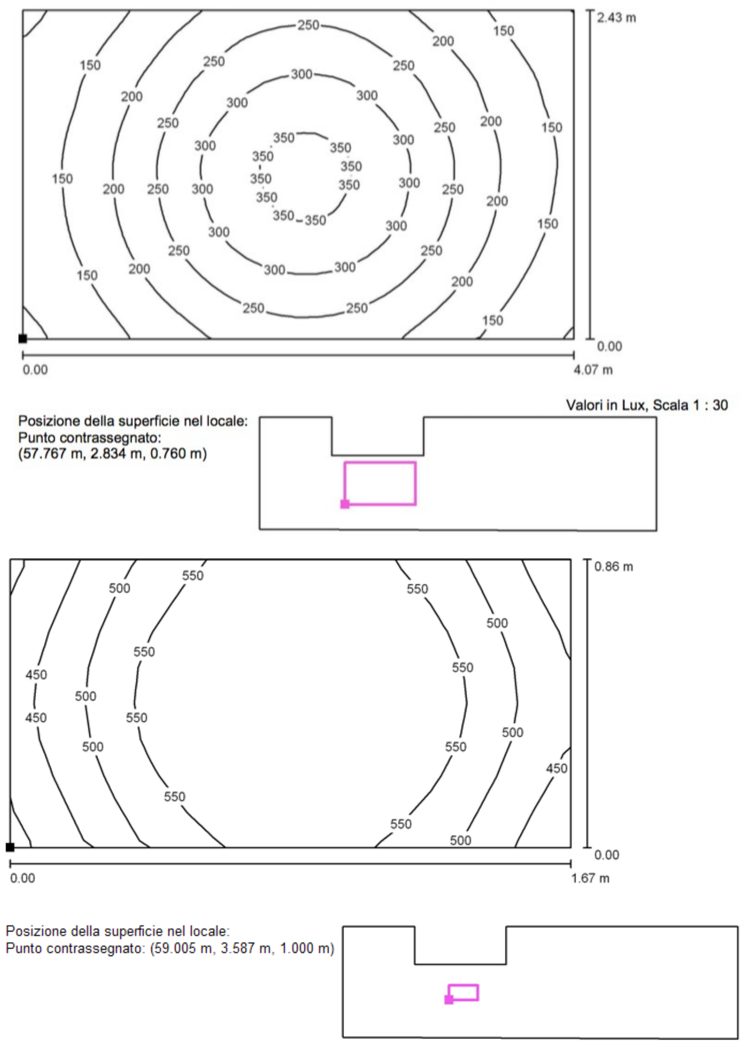


Figure 8. Isolines of artificial lighting on the living area in residential case (above) and on workplane in office case (below).

To do this, laboratory has been ideally divided in several zones according to the assumed end use. Indeed, during the tests, two different uses of the space were simulated considering the related illuminance levels and occupation time schedules: the case of a residential environment and that of an office. The set up illuminance related to the tasks and the daily use of the artificial light is very different in the two end uses [47] [48]. The laboratory was ideally divided into six zones: an entrance zone, a kitchen and other three zones (Z.1, Z.2 and Z.3). For the residential case a living room (Z.1) a dining room (Z.2) and a bedroom (Z.3) were simulated. For the office case two work stations (Z.1 and Z.2) and a manager office (Z.3) were simulated (Figures 7 and 8).

4.1.3. The control system

As explained in [15] and in [49], Daylight-linked Control Systems (DLCs) can work according to the control algorithm, in "closed-loop" and "open-loop" systems. The first one detects illuminance of the control zone considering both daylight and artificial light contribution continuously. In this way, the system receives feedback from the room and can make the necessary adjustments. On the other hand, open-loop systems only detect available daylight levels. The system sends the corresponding signal to the controller to provide the corresponding lamp output. Different typologies of daylight-linked systems can have different performance, but the BAC factor method does not consider this detail. For this reason, in the experimental campaign, BFs were calculated and compared with the values provided by the standard EN 15232, by testing different DLCs systems in different periods of the year. Figure 9 shows the section and plan of the laboratory with sensors and luminaires' location

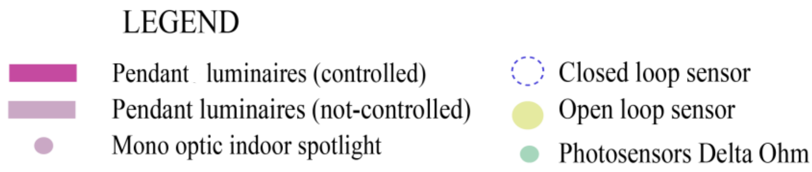


Figure 9. Section and plan of the laboratory with sensors and luminaires' location

The methodology was applied using the following control systems:

i.) System equipped with a closed-loop sensor installed on the ceiling;

ii.) System equipped with an open-loop sensor installed on the ceiling;

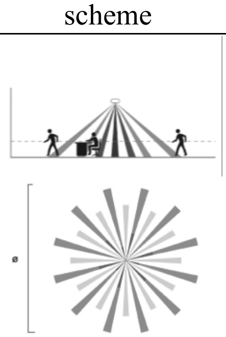
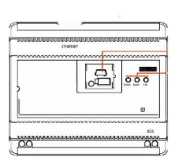
iii.) Same system used in ii.), with the sensor located in another point of the ceiling.

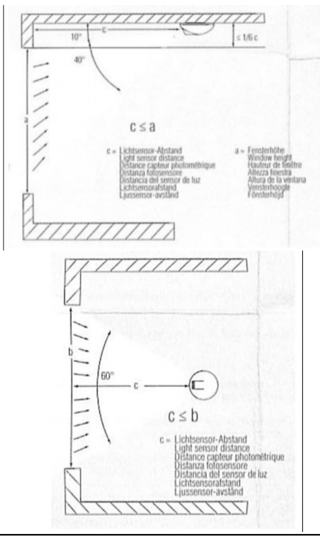
System i) was composed of:

- n. 4 basic controls (common switches);
- n.1 scenario programmer;
- n.1 closed-loop photosensor;
- n. 3 manual actuators;
- n.1 touch dimmer.

To implement System ii), the closed-loop sensor was replaced with an open-loop one connected to another DALI electronic ballast. Finally, System iii) was composed of the same devices as System ii). The collected data are related to a lighting system controlled by a DALI control ballast able to dim the luminaires according to the daylight contribution (Table 3).

Table 3. Pictures of the photosensors, field of view, positioning scheme, and control system ballasts. On the right the switchboard.

Photosensor	Field of view and positioning scheme	Ballast	Switchboard
			



According to the aim to test actual systems, sensors position has been selected according to the user manual of the commercial sensors.

In order to place the photosensor, some simulations considering only the 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 ANNEX, some isolines of these simulations are shown. The simulation supported as well the selection of the daylight zones and of the luminaire to be controlled by the sensors. According to the aim of this work, real cases study with actual lighting control system have been chosen. The commissioning procedure has been carried out by following step-by-step the procedure suggested by the user manual of the commercial sensors. Following the procedure and indications reported in the manual:

• The light sensor opening must face the source of daylight (window).

• Ensure that no artificial light or direct sunlight reaches the light sensor.

• Ensure the distance between light sensor and window does not exceed the window height: $c \leq a$ (see drawing "1 Side view").

• Install the light sensor in front of the centre of the window; ensure the distance between light sensor and window does not exceed the window width: $c \leq b$ (see drawing "2 View from above").

• If the window lintel height clearly exceeds 1/6 of the distance between window and light sensor (see drawing "1 Side view"), the light sensor must be installed suspended or inclined.

• Avoid large-scale shading of the light sensor's angle of view, e.g. by window cross bars, high window lintels or luminaire housings located in front of the light sensor. The maximum permissible shading is 15%.

As explained in [45], system i was configured by the software Virtual Configurator by Bticino and programmed by using the Software MyHome Suite by Bticino [50] which can manage several BAC functions, including lighting control.

In this case, it was necessary to select the sensor to be configured and the illuminance setup. An enter key was utilized to send the command to the sensor. Figure 10 shows the screenshots of the two software.

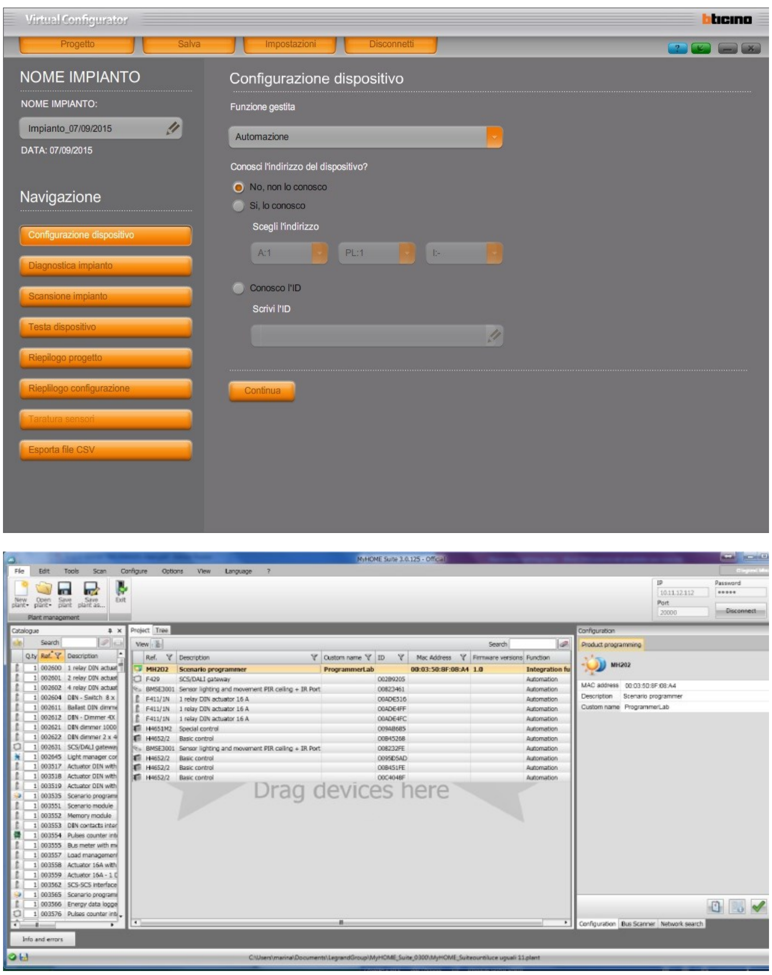


Figure 10. A screenshot of the software Virtual Configurator (above) and a screenshot of the software MyHome Suite.

4.1.4. Measurement campaign

A 13 months-long period of measures was undertaken, to analyse the lighting control systems' performance in different seasons and operation conditions.

In particular, during the experimental campaign, the following measures were taken:

- indoor illuminances, by six photosensors located in six different points of the room;
- electricity data as power and current absorbed by the lighting system, and supply voltage.

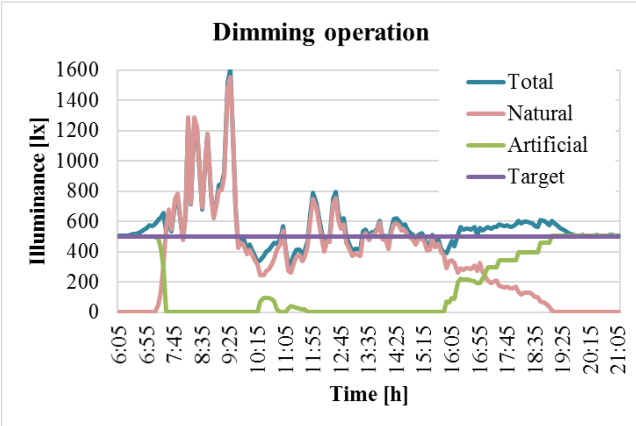
For obtaining a wide set of realistic energy consumption values, various scenarios were tested based on the following variables:

- different occupancy schedules;
- seasons time (winter time and summer time);
- daily natural light contribution (measured through the ALD values calculated for the whole day);
- different illuminances for the two end-uses (residential and office) in order to have specific task values on the horizontal plane in different periods of the year;
- different control system typologies (explained more in detail below);
- different sensors' locations.

In a previous study, the authors tested these systems to evaluate their performance in terms of energy (actual consumed energy compared to the quantity of energy they should have ideally consumed exploiting the daylight contribute) and comfort (maintained illuminance task values) [43].

Figure 11 shows two samples of measures of illuminance values taken during on-off and dimming operations. It can be noted that commercial DLCs, also when operating in dimming mode, can give problems of "overilluminance" (e.g. at 6:45) or "underilluminance" (e.g. between 15:25 and 16:05) with respect to the task illuminance value chosen as a threshold (Fig. 6.a). Furthermore, the empirical BAC Factor method was applied considering an on-off strategy (Figure 11) as well. In this case, the electrical consumption was calculated "ex post" considering that the luminaires were turned on at 100% of the luminous flux when the actual system dimmed the luminous flux (e.g. 50%).

The occupancy schedules for the residential and the office scenarios are taken from [43]. Table 4 summarizes the scenarios and systems tested in the 13 months-long campaign.



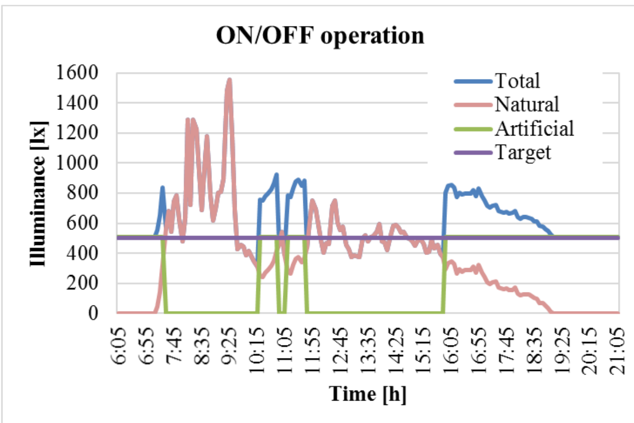


Figure 11. Illuminance values measured in dimming (above) and on-off (below) condition**.**

Table 4. Control systems and scenarios tested and correspondent periods.

System	End use	Period
i	Office	From 04-10-2016 To 23-04-2017
	Residential	From 14-07-2017 To 31-08-2017
ii	Office	From 31-05-2017 To 21-07-2017
		From 15-11-2017 To 26-11-2017
	Residential	From 06-08-2017 To 17-09-2017
iii	Office	From 22-10-2017 To 11-11-2017

Residential	From 18-09-2017 To 16-10-2017

4.2. Case study 2: the lighthouse in Lampedusa

4.2.1. The site

The second case study is a room used as an office at the lighthouse of Lampedusa Island in the Mediterranean Sea.

The lab has an area of 20 m^2 and a height of 4.3 m. The room has one window east-located, mounting clear single-glazing with aluminium frames with a manual damper system.

It is located at latitude 12°36'10"80 E and longitude 35°30'10"80 N. According to the Decree DPR 412/93 classification, as well Lampedusa is considered in climatic zone B. The external façade is covered with white plaster. The room is on the ground floor. All the indoor walls are white painted (ρ=0.8), while the floor is covered with tiles (ρ=0.4) and the ceiling surface is covered by a white plaster (ρ=0.9). In the laboratory four wood desks are present. The glass has a light transmission factor of 0,8. During the measurement the existing blinds were completely open. This façade is partially covered by a cooling system feature.

Figure 12. The external (left) and internal (right) views of the room.

4.2.2 The lighting system

The lighting system, installed in the laboratory, is composed of 4 pendant luminaires (Figure 13), equipped with 33 W characterized by a luminous flux of 3960 lm.

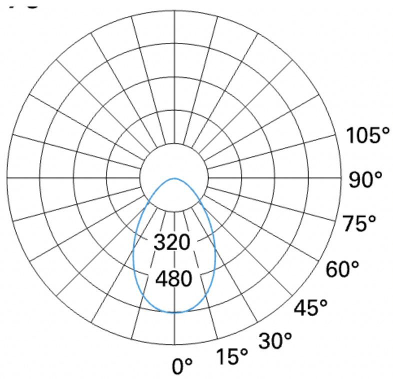


Figure 13. Photometric diagram of the suspended luminaire

As well in this case, the luminaries are characterized by a power supply unit with DALI interface. Luminaires have a colour temperature of 4000 K and a luminous efficacy of 110 lm/W. The lighting power density is 6.6 W/m^2 for the whole area. Figure 14 shows the section and plan of the laboratory with sensors and luminaires' location.

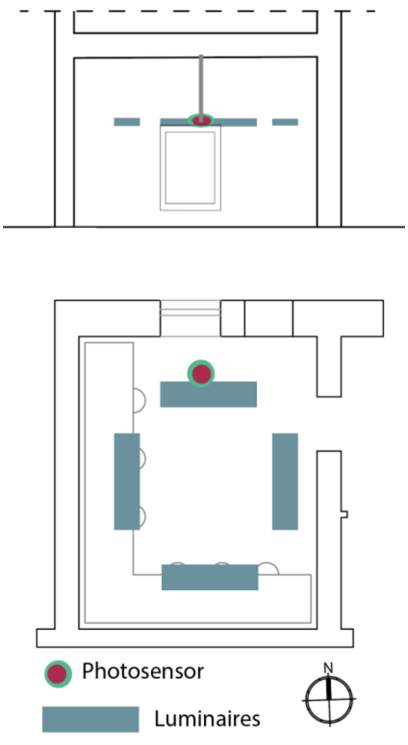


Figure 14. Section and plan of the laboratory with sensors and luminaires' location.

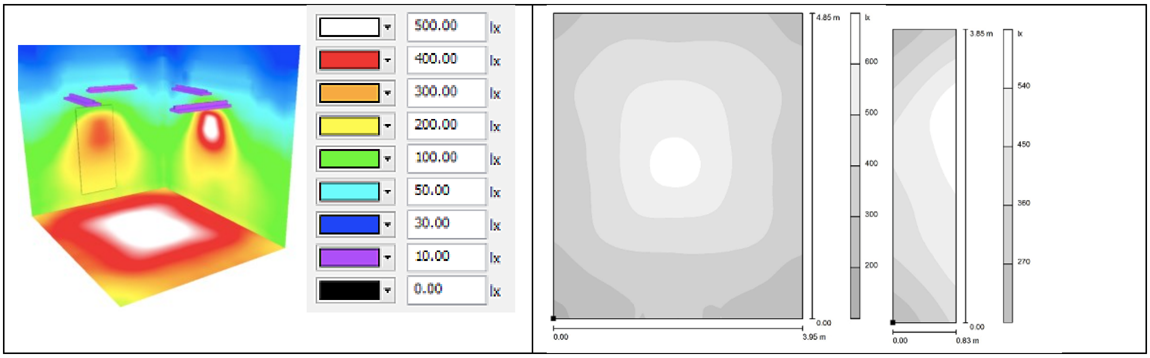


Figure 15. False colour rendering and isolines calculated on the floor and on one of the desk.

4.2.3 The lighting control system

In the lighthouse, the same control systems indicated by ii) and iii) in Section 4.1.3 are present. However, in this case, being the height of the room 4.3 m, the sensor used to control the luminaires was installed using a vertical bracket (figure 16).

Figure 16. Sensors and luminaires installed in Lampedusa.

4.2.4. Measurement campaign

The measurement campaign was 1 month-long. Although the measurement campaign in this second case is much shorter than one year, the case is interesting for showing to the reader a further example of how different control systems can influence the final value of the actual consumption, on which is based the calculation of BAC factors.

As well in this case, the indoor illuminances and the electricity data were measured. The illuminance was measured by two photosensors, one located on a desk and one near to the photosensor used to control the luminaires.

The occupancy schedule considered is a common office daily schedule (from 09:00 to 17:00).

5. RESULTS

Tables 5 to 7 report the values calculated by eq. (2) for the case study in Palermo. The performances are different throughout the year. For this reason, the comparison of the three different systems using the BAC Factor method was done separately for winter and summer, as well as on a yearly basis. Indeed, a correct evaluation of BF must take into consideration the actual contribution of natural lighting during the daytime, especially in presence of dimming control that, during winter or in rooms characterized by insufficient natural lighting, can become ineffective. Nevertheless, there is not a good correlation between BF and ALD 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.

It can be noted that in the practice, only a comparison carried out taken into account yearly average values is meaningful. Indeed, a single BF value referred to a day or a season can be highly different from the theoretical BF, depending on the daylight contribution of the specific day.

Furthermore, despite BFs are defined to assist in the valuation of the buildings consumption during a year, a comparison based on seasonal values can be useful to allow important information about the performance of the system throughout the year.

Results demonstrate that the BF values calculated for C and A classes are quite similar to the theoretical BF just in some scenarios. The BF values calculated using the system i) are more similar to the theoretical BF values. It must be underlined that the performances of system i), in terms of visual comfort and energy, were lower than the ones of the other systems.

Mainly for the residential cases, but in general for all cases, it can be seen that there are no significant energy savings during the winter period compared to the case without automation. This is because the occupancy of the residential scenarios is mainly in the second part of the afternoon, so, during winter, the presence of people is considered after twilight.

The percentage difference was calculated as follows:

$$\frac{BF_m - BF_{th}}{BF_m}\%$$

Where BF_m is the Bac Factor calculated by using the actual measured values and BF_{th} is the Bac Factor value suggested by the standard.

Table 5. Calculated average values of BF for system i) and comparison between actual and theoretical BF (Palermo case study).

Class A		**Residential**			**Office**		
		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	-15.3%	25.2%	4.9%	6.1%	17.1%	11.6%
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	-6.4%	0.7%	-2.9%	-4.3%	25.0%	10.3%

Table 6. Calculated average values of BF for system ii) and comparison between actual and theoretical BF (Palermo case study).

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	-15.3%	59.6%	11.0%	58.4%	32.6%	45.5%
Class C		**Residential**			**Office**		
		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	-5.4	25.8%	10.2%	51.3%	17.6%	34.5%

Table 7. Calculated average values of BF for system iii) and comparison between actual and theoretical BF (Palermo case study).

		Residential			Office		
Class A		Winter	Summer	Yearly	Winter	Summer	Yearly
	Measured	0.98	0.64	0.8	0.64	0.64	0.64
	Theoretical		0.85			0.79	
	Percentage difference	-15.3%	24.8%	4.8%	19.3%	18.48%	18.87%
		Residential			**Office**		
Class C		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	-5.4%	6.8%	0.71%	9.9%	5.9%	7.90%

Hence, because of the absence of natural lighting, the luminous flux was at 100% for the most of the time period.

Although the difference is not so high, it can be seen that the energy savings expected are lower than the measured one. From Table 5 (i. system) it can be seen that the measured BF values for the Class C lighting systems are quite close to the theoretical BF in the residential case (percentage differences are not over 7%). As it is possible to note looking at the yearly average values, it is very low the percentage difference also for Class A.

BF values are very close to the theoretical one during the winter period in the office case.

Regarding the BF related to the ii) system, they are very similar to the theoretical ones for class C both in the residential and in the office case and mainly in the winter period.

Finally, the difference between BF values calculated for the third system and the theoretical ones is very low mainly for the class C case.

Table 8 shows the results of the analysis conducted for the case study of Lampedusa. It can be noted that the difference between the calculated BF and the theoretical ones suggested by the standard is slightly higher in the calculation conducted for class C. It must be reminded that this calculation was conducted by using a smaller set of data. Indeed, the measurement campaign was carried out in a shorter period (1 month) and for one end-use (i.e. office).

Table 8. Calculated average values of BF and comparison between actual and theoretical BF (Lampedusa case study).

	Office	
Class A	Calculated	0.68
	Theoretical	0.79
	Percentage difference (Daily)	13.6%
	Office	
Class C	Calculated	0.81
	Theoretical	0.91
	Percentage difference (Daily)	11.4%

Looking at the plot in Figure 17, it can be noted that, in general, as already mentioned, there is not a good correlation between the BF and the ALD index, mainly for i) and ii) systems. Anyway, as a general trend, the higher ALD the higher BF. In other words, in the days where the artificial light demand is higher due to a lack of daylight, the efficacy of the automation systems become less valuable.

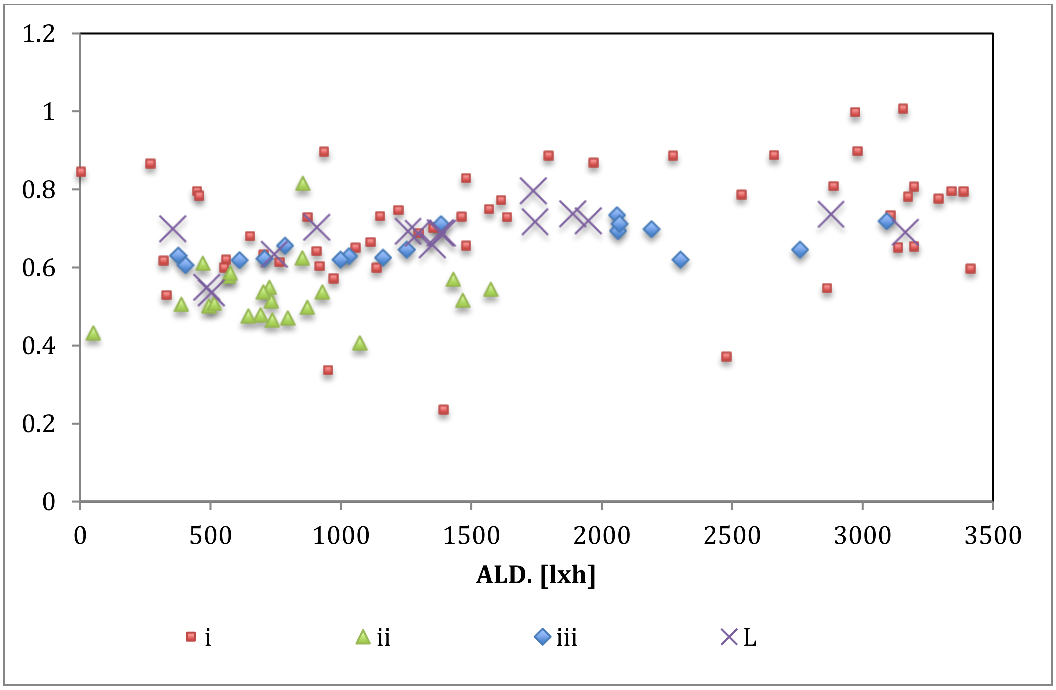


Figure 17. Relationship between BF calculated for office in dimmer operation and the ALD values for the three systems ("i" is a closed-loop sensor installed on the ceiling; "ii" is an open-loop sensor installed on the ceiling; "iii" is the same system used in "ii", with the sensor located in another point of the ceiling; "L" is the same system used in "ii", with the sensor located in case study in Lampedusa).

Meanwhile, the values calculated for the system i) show that the performances of this system in terms of energy and visual comfort were lower than the performances of the other systems.

It is important to note that the definition of BF is antecedent to the spread of the more efficient LED technology [6] [12] [20]. Furthermore, it is clear that the use of more efficient light sources increases the relative weight of the control system' consumption on the total expenditure. In order to appreciate this effect, BF were calculated as well for a less efficient lighting system (system 2) characterized by a higher absorbed power (300 W) and connected to the same control system of the previous exercises, having unaltered absorbed power. It has to be noted that, when a daylight harvesting system is required to be dimmed at a certain percentage, it will be dimmed according to it, even if it is LED of fluorescent. However, it has to be noted that different light sources typologies can be coupled by different ballast and additional fittings characterized by different absorbed power. This latter, as demonstrated is not considered in the BF calculation.

The consumption of this ideal system was calculated as:

$$E_2 = \frac{E_1}{P_1} P_2 \tag{4}$$

where E_1 is the energy consumption of the more efficient lamps, E_2 is the energy consumption of system 2, P_1 is the power absorbed by system 1 and P_2 is the power absorbed by system 2.

In the following tables 9 to 11, the comparison between the actual BF, daily calculated, and the theoretical ones calculated for system 2 are shown.

It can be noted that the BF calculated with different lighting systems characterized by different efficiency are less or more different. As can be observed in Figure 18, the main differences were found in the offices case.

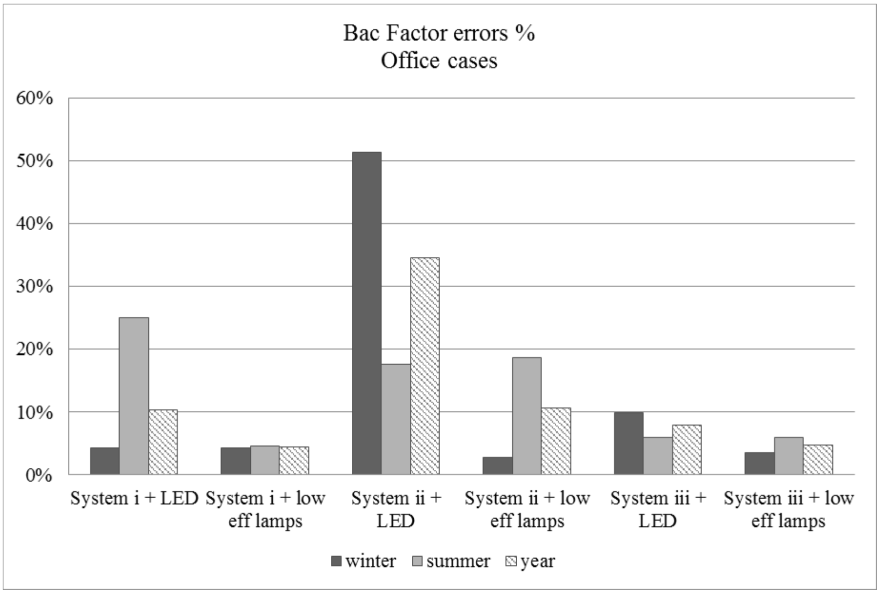


Figure 18. Comparison of difference (between the calculated BF and the theoretical ones suggested by the standard) affecting BF (Class C) in case of LED and low efficiency light sources in office operation.

i							
Class A		Residential			Office		
		Winter	Summer	Yearly	Winter	Summer	Yearly
	Daily	0.97	0.61	0.79	0.73	0.64	0.68
	Theoretic.		0.85			0.79	
	Percentage difference (Daily)	-14.1%	28%	6.9%	7.96%	18.9%	13.5%
Class C		Residential			Office		
		Winter	Summer	Yearly	Winter	Summer	Yearly
	Daily	0.98	0.92	0.95	0.95	0.95	0.95
	Theoretic.	0.93					0.91
	Percentage difference (Daily)	-5.38%	0.72%	-2.33%	-4.3%	-4.5%	-4.4%

Table 9. Calculated average values of BF for system i with less efficient light sources and comparison between actual and theoretical BF.

Table 10. Calculated average values of BF for system ii with less efficient light sources and comparison between actual and theoretical BF.

ii							
Class A		Residential			Office		
		Winter	Summer	Yearly	Winter	Summer	Yearly
	Daily	0.98	0.53	0.75	0.46	0.53	0.49
	Theoretic.		0.85			0.79	
	Percent. Difference (Daily)	-15.1%	60.2%	11.3%	42.4%	32.8%	37.6%
Class C		Residential			Office		
		Winter	Summer	Yearly	Winter	Summer	Yearly
	Daily	0.98	0.69	0.83	0.89	0.74	0.81
	Theoretic.		0.93			0.91	
	Percent. difference (Daily)	-4.9%	25.8%	10.4%	2.7%	18.6%	10.6%

Table 11. Calculated average values of BF for system iii system with less efficient light sources and comparison between actual and theoretical BF.

iii							
Class A		Residential			Office		
		Winter	Summer	Yearly	Winter	Summer	Yearly
	Daily	0.97	0.63	0.80	0.68	0.64	0.66
	Theoretic.	0.85					0.79
	Percent. difference (Daily)	-13.9%	25.5%	5.84%	13.9%	19.0%	16.5%
Class C		Residential			Office		
		Winter	Summer	Yearly	Winter	Summer	Yearly
	Daily	0.98	0.87	0.93	0.88	0.86	0.87
	Theoretic.		0.93			0.91	
	Percent. difference (Daily)	-5.4%	6.1%	0.4%	3.4%	5.9%	4.7%

In the winter season, for system ii), C class, it is possible to see that the difference is very high (2.72% for the low-efficiency lighting system and 51.36% for the LED one). Likewise, the BAC factor calculated for system i) in the office case in the summer season has a difference between the calculated BF and the theoretical ones suggested by the standard of -4.5%, considering the less efficient lamps, and of the 25% considering the LED lamps. On the contrary, in all the other cases the calculated values are different from the factor given by the standard, but with lower difference between the calculated BF and the theoretical ones suggested by the standard. However, it means that the standard should be updated to consider the effect of the higher efficiency of modern lighting sources.

6. CONCLUSION

This paper presents the calculation of empirical BF calculated for different lighting systems installed and tested in two cases study in South Italy. The first one is the laboratory of Thermal Solar Systems for Summer and Winter Air-conditioning of the Department of Engineering of the University of Palermo. Here there are four windows southeast located (2.40 m wide and 2.60 m high) and two different control systems applied to the same lighting system were used. A measurement campaign (long 13 months) was performed collecting illuminance and energy data with a time step. In order to demonstrate that the conclusions obtained for the first case study can be extended to other buildings, another case study was taken into account. It is an office-room of the lighthouse of Lampedusa (a room has an east-located window). Here a control system was tested for a month-long period. Although the measurement campaign in this second case is much shorter than one year, the authors have considered the case interesting for showing how different control systems can influence the final value of the actual consumption, on which is based the calculation of BAC factors.

The measured values were used for evaluating the actual yearly and seasonal consumptions for both a residential and an office environment (in the first case, only for the office environment in the second case), with the aim of assessing the accuracy of the BAC factor method as well as to relate the results also in terms of provided visual comfort for occupants.

In particular, the method was applied for a commercial system equipped with a closed-loop sensor installed on the ceiling and for a commercial system equipped with an open-loop sensor installed on the ceiling, but changing two different locations of the photosensor. Analyzing with more detail the difference between the BFs 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 assert 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. system iii) of the first case study. But, in other cases (e.g. system i, office) 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.

The main differences are because the theoretical values do not consider several parameters such as the influence of specific daylight contribution in a yearly analysis, the different use patterns assumed for the lighting system, the imposed task illuminance values, the stand-by energy consumption of lamps and control devices, the sensor location, etc. On the other hand, the actual performances of these systems were not as the expected ones. Indeed, it was noted that the expected consumption were higher than the ones measured in real condition. It was caused by some issues related to some parameters (e.g. the location of the sensors) and made the factors closer to the theoretical ones (that, as said, do not consider many parameters by causing higher values).

It is worth nothing that, regarding the sensors location, it has been demonstrated that the same control system with sensors in different positions gives place to different energy consumptions. Sensors location is debated in the literature with regards to the visual comfort issue and to the effectiveness of the artificial lighting control. Some papers provide indications and methods to optimize sensors location. The analysis done in this paper shows how sensors location impact the energy consumption.

As said, location is one of aspects not considered by BF method, while the first case study shows that this is a fundamental element in the control system design and able to greatly impact on the final energy consumption and the difference between the theoretical BFs and the calculated ones.

In addition, the Standard EN 15232 does not consider many important aspects of a lighting system and of a 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, rated power and yearly energy consumption of the control devices, photosensor typology, and other technical parameters are not considered, too. Finally, the BF determination is antecedent to the more efficient LED technology spread. As demonstrated by calculating the BAC factor for different lighting systems characterized by different absorbed power, the standard should be adapted according to the efficiency of the lighting sources.

For this reason, the expected savings seem lower than the actual ones. Indeed, they do not consider that the efficiency of this type of lighting source and of the control system is higher. In general, it can be affirmed that the differences between the calculated BF and the theoretical ones, suggested by the standard, are not so high even if the standard EN 15232 suggests to apply the method provided by the standard EN 15193, for which the difference between the calculated BF and the theoretical ones, suggested by the standard, is higher. As will be shown largely in this work, one of the reasons is because this kind of system seldom works as expected.

Finally, it is worth underlying that the results obtained in this study refer to two specific locations in South Italy and that, presumably different results would be obtained for sites with higher latitudes. Nevertheless, the two case studies have provided sufficient information to open a discussion on how the BF method can be improved for considering all factors that actually influence the performance of DLCSs.

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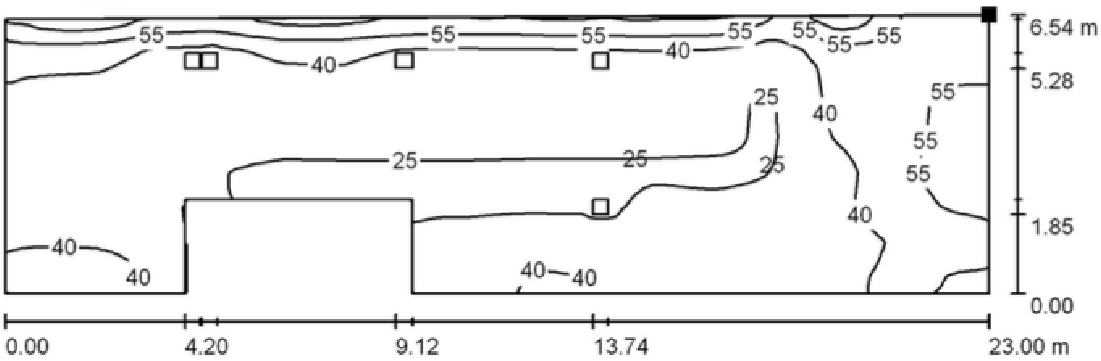
ANNEX



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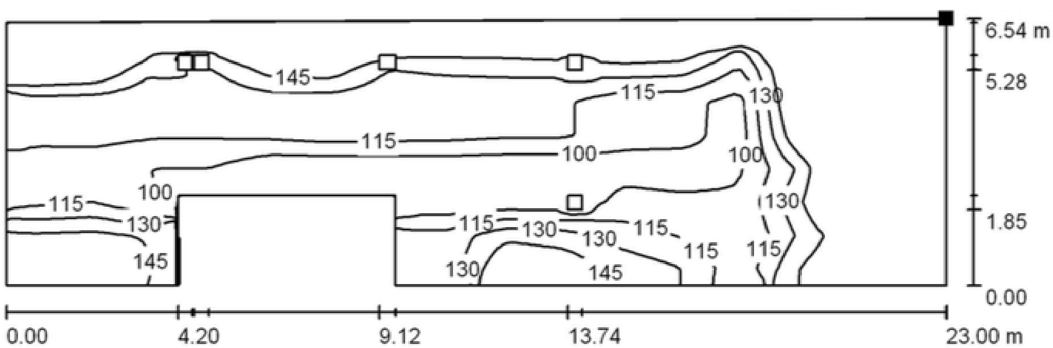

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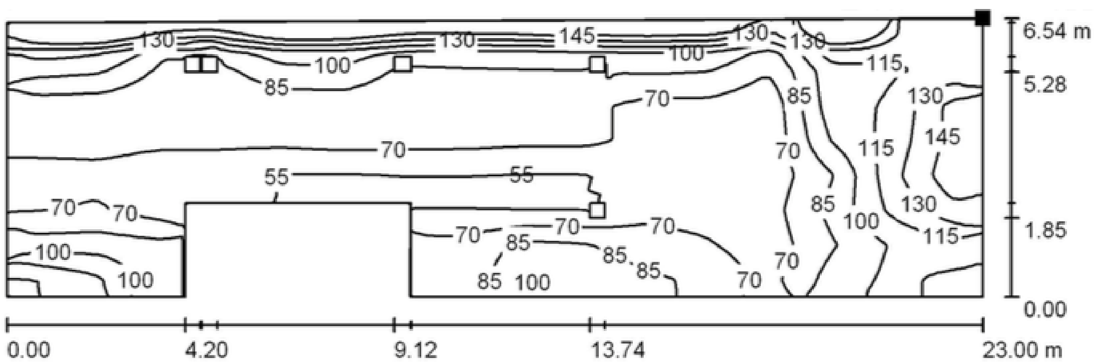

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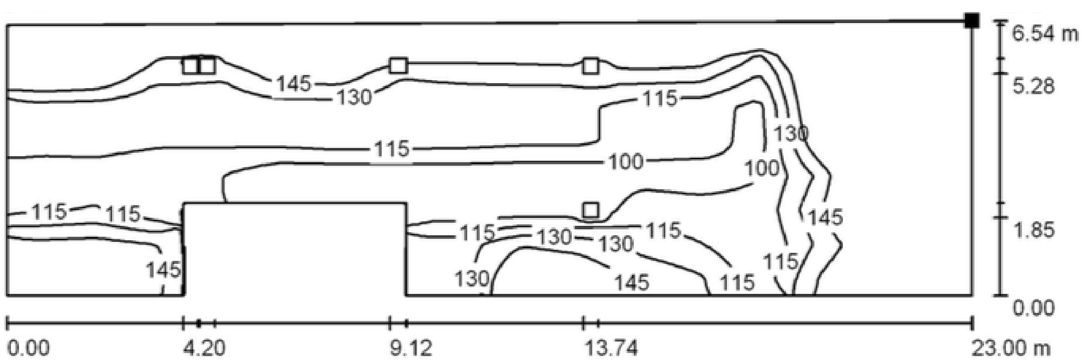

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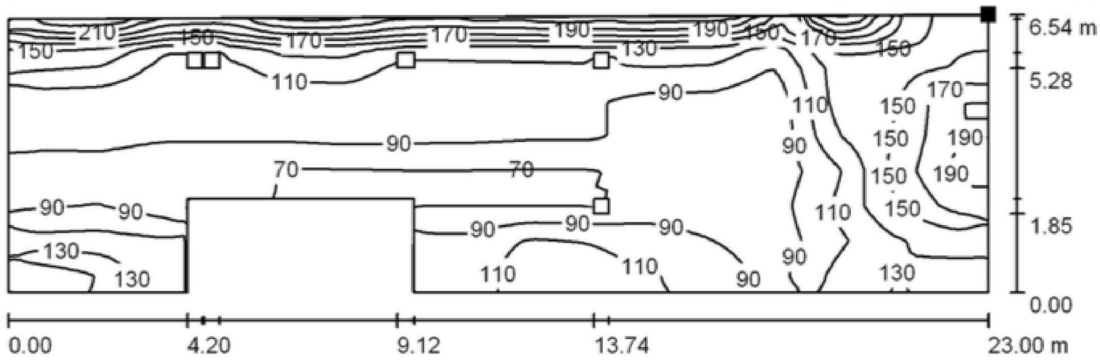

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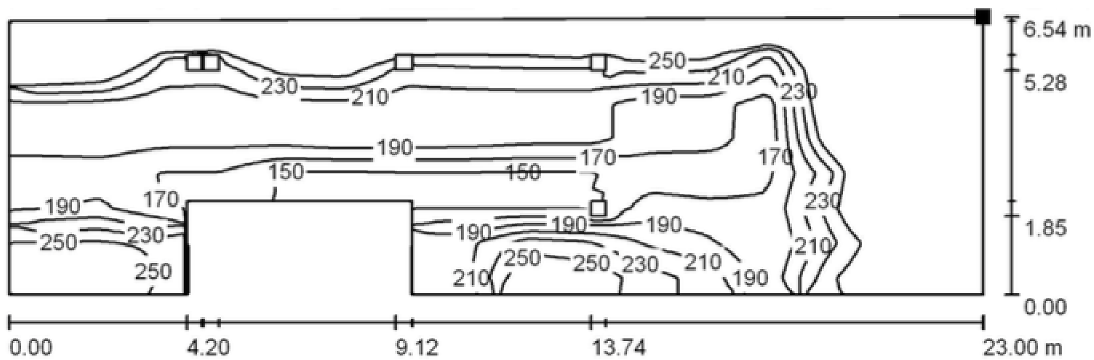

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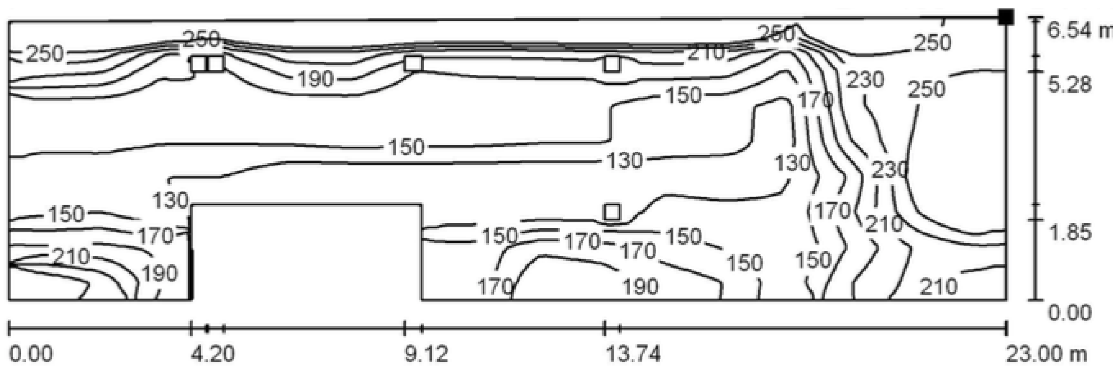

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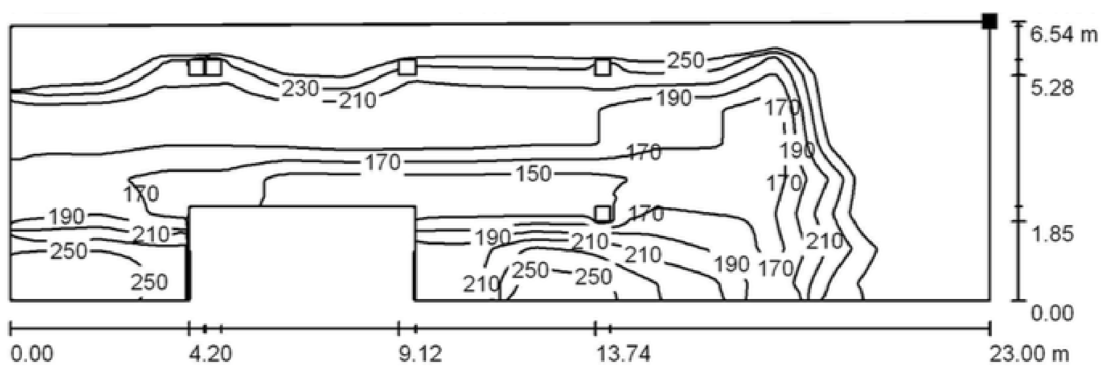

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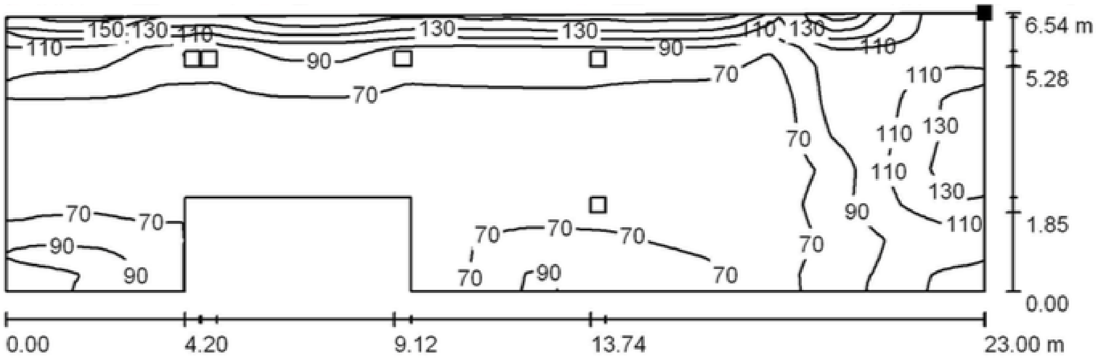

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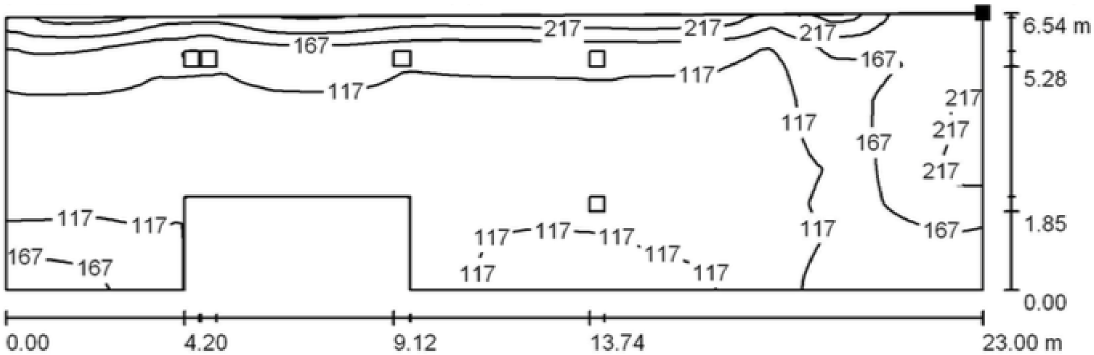

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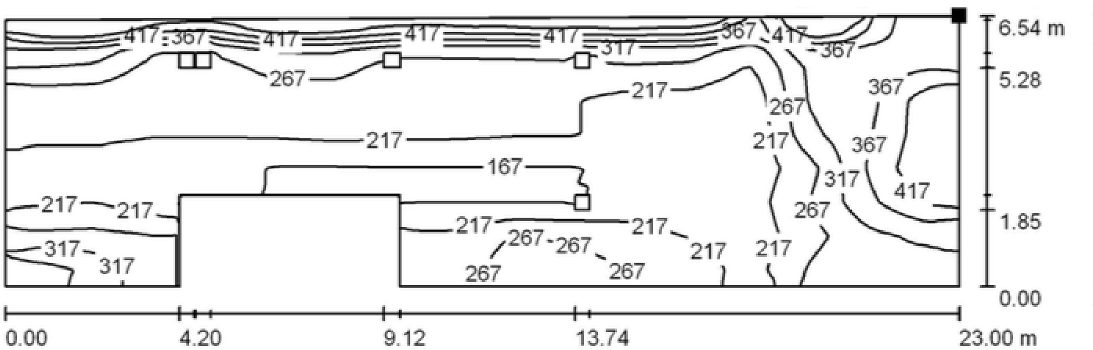

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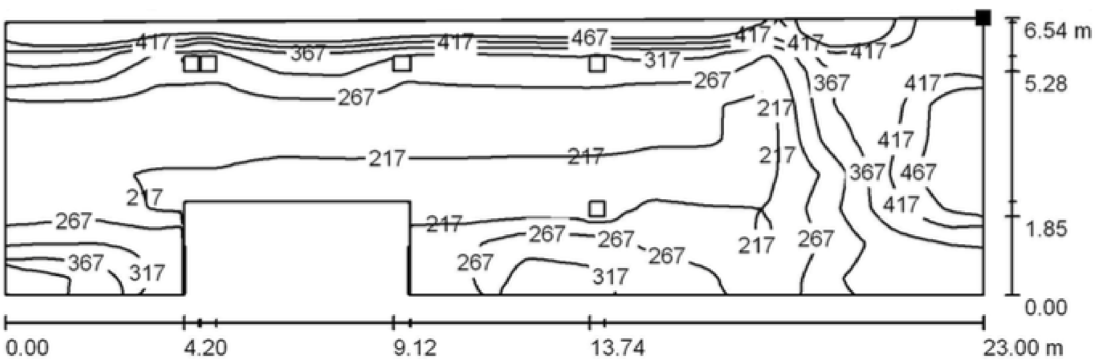

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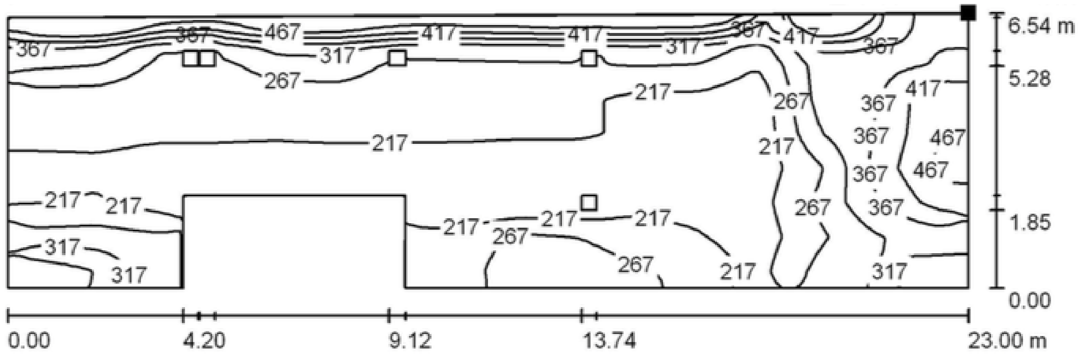

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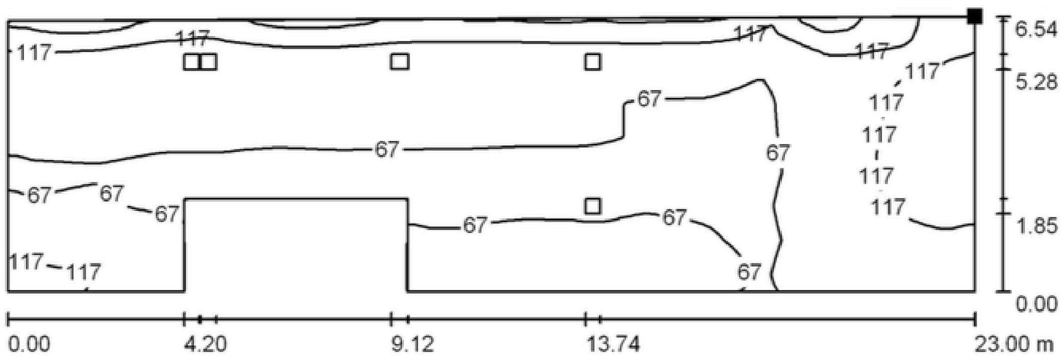

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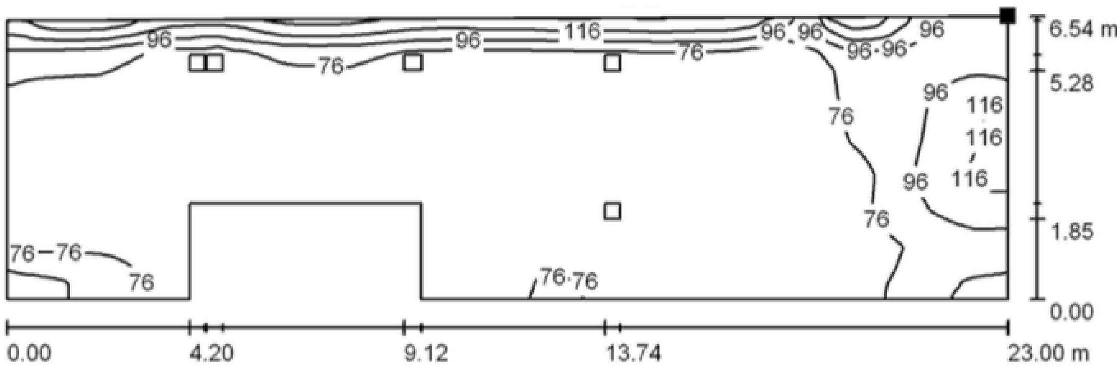

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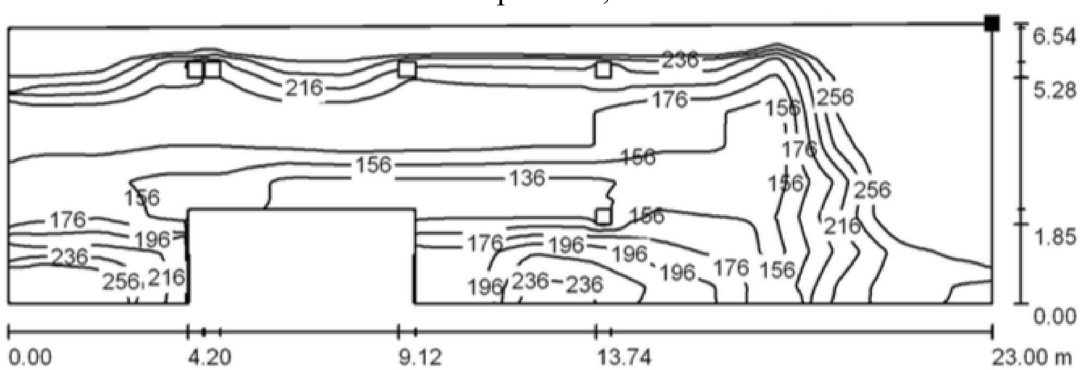

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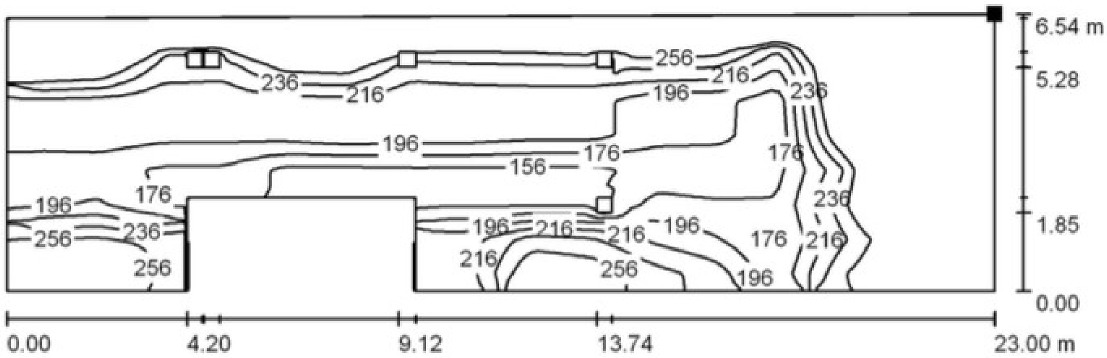

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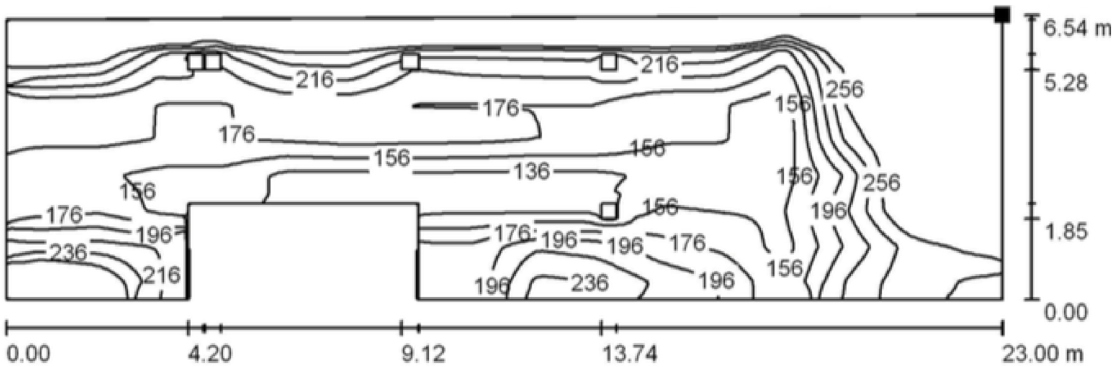

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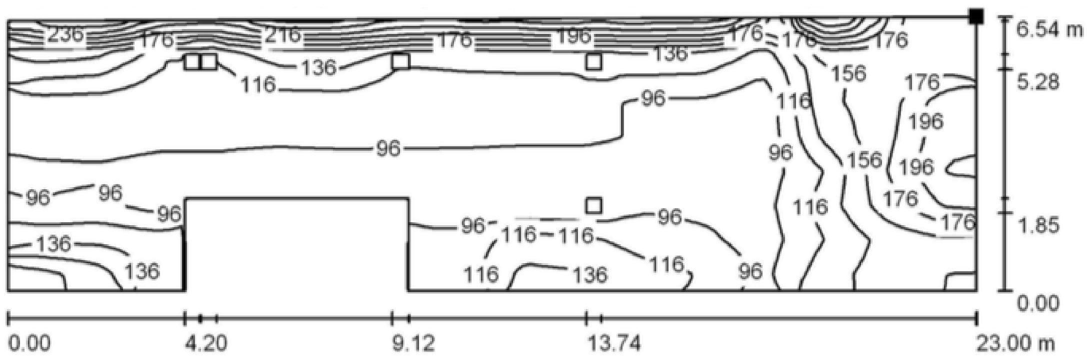

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Figure 1b. Isolines of daylight distribution on the ceiling performed by Dialux