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A First Approach to Universal Daylight and Occupancy Control System for Any Lamps: Simulated Case in an Academic Classroom

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Abstract

This paper presents a lighting control system based on natural light monitoring and on occupancy control, characterized by installation easiness, even for existing plants, and cheapness.

The system is based on a smart control unit and lighting control devices that can be directly mounted on the lamps in series connection. The installation is noninvasive and does not require any changes in the wiring system, since the communication between each lamp and the control system is realized by means of a 2.4 GHz wireless protocol. The system functionality is ensured with any lamps, also with non-dimmable ones. Tests and functionality verifications on the system were performed in laboratory, proving the applicability to real cases and performances that are comparable to the ones achievable with dimmable LED lamps, but with a significant cost saving.

Hypothesizing the application of the proposed system and of different control technologies and strategies to a real academic classroom case study, different lighting scenarios have been simulated. Obtained results allow quantifying the effects in terms of energy consumption and CO_2 emissions relative to such scenarios, achieving up to 69.6% of energy saving and 30.5% of CO_2 emissions avoided. From an economic point of view, the comparison between the proposed control system and commercial systems shows a shorter PayBack Period, from 9 to 5 years.

Keywords: lighting control; universal lamp dimming; wireless system; energy saving; economic analysis.

1. Introduction

Energy consumption for lighting is, nowadays, responsible of about 20% of the overall energy consumption [1]. This datum justifies the recent attempts for searching efficient technologies, able to contribute to energy consumption reduction.

The high performances of LED (light emitting diodes) lamps pushed their rapid spread [2], leading to a direct energy saving.

According to a study of Ozenc et al. [3], LED lamps, besides having a higher lighting efficiency compared to fluorescent lamp, allow high savings in case of dimming. Hypothesizing a 50% dimming ratio, fluorescent lamps lose 24% of lighting efficiency, whilst LED lamps 1.3%. Therefore, in terms of energy efficiency, LEDs are more suitable for dimming than fluorescent lamps.

Differently, according to Doulos et al. [4], control systems are still not sufficiently examined. Lighting control techniques and strategies represent a complex matter, due to their planning process, to the proper matching of the dimming system for the used luminaires [4], to the installation features [5] and to the difficulties on the evaluation of investment payback time [5-6]. For all these reasons, spread of lighting control systems is slower than lamps and luminaires. Nevertheless, research on lighting control systems proceeds along different directions. In some cases, scientific developments aim to an upgrade of light control technologies [7-8]. In other cases, the scope is searching for a reliable evaluation system of real energy savings [9].

An interesting review on lighting control technologies is presented by Haq et al. [10]. Yu and Su [11] presented a literature review in which they state that, amongst all lighting control systems, the ones more commonly employed are the high frequency dimming control and the on-off control; the choice of the control system deeply influences the energy saving potential. Salata et al. [12] discussed a case study of a classroom of an academic building. Results obtainable by considering the interplay between natural and artificial light are highlighted. A new lighting system is proposed, able to manage the automatic partialization of motorized indoor roller blinds and the presence of occupants in the room.

Energy saving is well discussed in literature. The energy saving amount can vary on monthly and seasonal basis, as assessed in [13]. In the paper, monthly savings vary from 20% in December to 47% in June and July. Energy saving of 21% in winter season increases to 45% in summer. On seasonal basis, savings differ according to weather conditions. The overall annual energy saving achievable by adopting a daylight responsive control system is up to 31% for climate conditions similar to the ones of Istanbul. In the paper by Martirano [14], the consumption relative to two adjacent classrooms has been evaluated. In particular, the light control system foreseen for the two rooms is conceived to meet the needs required by scheduling, luminance control, occupancy, daylighting and zoning. The evaluations are carried out using the LENI (lighting energy numeric indicator) methodology. According to the author, the energy saving achievable by adopting action in power reduction (like, for instance, more efficient lamp) is almost the 20%, while the savings obtainable by using lighting control systems (like occupancy sensors) depend on the control mode (dimming or switching) and swing between 35% and 42%. By implementing control systems and efficient equipment, the energy saving accounts for 54%. The work of Bardhan and Debnath [15] deals with the analysis of the energy saving potential of a residential building when, as daylight performance parameter, the Useful Daylight Illuminance (UDI) is considered. It turns out that energy saving potential depends on the orientation and on the window-to-wall (WWR) ratio. The maximum energy saving for the analyzed building, equal to 26%, is achieved with a south-east orientation of the functional space and WWR of 20%. In the work of Choi et al. [16], two methodologies of predicting the lighting power savings are compared. One (Method A) refers to the relationship between lighting energy and illuminance. These two parameters, which can be considered as input and output of the system respectively, are also evaluated according to the dimming ratio of the luminaire. The second approach (Method B) consists in taking into account the indirect illuminance in the evaluations carried out through Method A. Results obtained via method A and B are then compared to the lighting energy saving experimentally measured. In reference [17], the energy and power consumption of three identical classrooms equipped with different dimming systems have been compared. An open-loop system was installed in a classroom, whilst in the other two there were two different closed-loop systems (with individual daylight sensor per luminaire or centrally positioned sensor). Results gathered during 12 months, during which the rooms were occupied for teaching purposes, showed that the daylight control system with open-loop system lead to a 46% lighting energy saving. This value is higher than the saving due to closed-loop system, which yielded to 34% and 18% energy saving, the latter being recorded for the room with central positioned sensor.

Detailed studies on lighting control for daylighting and occupancy adaptation show the different approaches adoptable. A work proposed by Peruffo et al. [18] discussed a wireless mesh networked lighting system with multiple sensors equipped with a central controller, evaluated through a simulation performed with DIALux. In this study, it is underlined that wireless connections are simpler than wired ones, and they are useful for lighting controls retrofitting. Aghemo et al. [6] presented an experimental analysis given by the installation of custom-designed building automation and control systems for lighting and air conditioning on 11 offices in Turin (Italy). Lighting control is realized with digital dimming ballast (DALI protocol), while system nodes communicate with LonWorks protocol. Results show an energy saving variable from 17% to 32%, considering both the annual electric consumption and the parasitic energy consumption, due to sensors and controllers. A study conducted by Xu et al. [19] presented an energy performance evaluation for lighting systems with 8 different control strategies. The employed technology is based on commercial sensors (OSRAM LS/PD MULTI 3) and the data gathering core is a PLC (programmable logic controller). Results show that the employment of a generic lighting control system allows energy savings of the order of 50%. The combination of task lighting and dimming allows achieving energy saving up to 59%, still guaranteeing comfort for occupants. Doulos et al. [5] presented a study in which they quantify energy savings among 18 different EDBs (electronic dimming ballasts), identifying the relationship between light output ratio and control voltage, consumed power and control voltage, power factor and control voltage and between consumed power and light output ratio. Simulation results of an office building reveal significant differences in energy saving due to tested ballasts. Rossi et al. [20] discussed a comparison between two lighting control scenarios in an open office lighting model: the first scenario considered a daylight and occupancy adaptation based on pre-specified illumination targets, whereas the second scenario evaluated via simulations the performance of a lighting control based additionally on user control requests. In the work of Caicedo et al. [21], a lighting system with light sensors co-located at light source was considered, in order to assess by means of simulations how a central controller can minimize power consumption maintaining a minimum average illuminance level on the workspace plane. Prior-information for sensor calibration step were also provided.

In this work, different types of control systems, the development of the related technologies, the savings obtainable from their application and factors affecting their performance are debated. Moreover, trend of developments on lighting control and possible future advancements are discussed. The next part of the paper is organized as follows. In Section 2 the objectives of the work are presented. Section 3 reports the novel lighting control system and the simulated case study. Section 4 deals with obtained results. Finally, in Section 5 conclusions are given.

2. Objectives

Lighting control systems, although allowing relevant reduction of energy consumption, are often affected by design and installation complexity, high costs, difficulties in evaluating real energy benefits and technical management problems [5-6, 22]. These reasons determine their smaller spread compared to the possible expectations. As stated in [23], the spread of lighting control system is wider in new buildings than in old ones. This point of view negatively influences results on overall energy savings obtainable by the lighting sector. In fact, according to Pellegrino et al. [24], based on the small amount of new buildings realized in developed Countries, the energy saving potential can be realized only with the retrofitting of the existing building stock.

For these reasons, the main objective of the present work is the proposal of a novel automatic daylight control system and occupancy sensing, employable with different lamp typologies; it is conceived especially for application on existing buildings, thanks to its extreme ease of installation, wireless communication capability and to low investment cost. The idea of creating a new control system usable with any lamps aims at minimizing the negative aspects that usually characterize the installation of a lighting control system in existing buildings, i.e. high investment costs and possible modifications of lighting fixture, with the attempt of maximizing the diffusion of such systems. The proposed system differs from available literary solutions [25-28] and available commercial products because it allows to define a lighting control systems making use of any type of lamps, regardless of their dimmable and non-dimmable characteristic, also including the conventional light bulbs such as halogen and fluorescent lamps, beyond of LED ones. Up to now, all literary contributions that have been presented try to manipulate the driver circuit inside the LED lamp in order to make it compatible with external dimmers, so they appear as theoretical case studies rather than suitable for practical applications or large scale installations. On the opposite, commercial solutions up to now rely on the availability of very expensive dimmable LEDs or potentiometers, usually manual, that can be installed to dim traditional lamps and that are not able to work with non dimmable LEDs, since they are fabricated with a different technology process. So, the proposed system represents a unified solution for an efficient and automatic lighting control.

System performances of the proposed system were analyzed through laboratory tests, in order to evaluate its sensitivity by defining different illuminance levels for fluorescent and LED lamps, dimmable and non-dimmable.

At the end of the experimental laboratory phase, and after demonstrating the applicability of the system to real cases, being not possible to install the proposed system in public environments, since it is at prototypical stage, the feasibility of the system has been verified at simulation level. The case study is a classroom of the Faculty of Engineering of the University of L'Aquila, in central Italy.

At this stage, the aim is to carry out the energy and economic analysis of the performances of the lighting plant, considering different technologies and control strategies: fluorescent, dimmable and non-dimmable LED lamps, and with occupancy and daylighting adaptation provided by the proposed system. The economic analysis was deepened by comparing the system proposed in this paper, employable also with non-dimmable LED lamps, with a commercial lighting control system usually employable with only dimmable LED lamps.

The case study was analyzed via simulation carried out with Relux software, on a calibrated model, by considering both solely daylight and solely artificial light.

Therefore, the main research objectives can be summarized as follows:

1. design and description of a new universal daylight and occupancy control system employable with any lamps, based on microcontrollers, actuators and a wireless sensor network;
2. prove of the applicability of the system to real cases with different lamps (fluorescent, dimmable and non dimmable LEDs);
3. application of the system to a case study, through the use of a validated model, for energy and economic analyses of the results.

3. Methodology

In this section, the methodology employed for achieving the goals of this paper is discussed.

3.1 Lighting control system

Before describing the architecture of the proposed system, it is necessary to verify the state of the art, concerning how dimming is commonly performed. Generally speaking, the dimmer is a power electronic device used for lighting control. It can be useful in several applications as for the industrial and residential lighting control. Among the advantages for consumers to use dimmers there is the economic convenience with respect to other solutions and energy conservation.

Nowadays, phase-controlled dimmers based on a TRIAC (triode for alternating current) (or two thyristors) can be considered the more diffused for lighting control. In this scenario, several circuits have been developed and presented in the literature by using forward and reverse phase controlled approaches [29-30] also wired or wireless remote controlled. In particular, when the forward phase-controlled dimmers are considered, the TRIAC is triggered into conduction at some point during the AC half-cycle and continues to conduct until it self-commutates at the end of the half-cycle [31-34]. On the other hand, when the reverse phase-controlled dimmers are considered, the component is moved into conduction immediately after the zero crossing commutating off only in a chosen point during the half-cycle of the AC [35, 36].

Currently, the most popular dimmer in the market is the TRIAC phase control dimmer [31-33]. The TRIAC success reason is that it can be triggered at any time of the sinusoidal voltage and can be kept in conduction state until reaching 0 line voltage, so allowing the lamp to be dimmed in the range from 1% to 100%; however, it does not work for a kind of lamps. Nowadays, residential dimmers are designed to meet the needs of homeowners and architects in both style and function. Commercial companies offer a complete line of dimmers and dimming systems that are designed to meet the requirements of architects and specifiers of commercial space such as hotels, restaurants, offices and warehouses. This is true for both new and existing installations where replacing standard switches with dimmers and using dimmable LED helps saving energy and the associated utility costs. The actual problem is the absence of a so called real “universal” dimmer that allows for a fluid "dimming" of every conventional light bulb such as halogen lamps, fluorescent lamps and even dimmable and non-dimmable LEDs. While energy reduction is an important aspect, paying attention to the visual comfort needs of occupant users in terms of illuminance requirements is also important. This means that the dimming levels of each luminaire are also to be determined by corresponding electronic remote or internal to the lamps controllers related to physical aspects such that the total artificial light output contribution, in combination with daylight contribution also related to the human presence. As far as we are concerned, there are not commercial devices or systems that can be used in both novel and existing scenarios for building automation and lighting control.

3.1.1 Control system architecture

The proposed lighting control system has been conceived as a combined architecture embedding sensing elements and actuators that are managed by a dedicated control unit with a microcontroller. The system provides the optimum light level in any environments by means of an automatic control system able to define the necessary lighting conditions with respect to both natural lighting and occupancy conditions.

The lighting control system that has been designed allows the dimming of any lamps installed in the local power grid network, without requiring changes in the lamp type currently in use, in the ceiling lights or even a dedicated electrical system. A block scheme representation of the lighting control device is provided in Fig. 1. It can be installed directly nearby the considered lamp in series connection and it does not require any added connection since it is able to activate the by-directional communication with the master control unit on a 2.4 GHz wireless protocol, as shown in Fig. 2. The system performs a continuous monitoring of the lighting conditions if there are occupants; conversely, if the occupancy sensor does not sense anyone, the lamp is turned off after a fixed delay time that can be defined by the user. In this condition, the occupancy sensor continues to monitor the environment for further presences within its field of view and the logic unit for manually lighting by incoming users.

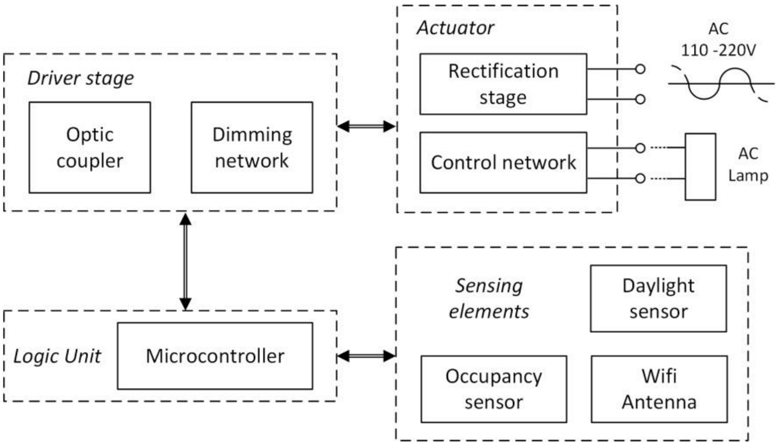


Fig. 1. The proposed lighting control system.

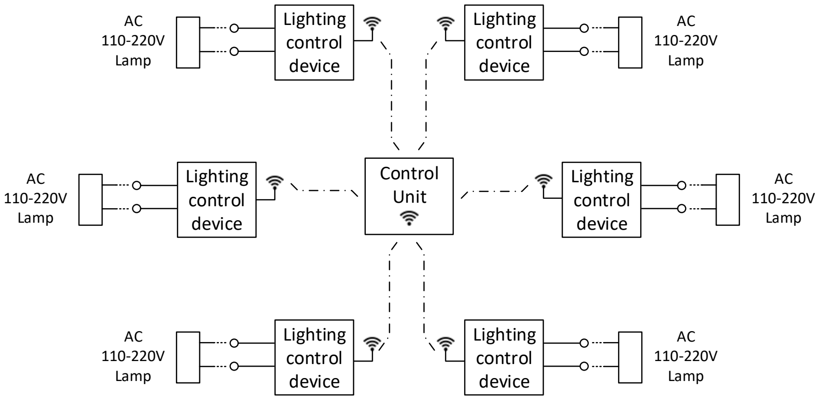


Fig. 2. The lighting control network architecture.

When lighting is necessary, as revealed by any control device, the logic unit that embeds a microcontroller defines suitable lighting conditions considering the natural lighting level in the same environment by means of the daylight sensor and the desired, pre-defined, target value. The desired brightness is achieved directly acting on the driver stage and actuator connected to the considered lamp and the lighting starts from very low level till reaching the necessary target value in about 1 second. The control method is based on the phase synchronization of the system with the power grid by means of a zero-crossing detection approach. Once the proposed control system is synchronized with the AC network signal, the dimming capability is achieved by cutting the amplitude of the sinusoidal voltage incoming to the lamp after a pre-defined time delay. The logic unit is programmed with a pre-calibrated relationship for each lamp type between the desired illuminance and the necessary time delay to achieve it. This means that only when the lamp is used at 100% of its brightness capability it is biased with fully sinusoidal voltages, otherwise the maximum value is set at lower value by the proposed algorithm that limits the amplitude of the biasing signal, so obtaining a lower RMS (root mean square) power level and lower light. In Fig. 3, some examples are provided; the picture shows different biasing signals for the lamp that determine different emitted light, accordingly.

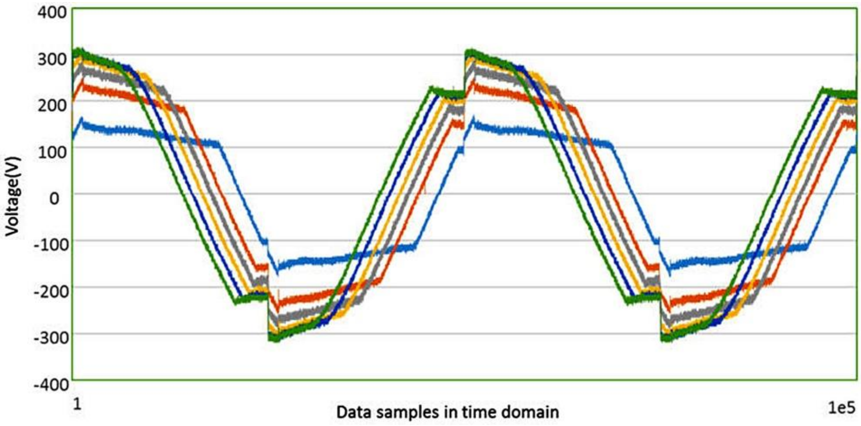


Fig. 3. Example of application: measured control signals that allow obtaining different lighting levels.

It is important to note that directly acting on the time domain, by cutting the voltage amplitude at the desired time instant, it is possible to achieve a continuous tuning system with performance not worse with respect to commercial dimmed lamps, as shown in the following. In this way, the brightness capability is fully controlled and it can be changed almost in continuous wave in the full range. Thanks to suitable circuitry choices, the proposed solution is robust also with respect to flickering phenomena due to harmonic distortions. This capability is ensured by using trap filters and frequency-selective low-impedance paths that avoid the injection of high-order harmonic components into the lamp. The same robustness is achieved also towards the whole lights grid, since the voltage clipping technique here adopted does not propagate distortions to the other lighting elements, because the harmonic components are filtered by the driver stage. So the harmonic content generated by the system is not greater of those provided by commercial dimmer or dimming circuits integrated in dimmable LEDs; anyway, although any lamps can be sensitive also to the provided low harmonics levels, a common EMI (electromagnetic interference) filter may be introduced in the electrical grid to completely solve the problem. In addition, since in this approach the lamp is defined as a generic complex impedance, usually modeled with a resistor and an inductor in series, the lamp type changes do not affect the overall capability and characteristics of the control system. The only action which is required in this case is choosing the proper configuration algorithm for the microcontroller.

A remarkable additional feature relies in the characteristics of the driver stage. Since the system directly works on the AC 110-220 V 50-60 Hz power grid network, while the logic unit usually requires lower voltage values, the driver stage in Fig. 1 is conceived performing also a decoupling between the high and low voltage networks by means of an electro-optic transducer. An optic coupler is used between the logic control unit and the dimming network and actuator so providing a complete isolation of the sensing and control elements with respect to the electric grid. This is a key feature since it makes the provided system not invasive and at the same time shielded from possible network disturbances and overload, that may damage the control system. More in detail, the delay time defined by the logic unit to obtain the desired brightness level is managed by the microcontroller defining a gate, digital, control signal which excites the optic transmitter. The pulsed light activates the photosensor inside the optic coupler so determining the current flow on the dimming network by switching on and off a power MOS (metal oxide semiconductor) transistor directly connected to the high voltage network. It is notable to consider that the use of a MOS transistor to drive the current flow is an additional key point of the proposed system. In fact, in despite of a classical TRIAC that properly works on a resistive load (i.e. a fluorescent lamp which can be considered as a R-L equivalent network), a power MOS transistor, controlled by means of the gate voltage, ensures good operations for any load, that means for any kind of lamps. This strategy has the further advantage to transfer in a high voltage system the control capability and sensitivity proper of a micro electronic system, with unmistakable advantages in terms of accuracy and power handling. In Fig. 4 an example is given, reporting both the digital timing signals and the current profile flowing into a non dimmable LED lamp.

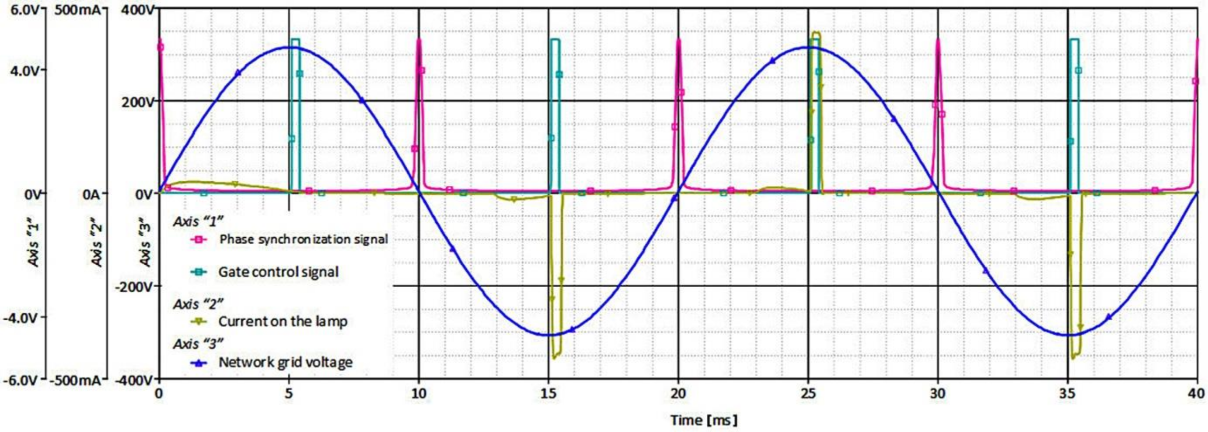


Fig. 4. Example of application: timing signal of the provided control system.

Finally, at system level, each control system installed nearby a lamp is able to communicate by means of a 2.4 GHz wireless communication system with a high-level control unit (Fig. 2) which embeds a microcontroller and a wireless transmitter and it can be considered as the local user interface. It allows setting the desired lighting target to provide in the considered environment, to set the proper calibration algorithm with respect to the lamps currently in use and to define more complex lighting monitoring system. The latter means that the sensing elements can be arranged also in different positions with respect to the lamps locations considering the more suitable monitoring conditions for the local environment. In this case, the control unit is in charge to determine the overall lighting and occupancy conditions and to define the operative instruction for each logic unit, accordingly. The sensing elements have an internal battery that, with a normal use, allows about 1 year operations; anyway, if they are installed together with the logic unit and close to each lamp, their DC power supply can be directly obtained from the logic unit that define the necessary DC bias voltage from the electrical grid, by using an AC/DC switched mode power supply (SMPS), useful for reducing the board dimensions.

It is important to notice that the dimming of the lamps has a minimal influence on the total power consumption of the lighting system. The control unit has a typical power consumption of 3 W and a single unit is needed for each scenario, while the complete lighting control device used nearby each lamp requires about 0.5 W when active in receiver mode and 1 W when active in transmission mode. Anyway, some of the on board sensors and circuits are in sleep mode when no significant events are detected and this allows to reduce the operation time and so the effective power consumption. In additions, as already said, also a lower number of sensing elements with respect to that of the logic units and lamps can be used, since sensors can be arranged also in different positions with respect to the lamps locations; this allows to further decrease the real power consumption of the proposed system. Anyway, in the worst case, that consists of using a complete lighting control system for each lamp, the total power consumption required by the electronic system is much more lower of that supplied to the lamps in a typical scenario.

In Fig. 5, photographs of the lighting control system are shown. It is evident from the implemented components that the current system dimensions can be reduced, for a commercial device, achieving a very low occupation area making it easily installable.

(a) (b) (c)

Fig. 5. Photograph of the lighting control system prototype. (a) Driver stage, actuator and control unit. (b) Standalone photosensor. (c) Standalone occupancy sensor.

3.1.2 Experimental analyses

Experimental analyses, carried out in the laboratory, have the purpose of:

- verifying feasibility and applicability of the proposed lighting control system for different lamp typologies, both dimmable and non-dimmable;
- proving that the proposed control system can dim also non-dimmable lamps from 100% to 10%, without typical inconveniences, like flicker.

For all the experimental tests, a box was employed, in order to measure the illuminance values provided by the lamps (Fig. 6). The lamp was fixed in the upper part of the box, while the illuminance measuring probe was placed at the bottom. Before carrying out the experimental tests, the illuminance zero value inside the box has been verified, in order to obtain measurements with artificial light only. Experimental tests were realized with voltage and frequency values equal to 220 V and 50 Hz, respectively. Moreover, all measured values were recorded after electrical stabilities were provided.

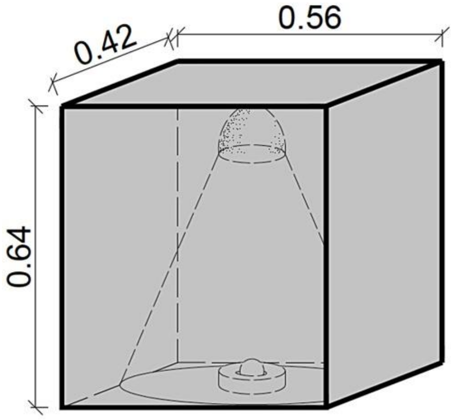


Fig. 6. Box for experimental tests. All the values are expressed in [m].

For the experimental phase, the proposed lighting control system has been applied to three different lamps: fluorescent, dimmable LED and non-dimmable LED (Table 1).

Table 1
Technical specification of fluorescent and LED lamps, for laboratory tests.

Physical quantity	Fluorescent lamp	Non-dimmable LED lamp	Dimmable LED lamp
Correlated color temperature[K]	4,300	2,700	2,700
Luminous flux [lm]	1,000	470	810
Power [W]	20.0	5.5	10.0
Luminous efficacy [lm/W]	53.3	85.5	81.0

For each lamp, different dimming levels were imposed, varying illuminance from 100% to 10%, considering step size of 10%. Illuminance values have been measured by a luxmeter, whose characteristics are reported in Table 2. For each dimming level, the required power consumption has been evaluated by measuring voltage and current levels by means of an oscilloscope.

Table 2
Metrological properties of the luxmeter.

	Measuring range [lx]	Accuracy
Luxmeter	0.1 – 200,000	± 3% ≤ 20,000 lx ± 5% > 20,000 lx

3.2 Case study

The analysis of a case study has the aim of evaluating the effects derived from the installation of the proposed lighting control system, analyzing how technologies and control strategies influence the energy and economic indicators. Furthermore, to better understand the economic feasibility of the proposed system, it has been compared to a commercial system, from the economical point of view.

Since education buildings represent a relevant research area for those who are involved in building design [37], a classroom of the structure which hosts the Faculty of Engineering of the University of L'Aquila (IT) was chosen. The

Faculty is made up by three wings (A, B and C of Fig. 7) and by a historical building, currently under reconstruction after the earthquake that hit the city of L'Aquila in 2009.

Structures of wing A and B have three floors, hosting classrooms, offices and laboratories. Wing C hosts the lecture hall and the library. The overall area accounts for 12,780.0 m^2.

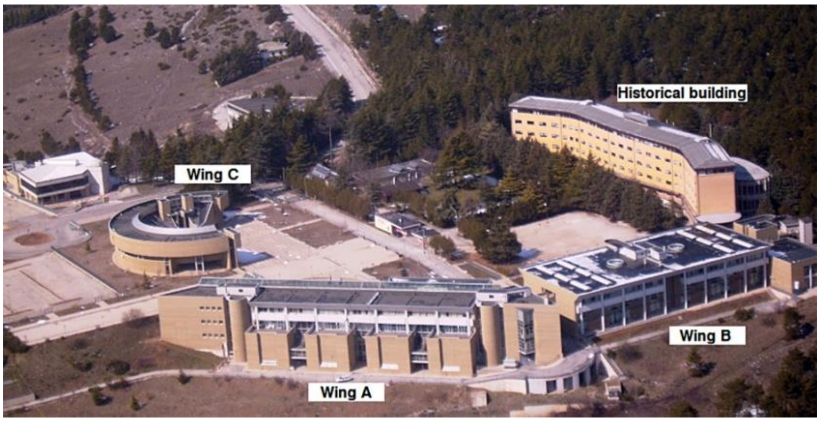


Fig. 7. Overall view of the Faculty of Engineering of University of L'Aquila.

3.2.1 Case study description

The case study analyzed is a classroom, called B 0.9, at the ground floor of wing B which is East-West oriented. Classroom geometry is regular: main dimensions are equal to 6.98 m x 8.45 m, the net area is 59.00 m^2 and the height is 3.70 m (Fig. 8). The classroom has a glazed west-facing wall, having three windows, whose dimensions are equal to 1.70 m x1.90 m and a French window with dimensions of 1.90 m x 2.90 m.

As a whole, the net transparent glazed area is 15.2 m^2. The west-wall surface (including window frames and transparent area) is equal to 25.8 m^2. Therefore, the window-to-wall ratio (WWR), given by the ratio between net glazed area and wall area, equals 0.59. The Window-to-Floor-Ratio (WFR), calculated as the ratio between the glazed area and the net area of the room, is 0.26.

Being the wing B quite detached (Fig. 7), the classroom does not have external obstructions, except for shading due to a horizontal overhang 1.10 m width that has been modeled. In the lecture room, there are 27 seats, arranged on three rows having 9 seats each.

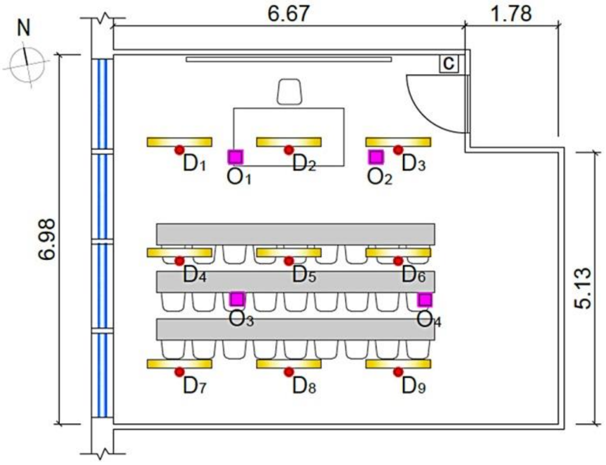


Fig. 8. Classroom and sensors layout: purple squares for occupancy sensors, red circles for daylight sensors, and control unit indicated with letter (C). All the values are expressed in [m].

In the classroom, there are 9 luminaires with fluorescent lamps (type OSRAM Lumilux Cool White) of 36 W each (yellow rectangles of Fig. 8), mounted on the ceiling, with an overall installed power of 324 W. Luminaires have a paraboloid optic with mirror-reflective surface with high reflection. Manually controllable internal vertical blinds allow the reduction of natural light in the room, but they are not considered in this study. According to standard EN 12464-1 [38], reference parameters for educational buildings are:

- average maintained illuminance: Em = 500 lx;
- uniformity on working plane: U ≥ 0.6;
- unified glare rating: UGR ≤ 19;
- color rendering index: CRI ≥ 80.

3.2.2 Model description and calibration

Possible energy saving estimation due to lighting control system is a complex matter, because of the high number of variables and their interplay [22]. For this reason, simulation tools are very useful instruments in daylighting design process [39]. Indeed, according to Reinhart and Fitz [37] about the 80% of works concerning daylight are carried out by using software.

The case study was modeled with the Relux software, developed by RELUX Informatik AG in Switzerland. This software is a tool for lighting simulation, easy to use; it provides reliable results, both for artificial lighting and for daylighting simulations. In fact, according to a study, which is part of IEA-SHC Task 31, by Maamari et al. [40], where the validation of two software in 32 scenarios is presented, Relux has showed better results than the analytical assessment. Shailesh and Raikar [41] presented an analysis of the interaction between natural and artificial light in a commercial office building in India, by means of computer simulations using Relux software, in order to demonstrate the potential of energy saving by adopting daylighting harvesting solutions. Yu et al. [42] discussed an application of Relux simulation to investigate energy saving potential from daylighting in a new educational building in UK. The last part of the work shows the comparison of the annual energy saving by various estimation methods, showing the reliable results gathered from Relux.

The model of the classroom investigated in this work was realized by accurately reproducing the real room layout with its furniture and blackboard. For this case study, we have considered the following sensors configuration: 9 lighting control devices, one for each lamp, 4 separated occupancy sensors to cover all the floor area, and one control unit (Fig. 9a). In the model, the following reflectances were set: ceiling with white plaster (71%), walls with white plaster (76%), floor with grey ceramic tiles (11%).

The measuring plane was positioned 0.75 m far from the floor, analogously to the real height of the desk, which is considered as workplane.

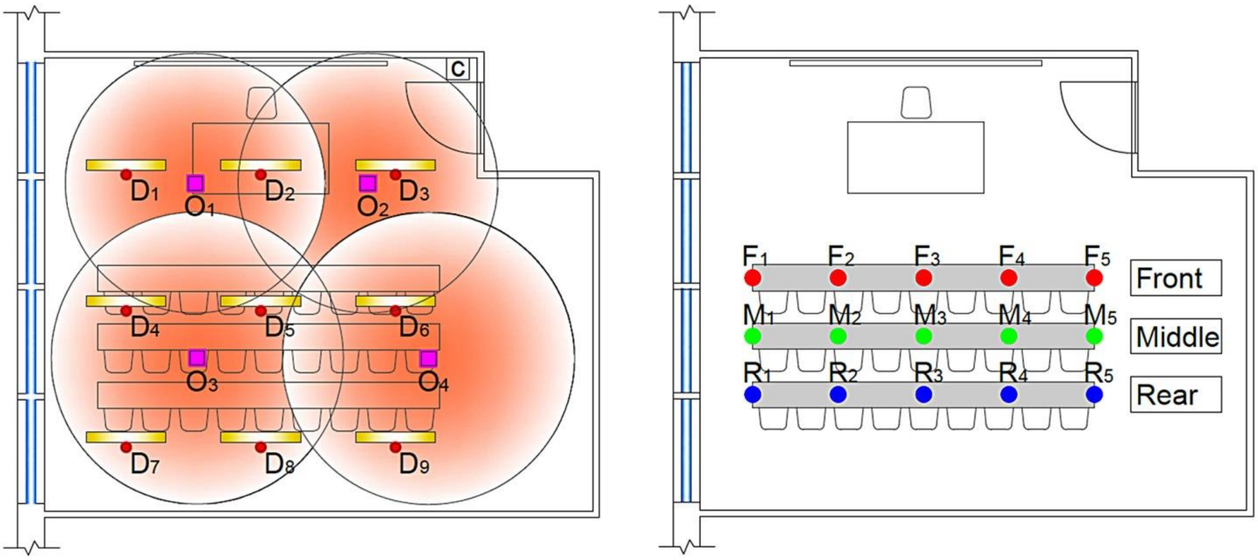
The Relux model of the classroom was calibrated both in daylight condition and in artificial lighting. Lighting results with natural light were compared to those measured in field. Measurements were carried out on June 9th, 2017, under clear sky conditions. The simulation was performed by considering CIE (International Commission on Illumination) Clear Sky Model conditions. Data of natural light were measured with a luxmeter, whose technical characteristics are reported in Table 2.

The virtual measuring plane was retrieved according to the real desk layout in the room. Therefore, 5 evenly spaced measuring points were selected for each of the three desk rows, as shown in Fig. 9b.

For each measuring point, 9 acquisitions were carried out, from 9.00 am to 5.00 pm, with a sampling rate of one hour, to evaluate how natural light irradiates in the room along time. The measuring probe was positioned on the desk, considered as workplane, which is 0.75 m high, at a minimum distance of 1.30 m from vertical walls, to gain the global horizontal illuminance. By comparing simulated and measured data, the model was deemed calibrated, as the deviation (Δ (%)) was within ± 20% (Eq. 1).

$$\Delta(\%) = \left(\frac{\mathrm{M} - \mathrm{S}}{\mathrm{M}}\right) * 100 \tag{1}$$

where (M) stands for the measured value, and (S) for the simulated one.



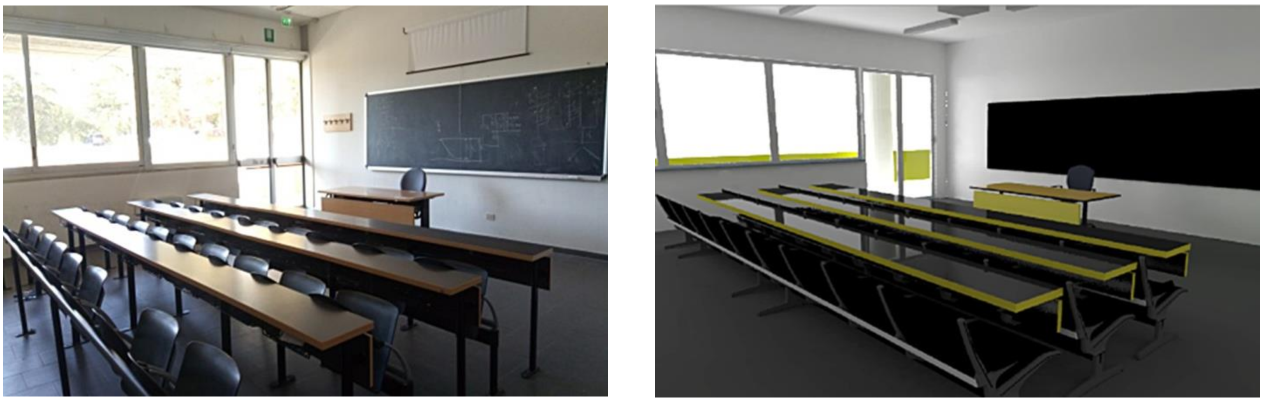
(a) (b)

Fig. 9. Room layout. (a) Positioning of: luminaries (yellow rectangle), occupancy sensors (purple square), photosensors (red circle) and control unit (letter C). (b) Data acquisition grid: *front*, *middle* and *rear* labels refer to the relative positioning of the desk rows to the professor desk.

After calibrating the model by considering only daylight, a further calibration was performed in solely artificial light. In this case, measurements were performed during nighttime, with roller blinds completely shut down, to avoid the possible interference of external artificial lights.

Equipment and measuring grid were the same adopted for the calibration in natural light. Before performing measurements with lamps switched on, it has been proved that the measured illuminance was null. For each measuring point, 7 acquisitions were carried out, and the average of measured values of each point was then considered.

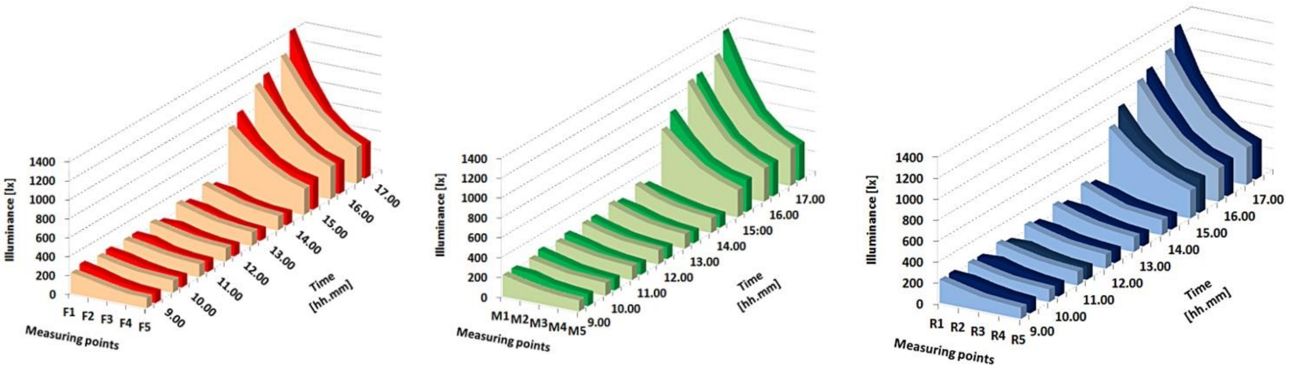
A picture of the room, and its 3D model under natural light, are proposed in Fig. 10. Under overcast sky conditions, the mean daylight factor of the classroom is equal to 2.64 %, and it is higher where the light enters.



(a) (b)

Fig. 10. Case study. (a) Picture. (b) 3D model render with lamps switched off.

Model calibration with natural light showed good results, for all measuring points and for all time steps. Fig. 11 shows the comparison between measured and simulated results, for each point and versus time, highlighting the natural light penetration in the room.



(a) (b) (c)

Fig. 11. Comparison between simulated (dark colors) and measured (light colors) illuminance values with natural light. (a) Front row. (b) Middle row. (c) Rear row.

Percentage deviation for each acquisition is reported in Table 3. Obtained results show that simulation results (S) are near to measured (M), with percentage deviation (Δ(%)) within the range ± 20%.

Table 3
Simulated and measured results, with their percentage deviation – natural light case.

		Point 1			Point 2			Point 3			Point 4			Point 5		
		M[a]	S[b]	Δ(%)	M	S	Δ(%)	M	S	Δ(%)	M	S	Δ(%)	M	S	Δ(%)
9.00	Front	221	256	-15.8	185	213	-15.1	144	156	-8.3	114	125	-9.6	112	113	**-0.9**
	Middle	218	229	-5.0	181	215	-18.8	138	163	-18.1	119	138	-16.0	110	122	-10.9
	Rear	223	230	-3.1	181	217	**-19.9**	137	164	-19.7	119	142	-19.3	107	127	-18.7
10.00	Front	230	243	-5.7	186	213	-14.5	151	162	-7.3	139	129	7.2	129	116	**10.1**
	Middle	226	260	-15.0	187	212	-13.4	150	163	-8.7	140	138	1.4	129	123	4.7
	Rear	228	224	1.8	184	219	-19.0	146	174	**-19.2**	132	144	-9.1	121	123	-1.7
11.00	Front	240	240	0.0	207	227	**-9.7**	168	161	4.2	147	131	10.9	136	119	12.5
	Middle	240	263	-9.6	203	221	-8.9	167	169	-1.2	150	137	8.7	138	120	13.0
	Rear	252	216	**14.3**	206	222	-7.8	167	172	-3.0	146	138	5.5	132	123	6.8
12.00	Front	258	213	17.4	214	217	-1.4	173	163	5.8	152	130	14.5	142	116	**18.3**
	Middle	266	270	**-1.5**	212	213	-0.5	170	163	4.1	154	139	9.7	142	124	12.7
	Rear	269	238	11.5	215	217	-0.9	170	167	1.8	150	143	4.7	136	127	6.6
13.00	Front	296	255	13.9	237	231	2.5	185	169	8.6	160	130	18.8	146	117	**19.9**
	Middle	304	276	9.2	239	238	0.4	187	177	5.3	160	141	11.9	146	122	16.4
	Rear	300	257	14.3	235	239	**-1.7**	186	183	1.6	160	145	9.4	141	126	10.6
14.00	Front	326	265	**18.7**	260	241	7.3	198	174	12.1	169	140	17.2	151	128	15.2
	Middle	337	287	14.8	249	237	4.8	196	189	3.6	168	150	10.7	149	129	13.4
	Rear	334	292	12.6	254	251	1.2	184	188	**-2.2**	162	156	3.7	143	133	7.0
15.00	Front	763	867	-13.6	586	607	-3.6	437	439	**-0.5**	337	351	-4.2	277	311	-12.3
	Middle	735	858	-16.7	567	624	-10.1	422	446	-5.7	334	360	-7.8	271	320	-18.1

	Rear	718	861	**-19.9**	547	613	-12.1	414	452	-9.2	328	363	-10.7	276	324	-17.4
	Front	1048	1103	-5.2	801	732	8.6	576	525	**8.9**	428	394	7.9	343	329	4.1
16.00	Middle	1060	1076	-1.5	776	768	1.0	544	524	3.7	417	397	4.8	332	334	-0.6
	Rear	1001	1056	**-5.5**	736	761	-3.4	524	515	1.7	400	392	2.0	316	333	-5.4
	Front	1193	1405	**-17.8**	895	943	-5.4	650	622	4.3	489	447	**8.6**	384	360	6.3
17.00	Middle	1159	1356	-17.0	844	937	-11.0	603	612	-1.5	473	444	6.1	372	359	3.5
	Rear	1126	1303	-15.7	821	870	-6.0	586	583	0.5	453	428	5.5	355	351	1.1

[a]M: measured values [lx]; [b]S: simulated values [lx].

N.B.: maximum and minimum percentage deviations (Δ(%)) of each time step are in bold.

In the case of solely artificial light, illuminance results from simulation agree with those gathered from multiple in field measurements. With respect to the natural light case, values are more uneven, mainly due to lamps' different installation time, that implies their different deteriorations [32]. In fact, to take into account the different performance decays due to different installation times, it has been necessary to tune the Maintenance Factor (MF) on the model. The obtained MF was 0.6. The comparison between measured and simulated results is proposed in Table 4 and plotted in Fig. 12.

Table 4
Simulated and measured results, with their percentage deviation – artificial light case.

	Point 1			Point 2			Point 3			Point 4			Point 5		
	M[a]	S[b]	Δ(%)	M	S	Δ(%)	M	S	Δ(%)	M	S	Δ(%)	M	S	Δ(%)
Front	187	207	10.8	204	225	10.3	208	210	**11.1**	197	210	6.7	165	166	0.8
Middle	299	264	**-11.6**	301	288	-4.4	294	268	0.5	288	268	-6.8	234	211	-9.8
Rear	247	265	7.4	271	285	5.2	276	265	5.9	259	265	2.4	213	207	-2.8

[a]M: measured values [lx]; [b]S: simulated values [lx].

N.B.: maximum and minimum percentage deviations (Δ(%)) of each time step are in bold.

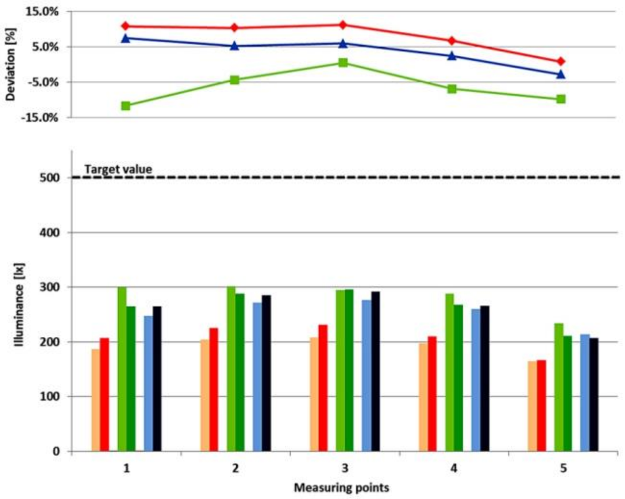


Fig. 12. Comparison between simulated (dark colors) and measured (light colors) illuminance values with artificial light. Red, green and blue refer respectively to front, middle and rear row.

Measured illuminance values, and consequently the values simulated through the calibrated model, are always lower than the minimum value required by standard EN 12464-1 [38] and equal to 500 lx (Fig. 13). These low values of illuminance are due to the reduced performance of the lamps installed in the academic classroom, caused by the natural deterioration of the lamps.

According to [16], illuminance level not fulfilling target value implies that measured and predicted energy savings cannot be compared. Therefore, before carrying out energy and economic analyses, on the calibrated model, it has been retrieved the lighting power necessary to obtain the target value (500 lx), employing the fluorescent lamp type described in Table 5. The increase of mean illuminance on workplane determines the increase of installed power from 324 W to 648 W.

(a) (b)

Fig. 13. Illuminance distribution for artificial lighting. (a) 2D contour plot. (b) Render with lamps switched on.

Table 5
Technical specification of fluorescent and LED lamps.

	Fluorescent lamp	Non-dimmable LED lamp	Dimmable LED lamp
Physical quantity	LUMILUX® Cool White	MASTER LEDtube Ultra Output	LR12840M – 18W
Lamp lenght [mm]	1,200.0	1,200.0	1,200.0
Correlated color temperature [K]	4,000	4,000	4,000
Color rendering index	> 80	> 83	> 83
Life time [h]	18,000	50,000	50,000
Luminous flux [lm]	3,350	2,500	2,700
Power [W]	36	18	18
Luminous efficacy [lm/W]	93.1	139.0	150.0

3.3 Lighting scenarios

The energy analysis was carried out to quantify consumption variations due to the application of the lighting control system proposed in this paper. Different scenarios were considered for the case study. The reference case refers to the actual lighting system installed, made up of fluorescent lamp without lighting control system. Case 1 concerns the substitution of fluorescent lamps with non-dimmable LED lamps, maintaining the same illuminance value on the workplane. Case 2 and 3 are related to the case 1 with the adding of, respectively, occupancy and daylight controls. The last one, case 4, evaluates the LED lighting system equipped with both occupancy and daylight controls. Lighting scenarios are summarized in Table 6.

In the model, all sensors of the lighting control system were placed in the ceiling (Fig. 9a), deeming this positioning the best adoptable [43].

Table 6
Lighting scenarios.

	Lamp type		Control system	
	Fluorescent lamps	LED lamps	Occupancy control	Daylight control
Reference Case	✓			
Case 1		✓		
Case 2		✓	✓	
Case 3		✓		✓
Case 4		✓	✓	✓

Characteristics of fluorescent lamps currently installed in the room and of LED lamps chosen for the energy retrofit are reported in Table 5.

3.4 Energy and economic analysis

The energy analysis was performed following european standard EN 15193 [44], applied through the ReluxEnergy module of Relux. Main evaluated parameters are annual energy consumption (W_L) in [kWh/y] (Eq. (2)) and LENI [kWh/m^{2}y] (Eq. (3)).

$$W_L = \frac{(\mathrm{P_N\,F_C})\left((\mathrm{t_D F_O F_D}) + (\mathrm{t_N F_O})\right)}{1000} \tag{2}$$

In Eq. (2), (P_N) is the installed electric power for artificial lighting [W], (F_C) is the constant illuminance factor, (t_D) is the annual operating hours during the daylight time [h/y], (F_O) is the occupancy dependency factor, (F_D) is daylight dependency factor, and (t_N) the annual operating hours during non-daylight time [h/y].

$$LENI = \frac{W_L}{A} \tag{3}$$

LENI is defined in Eq. (3) as the ratio between annual energy consumption and the total floor area (A).

Input values for ReluxEnergy module are reported in Table 7.

Table 7
Input values for ReluxEnergy setup.

Parameter	Setting
Location	L'Aquila (42°)
Building type	Academic building
Annual daylight time usage (t_D)	1,800 h/y
Annual non-daylight time usage (t_N)	200 h/y
Mantained illuminance	500 lx
Absence factor	0.25 (classroom)
Double glazed facade	Default values
Horizontal overhang angle	36.0° (French window) 47.7° (windows)

Based on energy consumption, for the considered scenarios, the evaluation of CO_2 emissions has been performed. The emission factor employed is equal to 0.46 $kgCO_2/kWh$ [45].

The economic assessment of all scenarios was carried out by considering the main economic indexes: PBP (payback period) and NPV (net present value). Both were evaluated considering base rate of 2% for 20 years (Eq. 4 and 5). Italian electricity price for domestic consumers, equal to 0.21 €/kWh was considered [46].

$$\sum_{t=1}^{PBP} \frac{F_t}{(1+k)^t} - F_0 = 0 \tag{4}$$

$$NPV = \sum_{t=0}^{n} \frac{F_t}{(1+k)^t} \tag{5}$$

where (F_t) is the cash flow at time (t) in [€], (k) is the base rate, (n) is time span [years], and (F_0) is investment cost [€].

The aim of the economic analyses is to prove that, thanks to the low cost of the proposed control system, to the possibility of installing it even on non-dimmable LED, and to the ease of installation, payback time achievable are lesser than analogous commercial systems. Table 8 summarizes technologies and control systems costs considered in the economic analysis. It is important to notice that the prices related to the proposed lighting control system refer only to the cost of electronic components that are necessary to develop the defined prototype system. For a complete budget analysis, also the fabrication costs may be taken into account. Anyway, they have not been reported since the production costs decrease with the increasing demand of products. Therefore, the marginal cost of production of each system is minimal, considering quantitative comparable to those of a commercial system, like that reported in Table 8.

In addition, the wiring costs for the commercial lighting control system and costs related to update of electric plant were not considered. This choice implies the underestimation of the total cost of common lighting control systems and, therefore, in this paper their NPV and PBP are much more favorable than reality even neglecting the fabrication cost of the proposed system.

Table 8
Technologies and control systems costs considered in the economic analysis.

Proposed lighting control system				
Description	Quantity	Units	Unit price [€]	Total price [€]
Non-dimmable LED Lamp (MASTER LEDtube Ultra Output)	18	pieces	36.98	665.64
Lighting control device without sensors	9	pieces	9.00	81.00
Control unit	1	pieces	20.00	20.00
Occupancy sensor	4	pieces	1.00	4.00
Light sensor	9	pieces	5.00	45.00
			TOTAL	815.64
Commercial lighting control system				
Description	Quantity	Units	Unit price [€]	Total price [€]
Dimmable LED Lamp (LR12840M – 18W)	18	pieces	56.28	1,013.04
Dimmer	9	pieces	31.98	287.82
Daylight and occupancy sensor (thePrema S360 DALI UP WH)	1	pieces	132.00	132.00
			TOTAL	1,432.86

4. Results

4.1 Lighting control system

Results of the experimental tests highlight that the proposed control system allows to dim different light sources, regardless of their dimmable characteristic. Dimming non dimmable lamps represents the novelty of the system that, moreover, has the capability of avoiding some typical inconveniences that might raise, such as flicker. Indeed, dimming different lamps with step of 10% of illuminance is always possible without flicker effects even when low illuminance levels are reached. Fig. 14 shows the different illuminance values (variable from 100% to 10 %), obtained with different dimming levels. The aim of the analyses is to show that, for each lamp considered for laboratory tests, illuminance can be changed linearly, without flicker problems. In this way, the proposed system demonstrates its universal applicability, allowing to hypothesize new scenarios for energy savings, especially in existing buildings, where no changes on luminaries and/or on electrical wiring are required.

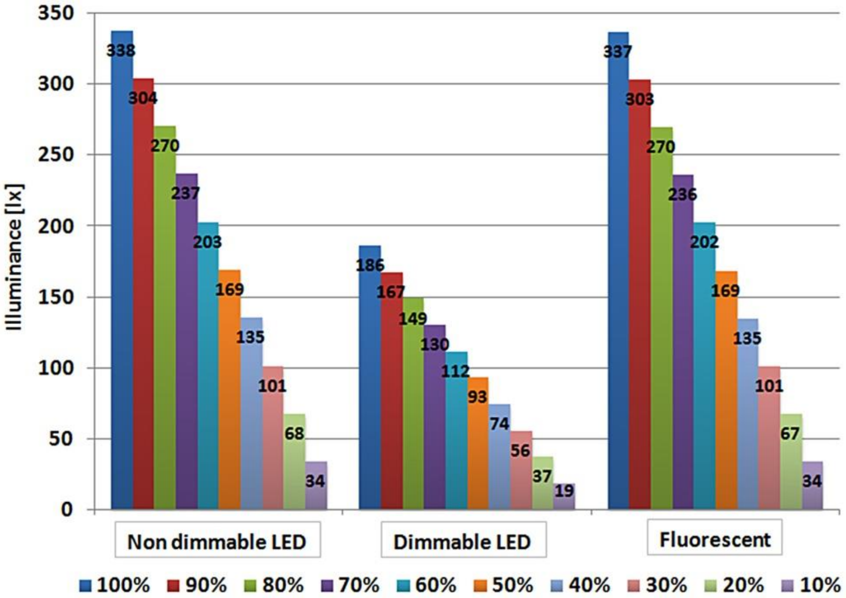
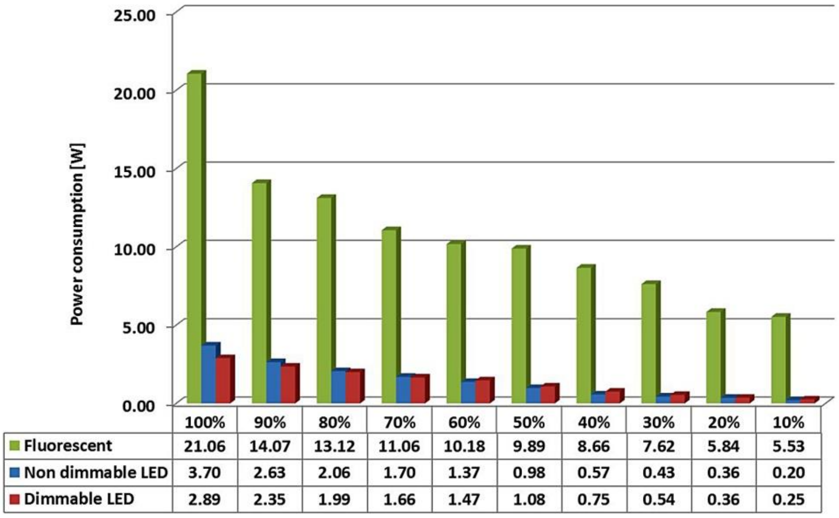


Fig. 14. Illuminance values with different dimming levels obtained through the use of the proposed lighting control system for the different considered lamps (see Table 1).

In terms of power consumption, Fig. 15 shows that the requirements in terms of absorbed power are dependent on the provided illuminance and similar behavior is obtained for both dimmable and non-dimmable LED lamps, as well as fluorescent lamp. Even if, in this last case, the power levels are higher, due to technology limitations.

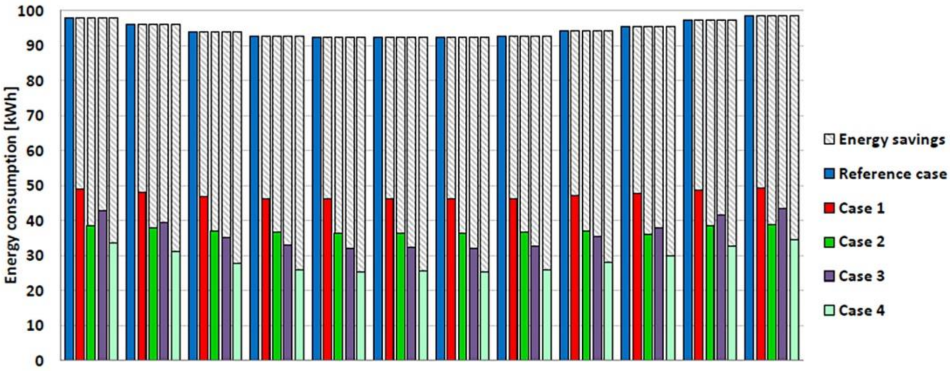


	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%
🟩 Fluorescent	21.06	14.07	13.12	11.06	10.18	9.89	8.66	7.62	5.84	5.53
🟦 Non dimmable LED	3.70	2.63	2.06	1.70	1.37	0.98	0.57	0.43	0.36	0.20
🟥 Dimmable LED	2.89	2.35	1.99	1.66	1.47	1.08	0.75	0.54	0.36	0.25

Fig. 15. Power consumption with different dimming levels.

4.3 Energy and economic assessments

Energy results of the case study, considering different scenarios, allow evaluating possible benefits obtainable with the installation of different efficient technologies and the proposed control system. Monthly consumption and energy savings obtainable with all the considered cases are plotted in Fig. 16.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Energy savings with respect to reference case [%]											
Case 1	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0	50.0
Case 2	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5	60.5
Case 3	56.4	59.1	62.5	64.4	65.2	65.0	65.3	64.6	62.2	60.2	57.4	55.7
Case 4	65.5	67.7	70.4	71.9	72.5	72.4	72.6	72.1	70.2	68.6	66.3	65.0

Fig. 16. Monthly energy consumption for all the considered cases.

Table 9 shows a summary of energy results for the scenarios. Energy savings from the installation of occupancy control (60.5%) and daylight control (61.4%) are quite near. The highest energy saving (69.5%) can be achieved by combining both occupancy and daylight adaptation.

Table 9
Energy results of different scenarios.

	Scenario				Energy results (according to EN 15193)		
	Fluo. lamps	Non-dimmable LED Lamps	Occupancy control	Daylight control	Energy consumption[a] (W_L) [kWh/y]	LENI[b] [kWh/m^{2}y]	Energy savings [%]
Reference Case	✓				1,137.0	19.3	N.A.
Case 1		✓			569.0	9.6	50.0
Case 2		✓	✓		449.0	7.6	60.5
Case 3		✓		✓	439.0	7.4	61.4
Case 4		✓	✓	✓	346.0	5.9	69.6

[a] Calculated by Eq. (2), with (t_D) equal to 1,800 h/y and (t_N) equal to 200 h/y [44].
[b] Calculated by Eq. (3).

Variations in terms of installed power, energy consumption, and CO_2 emissions are shown in (Fig. 17). Colored circles indicate energy consumption (Y-axis) for the scenarios and their sizes are scaled to installed power (in [W]), whose value is reported in the label. For each case, related CO_2 emissions are displayed with orange circles and the amount (in [kgCO_2/year]) is written in them.

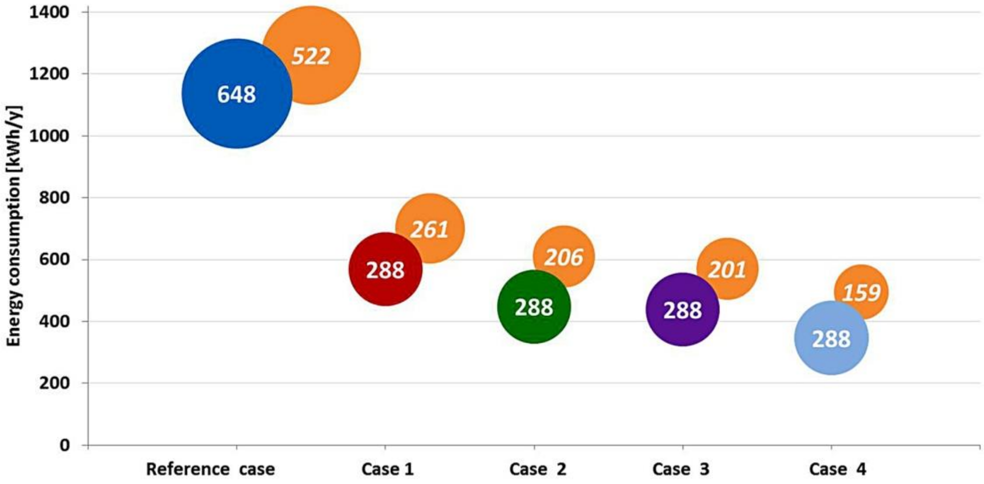


Fig. 17. Energy consumption, power installed and CO_2 emissions of the scenarios.

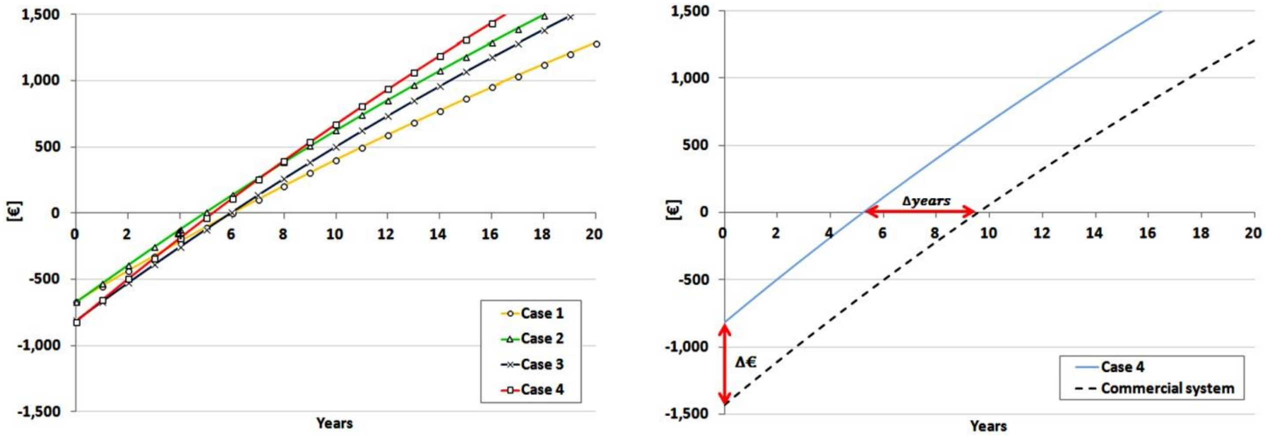
It is worth noting that all the cases considered for the retrofit have the same installed power, equal to 288 W, but energy consumption varies as well as CO_2 emissions. Particularly, the best case, in terms of energy and environmental aspects, is obtained by considering both occupancy and daylight sensors, since the energy consumption and CO_2 emissions are the lowest. Results from the separate installation of occupancy and daylight sensors (cases 2 and 3) are near, showing that the two systems provide similar benefits.

Economical analysis has been carried out by considering the Italian electricity price for domestic consumers [46]. From the economic point of view, all scenarios have positive NPVs and PBPs ranging between 4 and 5 years, proving the investments convenience. To appreciate the convenience of the proposed lighting control system, a further comparison with a commercial control system was carried out (Table 10).

Table 10
Economic results.

	Scenario				Economic results	
	Non-dimmable LED Lamps	Dimmable LED Lamps	Occupancy control	Daylight control	PBP [years]	NPV [€]
Case 1	✓				5	1,260
Case 2	✓		✓		4	1,660
Case 3	✓			✓	5	1,554
Case 4	✓		✓	✓	5	1,862
Commercial control system		✓	✓	✓	9	1,256

Cash flows and PBPs are shown in Fig. 18.



(a) (b)

Fig. 18. Cash flow and PBP. (a) Comparison between the different control strategies, realized through the proposed system. (b) Comparison between proposed (solid line) and commercial systems (dashed line).

It is worth noting that the best PBP is given by the installation of the proposed control system, considering only the occupancy sensors, thanks to their low cost. Anyway, it is possible to observe that the proposed control system, equipped with both occupancy and daylight sensors, nearly halves the PBP with respect to the commercial system (Table 10), reducing the payback time from 9 to 5 years. The reason of this difference is mainly due to the possibility of installing the proposed system with non-dimmable LED lamps. Moreover, the wireless communication protocol allows an easier deployment of sensors that allow providing better economic results, minimizing wiring and plant adaptation. To better understand economic benefits obtainable with the proposed control system, a further evaluation is proposed. By considering the average value of electricity price in Europe, equal to 0,18 €/kWh [46], the economic results are once again positive, even if slightly worse than the case with italian electricity price. Indeed, by using the european electricity price, the proposed system allows a PBP reduction with respect to a commercial control system, from 11 to 6 years, and a NPV increase, from 876.0 € to 1,481.0 €.

5. Conclusions

Lighting control systems with daylight and occupancy adaptation allow relevant reduction of energy consumption, but they are often affected by installation complexity, high costs, difficulties on the evaluation of real energy benefits, technical management problems, and, above all, proper matching of the dimming system for the used lamps. For these reasons, diffusion of these systems is lower than expectations.

This paper presents a new lighting control system, especially conceived for installation on existing buildings. This system is based on smart control unit and lighting control devices that can be directly mounted on the lamps in series connection. The installation of the system is noninvasive and does not require any changes in the electrical grid, since the communication between each lamp and the control system is based on long range wireless communication at 2.4 GHz. The system architecture has been proved in laboratory. The main and novel results obtained are its functionality with any lamps (fluorescent, non-dimmable LED, and dimmable LED), and its applicability to real cases.

At the end of the experimental laboratory tests, being not possible to install the proposed system in public environment, since it is at prototypical stage, the feasibility of the system has been verified at simulation level. The case study is a classroom of the Faculty of Engineering of the University of L'Aquila, in central Italy. The simulated model was calibrated both with natural and artificial light, showing deviation values within ± 20%. This phase allowed carrying out energy analysis of the performances of the lighting plant, considering different technologies and control strategies: fluorescent, dimmable and non-dimmable LED lamps, and with occupancy and daylighting adaptation, provided by the proposed system. The economic analysis, deepened by comparing the proposed system with a commercial lighting control system, clearly shows that the proposed system is affordable, reducing the payback time of the investment.

The main results obtained are:

- a new universal daylight and occupancy control system for any lamps. Laboratory tests on the system showed positive results;
- the application of the proposed system, simulated through the use of a validated model in a academic classroom, allows energy saving equal to 69.6 % and 30.5 % of CO_2 emissions avoided;
- improvement of the PayBack Period from 9 to 5 years, by comparing the investment costs of the proposed system with respect to a commercial lighting control system.

According to these encouraging results, future development of the proposed system will involve the application in real scenarios, once obtained the product qualification.

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