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Low-cost smart solutions for daylight and electric lighting integration in historical buildings

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Abstract. Research have shown that the correct integration of daylight and electric lighting reduces the energy use in buildings, while improving visual comfort. Smart shading systems, especially those electrically controlled, play an important role to control solar radiation. Similarly, smart and dimmable/tunable lighting can help to adjust the artificial light to the real users' needs. This paper presents preliminary results of an ongoing living lab study investigating how artificial lighting systems can be integrated with shading systems, placing human comfort at the heart of the study and yet saving energy. A manually controlled, commercial and low-cost smart system integrating two motorized shading devices and six dimmable LED luminaires with a different selection of CCT were installed in a private office in a historical building. Indoor and outdoor lighting conditions and energy consumption associated to the lighting system are constantly monitored to assess how the people use shading and lighting upon varying the boundary conditions.. Preliminary results highlight that users prefer to maximise daylight on the work plane as well as they generally use both shading and electric lighting systems in response to boundary conditions that cause serious discomfort.

1. Introduction

A proper combination of daylighting and electric lighting strategies can help to increase the energy efficiency of buildings and the users' satisfaction [1]. Over the years, much research has underlined the close relationship among daylight availability, users' satisfaction and energy saving [1,2].

Over the years, different energy and lighting retrofit measures have been proposed and applied to existing buildings [3–6], but only a few covered the case of historical listed buildings [7,8]. In Italy, about 2.1 million of the buildings realized before 1919 have been occupied [9], and many of these host offices and have been listed as having a historical-artistic value. A correct retrofit measure in historical buildings should account for two issues: the choice of the appropriate integrated system and the proper control methods of shading and electric lighting systems.

In regards to the first issue, the Italian legislation [10,11] must be considered. Such legislative framework excludes historical and architectural heritage from energy retrofitting to safeguard their integrity. This means that not all retrofit measures are eligible for historical buildings. In particular, it is very difficult, sometimes impossible, to: modify the size or position of the windows, select strategies or systems requiring substantial masonry, or use external shading systems on the façade. Systems with few and small components should be preferred.

Concerning the control methods, different solutions are currently available and generally divided into manual control or automated control. In the first one, the user can directly control the integrated system, intended as daylighting (e.g. shading device) and electric lighting (e.g. general lighting). The energy use is inherently unpredictable, but users tend to be quite efficient and some small degree of automation may account for human flaws, e.g. with an absence sensor switching off electric lighting when the user forgets. In the automated control methods, a controller adjusts the shadings and the electric lighting as a function of a physical quantity chosen as the control parameter, according to a set control logic. The control logic depends on the buildings and room characteristics, the shading and lighting systems properties, the control parameter, the occupants' behaviour as well as the activities [12,13]. If, on the one hand, automatic control systems can help in minimizing the lighting use, cooling loads and guaranteeing a defined setpoint of the control parameter, on the other, systems for automated control strategies are expensive, prone to malfunctioning, in some case sabotage, and they can bring to a reduction in workers'satisfaction, motivation and vigilance [14,15].

Considering the above, wirelessly controlled smart lighting systems and motorized indoor shading systems can represent a solution for the refurbishment of listed buildings. Moreover, providing these systems with manual controls can support users' needs. In this context, it is useful to investigate how the user interacts with such systems, thus suggesting strategies to accommodate energy efficient behaviours. With this aim in mind, a commercial low-cost smart system, integrating two motorized shading devices and six dimmable LED luminaires with a different selection of Correlated Colour Temperatures (CCT), was installed in a private office in the Department of Architecture and Industrial Design of the University of Campania (Italy). Indoor and outdoor lighting conditions, as well as energy use associated to the lighting system are constantly monitored to assess how people use the shading and lighting systems.

The general aims of the research are to:

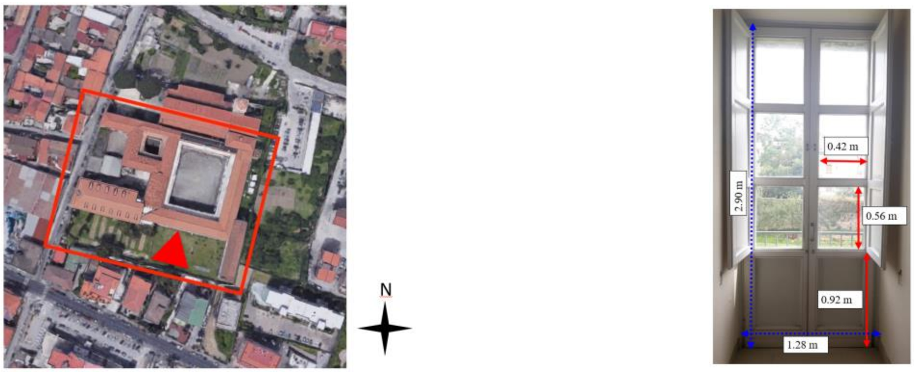
- quantify the energy use of both the lighting and shading system;
- investigate habits and readiness to use smart technologies for daylight and electric lighting control;
- evaluate the effectiveness of manually controllable low-cost solutions for daylighting and lighting integration applicable to historical buildings.
- The results here reported includes the characterization of the living lab and preliminary considerations following the tests with two users.

2. Living lab and measurements set up

In this study, users' behaviour and the energy use for electric lighting were evaluated in a real-world office (living lab) while performing ordinary working activities.

The office is a private office located on the first floor of the Abbey San Lorenzo "ad Septimum". The Abbey is located in Aversa (southern Italy, latitude 40°59' - longitude 14°11') and it was built at the end of the tenth century [16]. Nowadays, it hosts the Departement of Architecture and Industrial Design of the University of Campania. The office has a floor area equal to about 26 m^2 and a height of 5.45 m, while the walls (external and internal walls) have a thickness of about 1.00 m. The only window of the office is placed on the external wall outer side with an orientation of 15° South-South West. The window has a total surface of about 3.70 m^2, a ratio glass area/total window area equal to 0.38 [7,17]. **Figure 1**a shows the top view of the Abbey and the position of the living lab, while **Figure 1**b displays the internal perspective, the layout and the dimensions of the existing window.

For this research, commercially available low-cost manually controlled shading and lighting systems were installed in the living lab. The shading system consists of two motorised roller blinds manufactured by IKEA, with different visual transmission values. The first roller blind [18] can be used to limit the sunlight penetration inside the office (shading roller blind); instead, the second roller blind [19] can be used to block the sunlight penetration (blackout roller blind). Each roller blinds is equipped with a battery (no connections to the electric grid are required) and is pre-paired with wireless remote control. The lighting system consists of six smart led-based luminaires [20]; each luminaire has a nominal electric power of 29 W and luminous flux equal to 2200 lumen. The luminaires are provided with seven-steps dimming and three-steps tunable Correlated Colour Temperature (CCT) (2200 K – 2700 K – 4000 K). Both dimming and CCT tuning are controlled with remote control. For each CCT value, the user can choose any of the seven luminous flux levels for a total of twenty-one different electric lighting scenarios. The availability of wireless remote controls allows users to manage the roller blinds position and the electric light scenario directly from the office desk. **Figure 2**a displays the internal view of the living lab, the shading systems, the lighting system and the position occupied by the user.



a) b)

Figure 1. (a) Abbey's top view with the position and (b) the internal view and dimensions of the existing window.

During the monitoring period, physical quantities were acquired to identify the external weather conditions, the user's habits and interaction with the system.

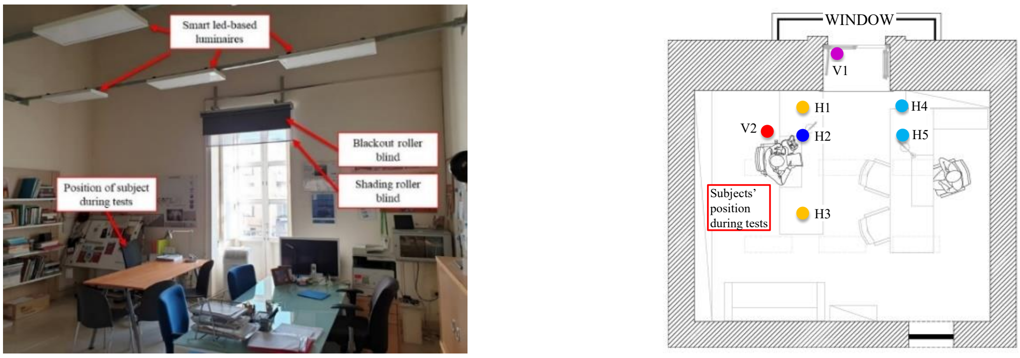
The weather conditions were evaluated by measuring: external horizontal global illuminance, external air temperature, and external vertical global illuminance on the window's external side.

The user's habits and interaction with the system were evaluated by measuring: occupancy, the roller blinds closing degree, the lighting setting for the electric lighting system (dimming level and CCT). These data were used in conjunction with the indoor illuminance distribution. The indoor illuminance distribution was measured using seven miniature lux-meters. **Figure 2**b shows the layout of the living lab with the relative position of the sensors and the subject during the tests. Although two working stations are provided, during the tests, the office is used by one person only. Five lux-meters were placed in a horizontal position at the work plane level, 0.73 m from the floor (sensors from H1 to H5 in **Figure 2**b), one lux-meter was placed in a vertical position just behind the glazing (sensor V2 in **Figure 2**b) and one lux-meter was placed in a vertical position at 1.22 m from the floor to simulate the eye of a user seated at the desk (sensor V3 in **Figure 2**b). Both the miniature lux-meters and the thermocouple were connected to a Fluke data logger [21].

Both roller blinds' positions were evaluated by measuring the distance between the bottom of each roller blind and the floor; the distances were measured using ultrasonic sensors installed on each roller blind.

The dimming level of the electric lighting system was evaluated by measuring the power required by the whole lighting system through the Fluke data logger [21], while the CCT was evaluated using an RGB sensor placed close to one of the luminaires. Both the ultrasonic sensors and the RGB sensor were connected to an Arduino Uno [22] acquisition system.

During the monitoring period, all quantities were logged at one minute time steps and then averaged every 10 minutes. **Table 1** lists the main characteristics of the sensors used during the monitoring period.



a) b)

Figure 2. (a) Internal view of the office and (b) office layout with the position of indoor sensors.

Table 1. Technical specifications of sensors for outdoor and indoor measurements.

Physical quantity	Manufacturer	Type	Range	Accuracy
External air temperature	Delta Ohm	Thermo-hygrometer	Temperature: -40 ÷ +60 °C	Temperature: ± 0.2 °C
External horizontal global illuminance	Delta Ohm	Lux-meter with silicon photodiode	0 ÷ 150000 lux	< 4%
External vertical global illuminance	Delta Ohm	Lux-meter with silicon photodiode	20 ÷ 200000 lux	λ curve, cosine corrected
Miniature lux-meters	PRC Krochmann	Lux-meter with silicon photodiode	0 ÷ 150000 lux	± 0.5%
Indoor air temperature	RS PRO	T-type thermocouple	- 75 ÷ 260 °C	± 0.5°C
Distance	-	Ultrasonic sensor HC-SR04	20 ÷ 4000 mm	3 mm
RGB	Sparkfun	ISL29125 RGB Light Sensor	0 ÷ 65535	-

3. Methodology

Preliminary measurements were carried out to: i) verify the functionality and the correct position of sensors, ii) characterise the living lab from the geometrical and photometrical points of view, and iii) define a baseline with which compare data acquired during the subjective tests.

The furniture size and relative positions were measured and modelled for future use. The reflectance values of the internal surface were acquired through the spectrophotometer Minolta CM – 2600d (spectral reflectance standard deviation within 0.1%). The reflectance value and colour of each surface were obtained as the mean of values acquired on three measurement points, using the standard illuminance D65. These data are listed in **Table 2**. The electric power required and the illuminance values provided by the six luminaires for each of the twenty-one combinations of dimming and CCT was measured. The electric power required by the standby mode was also monitored. **Figure 3**a displays the required electric power, while **Figure 3**b shows the illuminance values on the task area.

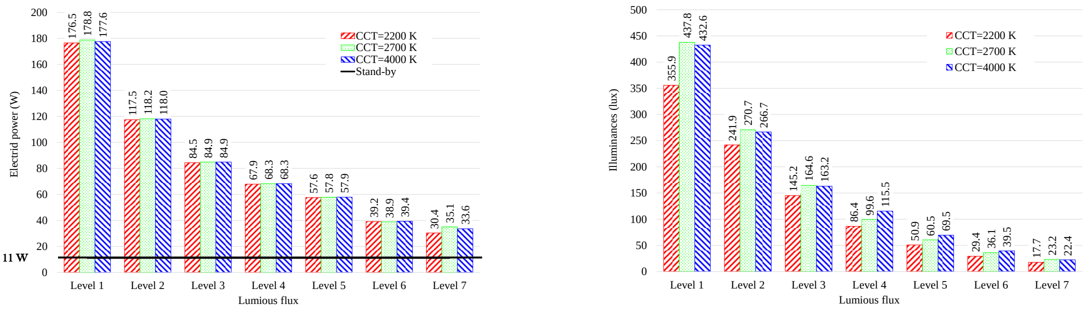
Finally, measurements of the daylight illuminance distribution inside the living lab with the shading roller blind completely closed were carried out to evaluate the actual ability of the shading roller blind to limit the sunlight penetration and prevent glare effects.

Figure 4 shows the daylight illuminance values acquired in two days during the winter period by the sensor placed just behind the glazing (sensor V1, see layout in **Figure 2**b), on the work plane in the task area (sensor H2, see layout in **Figure 2**b) and at eye level (sensor V2, see layout in **Figure 2**b).

Table 2. Reflectance and colour values of the main surfaces inside the office.

	Reflectance (%)	L*	a*	b*
Desk	28	59.84	15.48	27.08
Floor	53	78.12	2.12	12.58
Closet door	47	74.11	8.65	25.61
Closet	49	75.46	-1.22	-0.61
Walls	88	94.97	0.84	9.85
Door	85	93.92	0.07	3.32
Window	85	94.30	-0.21	3.05

The figure highlights how the shading roller blind can limit the sunlight penetration, but cannot prevent the occurrence of glare conditions. Also, considering the user's location during the monitoring period, the measurements point out the early afternoon as the most critical hours for the users from the visual point of view.



a) **b)**

Figure 3. Characterisation of the whole lighting system: (a) electric power required and (b) illuminance values on the task area (sensor H2).

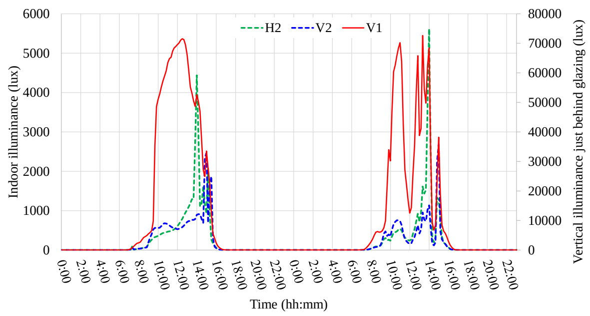


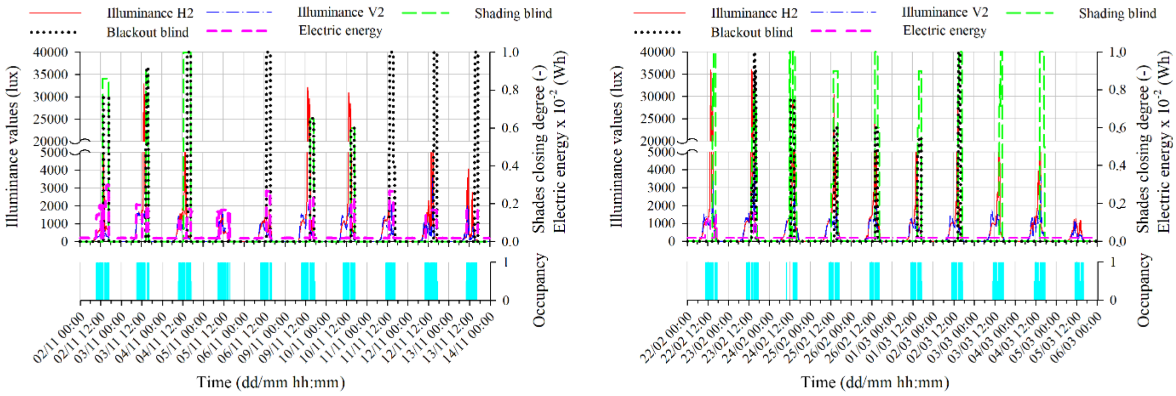
Figure 4. Indoor daylight illuminance distribution with shading roller blind completely closed with clear sky (27/11/2020) for the left and intermediate sky conditions (28/11/2020) for the right chart.

Following this characterisation, the living lab was intended to be used for subjective evaluations. The subject performed her/his ordinary office tasks, mainly focused on PC typing and reading. Physical measurements and user interaction with the shading and lighting systems were logged. During the two weeks, the tested subject can adjust the position of the two motorised roller blinds and the six smart luminaires through wireless devices according to their needs, directly sitting at the desk. To avoid that the smart system configuration could affect the user behaviour, at the end of each day of the test, the integrated system was brought back to its reference set-up. The reference set-up consisted of both roller blinds completely open and luminaires at 4000 K and the lowest dimming level.

4. Results and discussion

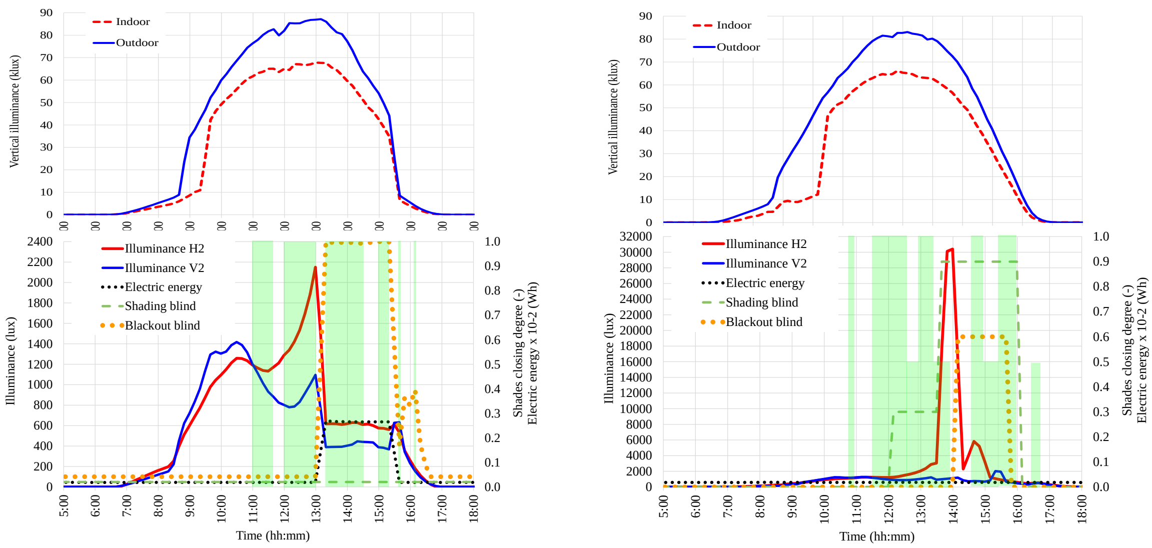
The results include some relevant measurements and few considerations about the behavior of the test subject. Because of the limitations in the data sample, no further statistical analysis on the behavior was added. **Figure 5**a shows the measured data for the whole 2-week period for the subject ID1, while **Figure**

5b displays the same information related to the subject ID2. **Figure 6c** and **Figure 6**d report the comparison between the outdoor vertical illuminance on the external surface of the window, the indoor vertical illuminance just behind the glazing, the illuminance on the task area (sensor H2), the vertical illuminance at eye level (sensor V2), the electric energy consumed by luminaires as well as the closing degree of both shading and blackout roller blind, for the subject ID1 and ID2, respectively; the light green regions indicate the occupancy of the office.



a) b)

Figure 5. Measurements of the full 2-week period (a) ID1 and (b) ID2.



a) b)

Figure 6. Indoor and outdoor physical quantities acquired during the subjects' monitoring periods (a) ID1 and (b) ID2.

The preliminary results (Figures 5a-b and Figures 6a-b) allow for some observations about user preferences and how the environmental conditions affect her/his behaviour. In particular:

- when the illuminance values on the task area (sensor H2) are lower than 2000 lux, neither the blackout roller blind nor the shading roller blind were used;
- considering the position of the subjects in the room and the illuminace values recorded by the sensor at eye position (V2), potential glare phenomena may occur in the early afternoon, so both subjects used the roller blinds when this sensor measured more than 3000 lux;
- the shading roller blind, but not the blackout one, was used to control the sunlight penetrating in the room;

- in cases for which the blackout roller blind was completely closed, the users preferred to switch on the electric light system even for computer-based tasks (as shown in **Figure 6**a);
- however, the user generally preferred to allow as much daylight as possible, even when the work plane is hit by direct sun radiation (as shown in **Figure 6**b);
- the user had few interactions with the smart systems and, generally, these occurred in response to strong discomfort. Looking at recorded data, they can possibly be discomfort glare, veiling reflections, or low daylight availability;
- if used, the electric lighting system is turned on for few hours per day. In these cases, the standby mode energy use becomes a not neglectable contribution to energy use for lighting.

Furthermore, the figures underline that the blackout roller blind closing degree strongly influences the electric lighting system use also with clear sky conditions. When the blackout blind is completely closed, the user considers the daylight amount in the room as not enough and then turns on the electric light. Nevertheless, with better adjustment of the blackout blind position, the user may avoid glare – if occurring - and rely on daylighting only. Finally, changes in dimming and CCT were limited, and no major conclusions could be drawn.

Despite the limited amount of data, the results are in line with literature on the topic. For example, it is well known that most of lighting and shading adjustments occur at departure or arrival, just as it is known that occupants tend to prefer daylighting over electric lighting. It is also generally understood that electric lighting is limitedly used when good daylighting design is provided, which makes the energy use for standby not of secondary importance.

While longer tests with more subjects would allow for a better understanding of general behavioural patterns, it seems that improving user behaviour might offer chances to save energy for lighting. For example, how can one avoid that user keeps the blackout blind down and switch on the electric lighting? Therefore, future longer term tests are planned to evaluate behavioural interventions, e.g. by using prompts or information strategies, in order to improve the energy efficient behaviour of the users.

5. Conclusions

A commercial low-cost smart system, integrating two motorized roller blinds (one shading and one blackout) and six dimmable and tunable LED luminaires, was installed in a private office located in a historical building. The integrated systems were controlled manually through wireless devices by the user, according to their preferences upon varying boundary conditions. This article provided a characterization of the living lab and showed some preliminary results from a short pilot test. The pilot test served to create a baseline for user behavior in relation the lighting and shading systems. The results are substantially in line with existing literature and they show: a general preference towards daylighting, a limited use of electric lighting, a limited interaction with the systems during the working hours, and some occurrences of energy wasteful behavior. Future work will examine whether users' training or alternative behavioural intervention might guarantee quasi-optimal use patterns of shading devices and artificial lighting, possibly comparable to those of automatic systems.

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References

[1] Xiong J, Tzempelikos A, Bilionis I and Karava P A personalized daylighting control approach

to dynamically optimize visual satisfaction and lighting energy use *Energy Build* 2019 193 111-26.
[2] Gentile N, Laike T and Dubois MC Lighting control systems in individual offices rooms at high latitude: Measurements of electricity savings and occupants' satisfaction *Sol Energy* 2016 127 113-23.
[3] Casquero-Modrego N and Goñi-Modrego M Energy retrofit of an existing affordable building envelope in Spain, case study *Sustain Cities Soc* 2019 44 395–405.
[4] Xin L, Chenchen W, Chuanzhi L, Guohui F, Zekai Y and Zonghan L Effect of the energy-saving retrofit on the existing residential buildings in the typical city in northern China *Energy Build* 2018 177 154–72.
[5] Gentile N, Dubois M-C, Osterhaus W, Stoffer S, Amorim CND, Geisler-Moroder D, et al A toolbox to evaluate non-residential lighting and daylighting retrofit in practice *Energy Build* 2016 123 151–61.
[6] Ma Z, Cooper P, Daly D and Ledo L. Existing building retrofits: Methodology and state-of-the-art *Energy Build* 2012 55 889–902.
[7] Scorpio M, Ciampi G, Rosato A, Maffei L, Masullo M, Almeida M, et al Electric-driven windows for historical buildings retrofit: Energy and visual sensitivity analysis for different control logics *J Build Eng* 2020 101398.
[8] Galatioto A, Ciulla G and Ricciu R An overview of energy retrofit actions feasibility on Italian historical buildings *Energy* 2017 137 991–1000.
[9] https://www.istat.it/it/files/2014/06/09_Paesaggio-patrimonio-culturale-Bes2014.pdf
[10] Italian Government. Legislative Decree n. 192 2005.
[11] Italian Government. Legislative Decree n. 311 2006.
[12] Haq MAU, Hassan MY, Abdullah H, Rahman HA, Abdullah MP, Hussin F, et al A review on lighting control technologies in commercial buildings, their performance and affecting factors *Renew Sustain Energy Rev* 2014 33 268–79.
[13] Konstantoglou M and Tsangrassoulis A Dynamic operation of daylighting and shading systems: A literature review *Renew Sustain Energy Rev* 2016 60 268–83.
[14] Boyce PR, Veitch JA, Newsham GR, Jones CC, Heerwagen J, Myer M, et al Lighting quality and office work: Two field simulation experiments *Light Res Technol* 2006 38(3) 191–223.
[15] Galasiu AD and Veitch JA Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review *Energy Build* 2006 38(7) 728–42.
[16] Faenza LM, Jacazzi D and Argenziano P Il sito di San Lorenzo ad Septimum sulla Via Campana: Permanenze sincroniche e modificazioni diacroniche. In: AA.VV Proceedings of the 6th International Forum Capri (Italy) 5-7 June 2008 Capri (Italy): Edizioni Scientifiche Italiane s.p.a. 2009 p. 211–52.
[17] Ciampi G, Rosato A, Scorpio M and Sibilio S. Daylighting contribution for energy saving in a historical building *Energy Procedia* 2015 78 1257–62.
[18] KADRILJ Shading roller blind, wireless, battery operated gray - IKEA [cited 2021 Feb 9] Available from: https://www.ikea.com/gb/en/p/kadrilj-roller-blind-wireless-battery-operated-grey-10408150/
[19] FYRTUR Blackout roller blind, wireless, battery operated gray, - IKEA [cited 2021 Feb 9] Available from: https://www.ikea.com/gb/en/p/fyrtur-block-out-roller-blind-wireless-battery-operated-grey-70408190/
[20] FLOALT LED light panel, 12x35" - IKEA [cited 2021 Feb 9] Available from: https://www.ikea.com/us/en/p/floalt-led-light-panel-dimmable-white-spectrum-40303076/
[21] Fluke 2638A Hydra Series III Data Acquisition System/Digital Multimeter, Fluke [cited 2021 Feb 8] Available from: https://www.fluke.com/en-ca/product/precision-measurement/data-acquisition/fluke-2638a
[22] Arduino - Home [cited 2021 Feb 8] Available from: https://www.arduino.cc/