Development of a first prototype for low-cost kit for DLCs design

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***Abstract*—This paper aims to present the development of a first prototype of a kit to improve the performance of the daylight control system during design, operating and post-commission steps: HW/SW components, procedures, and tools for the management of the control systems. In particular, these systems aim to support professionals in correctly designing, installing, commissioning, and post-monitoring lighting control systems using artificial intelligence techniques. Moreover, the design and development of the data acquisition system using an Arduino Uno WiFi with TSL2591 and its programming environment, with its variant of the C++ programming language, was utilized to acquire data from the sensors. The acquired data, were processed and transmitted to an online MySQL database. Furthermore, this paper presents the study that was conducted in order to develop the "box" of the prototype. Finally, the first measurement campaign is reported.**

Keywords—DLCS, Building Automation Control Systems, lighting design

I. INTRODUCTION

The utilization of Building Automation and Control systems (BACs) offers numerous benefits. Among these is the reduction of end-user electricity consumption and the realization of significant advantages from natural daylight, such as enhanced productivity, improved health, better visual comfort, and overall well-being—critical considerations especially amidst the backdrop of the COVID-19 pandemic. Even prior to the pandemic, individuals spent considerable amounts of time indoors. Moreover, BACs have a crucial role in Smart Buildings and their interaction with the Smart Grids. [1]. Consequently, there is a pressing need to evaluate design approaches and optimize building plant performance. Current system performances often fall short of their potential due to inadequate implementation, calibration, or commissioning, as well as suboptimal sensor positioning and quantity. This shortfall results in diminished energy savings, user dissatisfaction, or even complete control system deactivation. Within the project "SiciliAn MicronanOTecH Research And Innovation CEnter "SAMOTHRACE", the activity "*Innovative control systems and devices for artificial lighting*" aims to develop devices using innovative methods for monitoring lighting parameters in indoor environments equipped with Daylight-linked control systems (DLCs). These systems aim to support professionals in correctly designing, installing, commissioning, and post-monitoring lighting control systems using artificial intelligence techniques.

This paper presents the first study for the development of a first prototype of the kit. In next part, a literature review presents the state-of-the-art and market investigation of similar research presented in the literature as well as available devices and software tools. Then, the manuscript continues with the description of the experimental set-up and the case study analysis. This latter part encompasses as well the study of the "case" that includes the electronic board from the size, the shape, and the optical characteristics points of view. Finally, the first measurement campaigns used to calibrate the lighting sensor is shown.

II. BACKGROUND AND LITERATURE REVIEW

Daylight-linked control systems (DLCs) utilize signals captured by photosensors placed within the space, often mounted on the ceiling. Like any automated control system, this technology offers numerous benefits, but its effectiveness may decrease, leading to potential discomfort for occupants and negative impacts on their well-being [1]. This decline can be attributed to various challenges encountered during key stages of their lifecycle, including design, installation, configuration, operational control, and post-commissioning procedures.

Concerning the design phase, it is well-known that the presence and distribution of natural light within a space, where the control system is implemented, is influenced by various factors. These factors encompass the spatial geometry, the presence, size, orientation, and placement of openings, as well as the optical characteristics of surfaces and objects (e.g., furniture) within the space. Consequently, the standardization of control system algorithms and the information typically provided by manufacturers for installation often inadequately cater to the diverse array of environments (due to the varied combinations of these factors). Additionally, the effectiveness of lighting control systems is influenced by various external conditions, such as

This paper is funded by the project "SiciliAn MicronanOTecH Research And Innovation CEnter "SAMOTHRACE" adopted by Ministero dell'Università e della Ricerca (MUR).

neighbouring structures, furnishings, vegetation, and climatic factors.

To enhance performance, it's crucial to carefully select the types and quantities of sensors. Incorrectly sizing them—either too small or too large—can detrimentally impact the system's functionality, its ability to provide visual comfort (and partially affect energy consumption), and the payback time. Many studies presented in literature investigated how to optimize number and position of sensor used to measure environmental parameters [3] such as air temperature, relative humidity [4], or e.g. to identify the optimal sensor location for geotechnical and structural problems [5] [6]. Wang et al. [7] developed a novel sensor fault detection and self-correction method based on decentralized network structure for HVAC systems. Seyedolhosseini et al. [8] proposed a smart lighting control method for indoor environments with both dimmable (controllable) and uncontrollable external light sources. Khairul Rijal Wagiman et al. [9] presented a method to find optimal position of light sensors and their number. The optimum position of the sensors was determined based on a proposed mathematical model and then, an objective function and its constraints were formulated: average dimming levels of LED luminaires, and illuminance level and uniformity, respectively. Beccali et al. [10] used Artificial Neural Network to study the best position of the photosensor.

To select the useful tools in terms of hardware and software, a state-of-the-art and market investigation of similar research of the available hardware and software technologies has been conducted. Tian et al. [11] implemented an optimization platform using the coupled models of a coarse grid Fast Fluid Dynamics model for indoor airflow and Modelica models for HVAC aimed at the optimization of thermostat placement in a typical office room with a VAV terminal box in the design phase. Fontanini et al. [12] focused their attention on air quality by developing a data-driven sensor placement algorithm based on a dynamical systems approach. The approach utilizes the finite-dimensional Perron-Frobenius (PF) concept. The algorithm determines the response times, sensor coverage maps, and the number of sensors needed. As well Cheng et al. [13] aimed to develop a methodology to optimize temperature and CO_2 sensor placement for thermal comfort and IAQ monitoring in a multi-zone environment under limited field measurement.

The use of low-cost electronic boards, such as Arduino and Raspberry platforms, is always more common as well in the implementation of research projects [14] and in particular for environmental parameters monitoring [15][16][17][18][19][20][21][22]. Karami et al. [23] proposed for indoor environmental quality (IEQ) monitoring and performance assessment. They included different sensors such as temperature, relative humidity, illuminance, CO_2, VOC, PM2.5, and occupancy. Chiesa et al. [24] presented a IoT solution to control indoor illuminance levels by balancing daylight and artificial light able to control shading system. Budhiyanto and Chiou [25] used Arduino to develop a Surveillance Lighting Control System for classrooms environments.

III. Experimental Setup And First Measurement Campaign

According to the above-mentioned literature review two types of boards have been tested. An Arduino programming environment, with its variant of the C++ programming language, was utilized to acquire data from the TSL2591 sensor (lux Range: from 188 µlx up to 88,000 lx input measurements). The acquired data were processed and transmitted to an online MySQL database. A parallel system using a RaspberryPi 4 and the Enviro board was designed and implemented. The RaspberryPi 4 was selected as an alternative and complementary platform for data acquisition. The Enviro board, connected to the Raspberry Pi 4, contains the necessary sensors for illuminance, temperature, and humidity measurements. The LTR-559 light sensor enables measurement from 0.01 lx to 64,000 lx light detection range.

The illuminance values collected by the two devices were compared with the values measured with a time step of 5 minutes by using a Delta Ohm Data logger HD2102 portable luxmeter equipped by a probe for the measurement of illuminance LP471PHOT. It has a spectral response in agreement with standard photopic vision, class B according to CIE N° 69, user for correction of the cosine. The measurement range is 0.1 lux÷200·10^3 lux. In addition to the instantaneous measurement, this instrument calculates the time integral of the acquired measurements Q(t). Stores up to 38,000 samples with single channel probes and up to 14,000 samples with combined probes [26]. These data were transferred to a PC.

The Raspberry Pi 4 programming was implemented using a Python code written to acquire, process and transmit data from Enviro board sensors to an online MySQL database. Therefore, similarly to the Arduino acquisition system, the acquired data were stored in the database for further analysis. The electronic boards can be powered by the electricity from the grid, but the final kit have to be powered by a mobile battery. Regarding to this latter a battery PL103450 (3.7V, 2000mAh, 7.4Wh) was selected.

The Arduino MKR WiFi 1010 board was chosen for the following characteristics:

- Wi-Fi connectivity: equipped with a built-in Wi-Fi module that allows the card to connect to wireless networks, making it ideal for projects that require its use;
- Compactness: The board is relatively small and lightweight (61.50mm x 25.00mm x 32.00g), making it suitable for projects that require small size and low power consumption;
- Processing Power: It is based on Microchip's SAMD21 Cortex-M0+ 32 bit microcontroller, which offers enough processing power for a variety of projects, including light assimilation;
- Low Power Consumption: It is designed to consume a minimal amount of power, making it suitable for battery-powered projects;
- Ease of programming: It can be programmed using the Arduino development environment (IDE) which offers a wide range of libraries and resources to simplify project development;

- Compatibility: Compatible with a variety of shields (memory expansion cards), allowing you to add functionality quickly and easily.

The TSL2591 sensor is a semiconductor component used for detecting ambient light and luminous intensity. Furthermore, it is capable of measuring brightness in different lighting conditions, making it useful in a variety of applications, such as automatic lighting, adjusting the brightness of the screens or devices connected to it and detecting movement. Following some of its characteristics:

- High dynamic range: The sensor can detect a wide range of brightness, allowing for accurate measurement in different lighting conditions;
- Spectral Sensitivity: The sensor is sensitive to visible light (400nm-700nm) and infrared light (1mm-700nm), allowing for accurate measurement of mixed illumination;
- Built-in Filters: Includes built-in filters that help isolate ambient light and reduce interference from unwanted lights;
- Thanks precisely to its advanced features, the TSL2591 sensor is widely used in applications such as home automation, wearable devices, security systems, etc.;
- The rechargeable lithium battery with a specific format, in this case, the code indicates the dimensions (10mm x 34 mm x 50mm).

Furthermore, in order to make the above-mentioned instrumentation more "portable", a case has been developed. The case was designed to be simple and lightweight. It has pre-established spaces inside for the arrangement of the various components (battery-sensor-Arduino) and is made up of two bodies: container and cover. The three housing compartments of the case have been optimally sized, both considering the need to connect them and to facilitate maintenance. To this end, the battery housing compartment has been made slightly wider than the dimensions of the battery, and an additional compartment allows for the passage of the connecting cables. Anchoring systems for the components have been arranged in each space: a "TAB" for the battery compartment; and 4 cylinders to fit the Arduino.
A through hole has been made on the short side of the case for the USB input, located on the Arduino board. Finally, there are four holes for fixing the cover. The second body, i.e. the cover, has a hollow section for the placement of the sensor at the top left, which, thanks to the through slot, obtained horizontally from the body, serves for the assimilation of the light beam in correspondence with the TSL2591 sensor, completely uncovered, otherwise the recorded data would be compromised, not guaranteeing its optimal use. Regarding the color of the case, the choice of colors and surfaces with a low reflectance index is adequate for light measurement. In fact, in the technical and scientific sectors, black or dark objects are often used to reduce interference from unwanted reflections; For example, in optical equipment or telescopes, black or dark interiors are used to minimize stray light and improve image quality. The material chosen is PLC (Polylactic Acid). It is a type of material commonly used in 3D printers, also known as PLA, it is a biodegradable material derived from renewable resources such as corn, tapioca or sugar cane; this feature makes it very attractive for a wide range of applications, including those that primarily require a certain environmental sustainability [27]. In 3D printers it is often used to produce prototypes, spare parts and consumables, it is also highly appreciated for its ease of printing, the low tendency to warp (deformation during cooling) and the ability to produce objects with detailed fine and a smooth surface.

It is important to note that the biodegradability of PLC or PLA depends on the environment in which it is disposed of, if this process does not occur correctly, the decomposition process can take a long time and may not be complete; therefore, it is always advisable to dispose of biodegradable materials responsibly and following local recycling guidelines. Figure 1 shows the case with the components.

Fig. 1. The "case" with the components inside

To calibrate the sensor, several measurement campaigns have been conducted. In particular, the first two have been performed by considering the illuminance values due to an artificial lighting source, while the other ones have been conducted by considering the natural lighting.

IV. Results

Several measurement campaigns have been done by using the two different electronic boards and the luxmeter Delta Ohm Data logger HD2102 portable luxmeter equipped by a probe for the measurement of illuminance LP471PHOT. The error in measurements made with the Adafruit TSL2591 can be evaluated by considering the analog-to-digital conversion and the instrument's precision. The TSL2591 incorporates a 16-bit converter to reduce transmission signal noise. Given that the sensor measurements range up to 88,000 lux, the sensor has a resolution of approximately 1.34 lux. It can be assumed that measurements can be improved by averaging a certain number of acquisitions, thus mostly averaging out random fluctuations.

Repeated measurements were conducted using a constant light source to estimate the measurement's standard deviation and relative uncertainty over hundreds of data points. The relative uncertainty was evaluated to be between $1.59\times10^{-3} \approx 0.16\%$ for measurements below 40,000 lux and $5.21\times10^{-3} \approx 0.52\%$ for those above 40,000 lux. The probe for the measurement of illuminance LP471PHOT is a certified calibrated and the calibration uncertainty is <4% as declared by the manufacturer.

The first measurements campaigns have been carried out by using an artificial lighting source able to range the luminous flux according to the absorbed power. Graphs of acquired data from the Arduino Uno WiFi Rev.2 and Raspberry Pi 4 and from the reference instruments systems, are presented in the figure 2 and represent a first step in the foregoing measurement investigations. Statistical analysis techniques have been used to evaluate the precision and accuracy of the designed systems. The results are presented in tabular and graphical formats to focus any differences or similarities between the acquired data and the reference instrument measurements.

During the validation and analysis process, some important observations were made. Indeed, during first step of the measurement campaign, the data acquired from the Arduino Uno WiFi Rev.2 and Raspberry Pi 4 systems seemed to exhibit consistent and reliable performance, approximately matching the readings from the commercial technical sensors.

The data collected during the first measuring campaign showed that, in other environmental conditions and for a longer time period, the difference between the measures taken with the two prototype and the measures taken with the Delta Ohm luxmeter were significant.

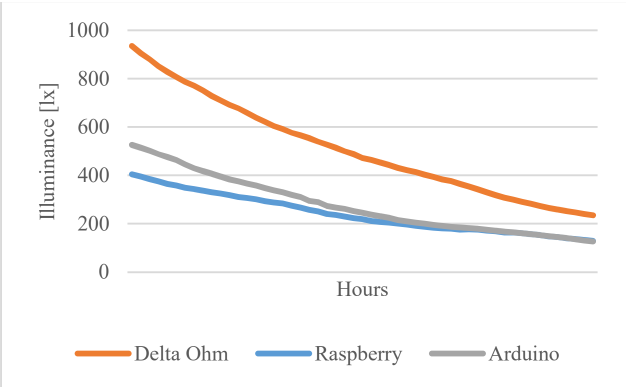

Fig. 2. Comparison of the illuminance values measured by Arduino, Raspberry and Delta Ohm instrument.

In this light, further experimental investigations were required to calibrate measurements under any condition, position, and without variations in accuracy based on the level of intensity. It is worth noting that calibration of the sensors will be performed to confirm the measurement accuracy of the data acquisition systems. Additionally, ongoing efforts will be made to optimize the data acquisition process further, minimizing potential noise and interference that may affect the acquired measurements.

The collection of other measurements was made in another room with variable daylight conditions. The calibration of the instrumentation was made by using same software above-mentioned. This activity was carried out by using an artificial lighting source characterized by the possibility to dim the luminous flux. The measurements have been taken with different percentage of absorbed power and, consequently, different illuminance values. This allowed for a comprehensive range of illuminance, facilitating a robust data set. Sensor readings from TSL2591 and Enviropi were recorded under these conditions. After this action, several measurement campaigns have been performed in order to calibrate the devices more accurately. In particular, the measurement was taken by considering different percentages of luminous flux: 100%; 95%; 90%; 85%; 80%; 75%; 70%; 65%; 60%; 55%; 50%; 45%; 40%; 35%; 30%; 25%; 20%; 15%; 10%; 5%; 0%.

Data analysis was conducted using the least squares method, incorporating both linear and polynomial (second and third-degree) regression models. Numerous calibration tests were conducted to ensure a comprehensive set of measurements.
The following table 1 shows the data taken with the different percentages of absorbed power before and after a test of calibration.

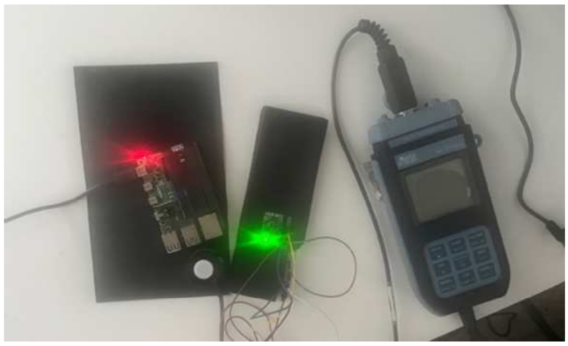

Fig. 3. The instrumentation used during the first measurement campaign: Arduino, Raspberry, and Delta Ohm luxmenter.

It was noted that, after the second calibration step, the data collected by the two electronic boards are more similar to the measures collected by using the Delta Ohm instrument.
The calibration process revealed critical insights into the sensor behaviour Polynomial regressions, particularly higher-degree models, showed close fits to calibration data but raised concerns of overfitting, which could impact accuracy in diverse light conditions. In contrast, linear regression demonstrated superior generalizability for diverse light conditions. Repeated calibration trials emphasized the importance of consistency in calibration parameters, leading to the identification of the most reliable model for these sensors.

Detailed data tables and graphical representations illustrate the regression analyses. The comparison with Delta OHM readings is extensively studied, highlighting the degree of alignment between the sensors and the standard instrument, and the implications of any discrepancies observed.

The study highlights the necessity of calibrating TSL2591 and Enviropi sensors. Future calibration efforts will aim to refine these methods, seeking a balance between accuracy and applicability. The report is supplemented with detailed data tables, graphical representations of the regression analyses, and a comparative study with the Delta OHM readings.

Table 1 shows the comparison between the data collected by the two devices and the data collected with the Delta Ohm luxmeter after the calibration.

TABLE I. COMPARISON BETWEEN THE DATA COLLECTED BY THE TWO DEVICES AND THE DATA COLLECTED WITH THE DELTA OHM LUXMETER AFTER THE CALIBRATION

Power	**Illuminance [lx]**				
	TSL2591	***Enviropi***	***Enviropi (calibrated)***	***TSL2591 (calibrated)***	***Delta Ohm***
100%	2000	2410	2307	2307	2304
95%	1787	2154	2062	2061	2061
90%	1585	1909	1827	1828	1828
85%	1391	1677	1605	1605	1606
80%	1214	1461	1399	1401	1401
75%	1058	1278	1224	1221	1224
70%	910	1099	1052	1051	1052

65%	780	939	899	901	901
60%	657	790	757	759	759
55%	537	647	620	621	621
50%	443	534	512	512	514
45%	357	433	415	413	413
40%	280	341	327	325	326
35%	216	256	246	251	249
30%	159	194	187	185	185
25%	115	139	134	134	134
20%	78	96	93	92	92
15%	47	59	57	56	57
10%	29	35	34	35	34
5%	13	19	19	17	17
0%	1	0	1	3	0,8

The sensibility of the photosensor installed in the Arduino device was tested.

The measurements from the TSL2591 sensor were acquired using an Arduino MkrWifi1010 board which sent them to a MySQL database. The graphs related to the detected data have shown a variable trend depending on the weather conditions and the position and height of the Sun during this period of the year. The curves of the two sensors show a similar trend over time. However, the direct comparison graphs between the measurements made by the two instruments, have shown a nonlinear behaviour of the TSL sensor, across the entire range of measurements. Therefore, it was necessary to divide the detected data into two ranges (greater or less than 40,000 lux), verifying a different trend line between the two groups of data.
The graph below shows a sample of the measurements of the two instruments.

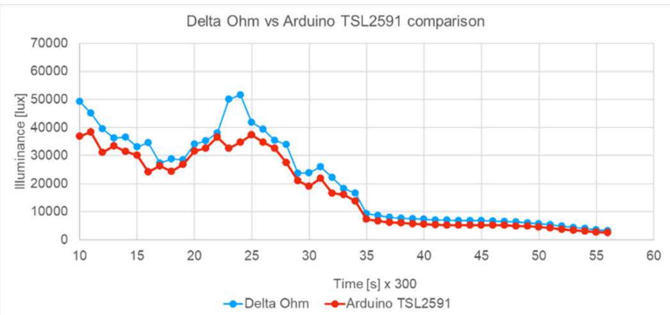

Fig. 4. Measured data comparison

The relationship between the measured data allows us to understand the nonlinear behaviour of the TSL2591 sensor.

The nonlinear behaviour of the sensor response led us to consider the possibility of variable calibration in relation to the level of the measured signal. Therefore, the dataset was preliminarily separated into two classes: greater than and less than 40,000 lux. The following graphs show the obtained trend lines. The range of lower values is the one that comes closest to the expected illumination values in the case study under examination, showing a strong correlation between Delta Ohm and Adafruit TSL2591 measurements with R^2~0.99.

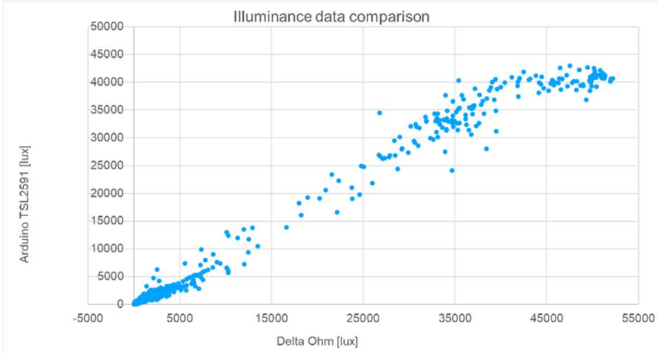

Fig. 5. Nonlinear behaviour of TSL2591 sensor.

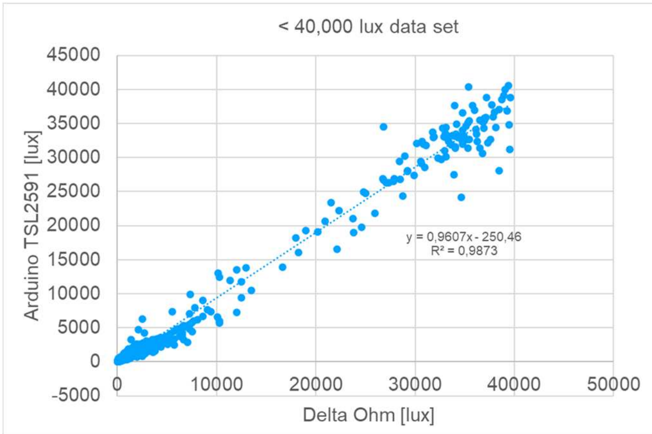

Fig. 6. Trend line relative to <40,000lux measurements.

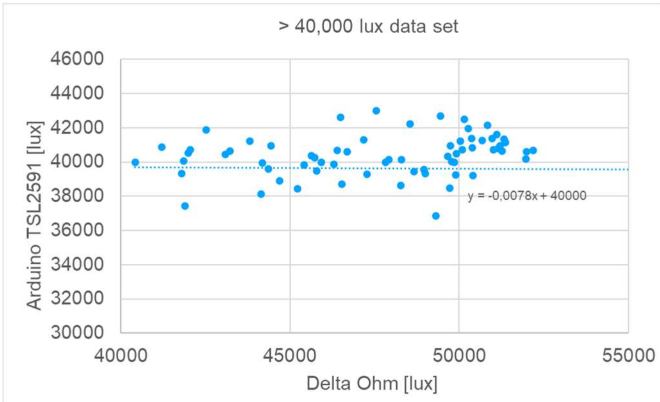

Fig. 7. Trend line relative to >40,000lux measurements.

Conclusion

This paper aims to present the development of a first prototype of a kit to improve the performance of the daylight control system during design, operating and post-commission steps: HW/SW components, procedures, and tools for the management of the control systems. In particular, the paper has presented the laboratory setup.

The instrumentation is described and the measurement campaign for calibrating the sensors used to measure the data installed in two different electronic board. Finally, some partial results have been presented. The comparison between the Arduino-TSL2591 data and those from the certified instrument Delta Ohm HD2102.2 showed a very strong correlation (R^2=0.98) in the range below 40.000 lux, while measurements above 40.000 lux, that actually are over the range of interest in this study, still present a weak correlation. In a future work the whole results of the measurement campaign will be presented together with the conclusion of the research.

ACKNOWLEDGMENT

This work received funding from the project "SiciliAn MicronanOTecH Research And Innovation CEnter "SAMOTHRACE" (MUR, PNRR-M4C2, ECS_00000022), spoke 3 - Università degli Studi di Palermo "S2-COMMs - Micro and Nanotechnologies for Smart & Sustainable Communities".

REFERENCES

[1] M. Beccali, L. Bellia, F. Fragliasso, M. Bonomolo, G. Zizzo, G. Spada, "Assessing the lighting systems flexibility for reducing and managing the power peaks in smart grids", Applied Energy, vol. 268, 114924. 2020.

[2] Z. Kong, J. A. Jakubiec, "Evaluations of long-term lighting qualities for computer labs in Singapore", *Building and Environment*, 107689. 2020.

[3] D. Yoganathan, S. Kondepudi, B. Kalluri, S. Manthapuri, "Optimal sensor placement strategy for office buildings using clustering algorithms". *Energy and Buildings*, Vol. *158*, pp. 1206-1225, 2018.

[4] M. Frei, C. Deb, R. Stadler, Z. Nagy, A. Schlueter, „Wireless sensor network for estimating building performance", *Automation in Construction*, vol. *111*, 103043, 2020.

[5] F. D. Udwadia, "Optimal sensor locations for geotechnicàl and stroctur. Il identification", 1984.

[6] C. Papadimitriou, "Optimal sensor placement methodology for parametric identification of structural systems", *Journal of sound and vibration*, vol. *278*(4-5), pp. 923-947. 2004.

[7] B. Wang, F. Wang, "Research on intelligent lighting distributed control algorithm based on sensor network technology", *Microprocessors and Microsystems*, vol. *81*, 103729. 2021.

[8] A. Seyedolhosseini, N. Masoumi, M. Modarressi, N. Karimian, "Daylight adaptive smart indoor lighting control method using artificial neural networks", *Journal of Building Engineering*, vol. *29*, 101141. 2020.

[9] K. R. Wagiman, M. N. Abdullah, M. Y. Hassan, N. H. M. Radzi, "A new optimal light sensor placement method of an indoor lighting control system for improving energy performance and visual comfort", *Journal of Building Engineering*, vol. *30*, 101295. 2020.

[10] M. Beccali, M. Bonomolo, G. Ciulla, V. Lo Brano, "Assessment of indoor illuminance and study on best photosensors' position for design and commissioning of Daylight Linked Control systems. A new method based on artificial neural networks", Energy, vol. 154, pp. 466-476, 2018.

[11] W.Tian, X. Han, W. Zuo, Q. Wang, Y. Fu, M. Jin, „An optimization platform based on coupled indoor environment and HVAC simulation and its application in optimal thermostat placement", *Energy and Buildings*, vol. *199*, pp. 342-351, 2019.

[12] A. D. Fontanini, U. Vaidya, B. Ganapathysubramanian, "A methodology for optimal placement of sensors in enclosed environments: A dynamical systems approach", *Building and Environment*, vol. *100*, pp. 145-161, 2016.

[13] J. C. Cheng, H. H. Kwok, A. T. Li, J. C. Tong, A. K. Lau, "BIM-supported sensor placement optimization based on genetic algorithm for multi-zone thermal comfort and IAQ monitoring", *Building and Environment*, vol. *216*, 108997, 2022.

[14] Kondaveeti, H. K., Kumaravelu, N. K., Vanambathina, S. D., Mathe, S. E., & Vappangi, S. (2021). A systematic literature review on prototyping with Arduino: Applications, challenges, advantages, and limitations. Computer Science Review, 40, 100364.

[15] Ferdoush, S., & Li, X. (2014). Wireless sensor network system design using Raspberry Pi and Arduino for environmental monitoring applications. Procedia Computer Science, 34, 103-110.

[16] Pereira, P. F., & Ramos, N. M. (2022). Low-cost Arduino-based temperature, relative humidity and CO2 sensors-An assessment of their suitability for indoor built environments. Journal of Building Engineering, 60, 105151.

[17]] A.S. Ali, Z. Zanzinger, D. Debose, B. Stephens, Open Source Building Science Sensors (OSBSS): a low-cost Arduino-based platform for long-term indoor environmental data collection, Build. Environ. 100 (2016) 114–126.

[18] A. Carre, T. Williamson, V. Soebarto, Design and validation of a low cost indoor environment quality data logger, in: J. Zuo, L. Daniel, V. Soebarto (Eds.), Revisiting the Role of Architectural Science in Design and Practice : 50th International Conference of the Architectural Science Association, The Architectural Science Association and The University of Adelaide, Adelaide, 2016, pp. 547–556.

[19] R. Edirisinghe, S. Setunge, G. Zhang, D. Dias, P. Samapth, Sensor network to validate IEQ of public building green retrofit, in: V. Telichenko, A. Volkov, I. Bilchuk (Eds.), 14th International Conference on Computing in Civil and Building Engineering, Moscow State University of Civil Engineering, Moscow, Russia, 2012, pp. 1–5.

[20] S. Habibi, Smart innovation systems for indoor environmental quality (IEQ), Journal of Building Engineering 8 (2016) 1–13.

[21] K.W. Mui, L.T. Wong, H.C. Yu, T.W. Tsang, Development of a user-friendly indoor environmental quality (IEQ) calculator in air-conditioned offices, IAQVEC 2016 - 9th International Conference on Indoor Air Quality Ventilation & Energy Conservation in Buildings. Songdo, Incheon, 2016.

[22] F. Salamone, L. Belussi, L. Danza, M. Ghellere, I. Meroni, Design and development of nEMoS, an all-in-one, low-cost, web-connected and 3D-printed device for environmental analysis, Sensors 15 (6) (2015) 13012–13027.

[23] Karami, M., McMorrow, G. V., & Wang, L. (2018). Continuous monitoring of indoor environmental quality using an Arduino-based data acquisition system. Journal of Building Engineering, 19, 412-419.

[24] Chiesa, G., Di Vita, D., Ghadirzadeh, A., Herrera, A. H. M., & Rodriguez, J. C. L. (2020). A fuzzy-logic IoT lighting and shading control system for smart buildings. Automation in construction, 120, 103397.

[25] Budhiyanto, A., & Chiou, Y. S. (2024). Visual comfort and energy savings in classrooms using surveillance camera derived HDR images for lighting and daylighting control system. Journal of Building Engineering, 108841.

[26] Delta Ohm https://www.deltastrumenti.it/images/pdf/deltaohm/luce/HD2102.1.2_it.pdf. Available on line (31/05/2024)

[27] Sood, R., & Pradhan, S. K. (2020). Design and development of a low-cost open-source 3D printer and its single response optimization using polylactic acid (PLA) material. Materials Today: Proceedings, 27, 2981-2991.