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How to control the Indoor Environmental Quality through the use of the Do-It-Yourself approach and new pervasive technologies

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Abstract

The article describes the results of the "Open-source Smart lamp" aimed at designing and developing a smart appliance that integrates a wireless communication system for building automation, following the maker movement philosophy. The device is able to get an overview of the potential of a nearable device equipped with a variety of sensors to broadcast digital data for the management and control of the Indoor Environmental Quality (IEQ) of the built environment. The Smart Lamp installed in a real office in order to test the reliability of the device in the management of the lighting and air quality levels.

Keywords: Indoor Environmental Quality; Indoor Air Quality; Indoor Lighting Quality; Indoor Climate Quality, Internet of Things; DIY; Nearable; Building automation; enabling technologies; ZEB.

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1. Introduction

In the past years, the actors of the building sector have been mainly involved in the design of new solutions to maximize the performance of technological systems for the definition of best solutions applicable to Zero Energy

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Building (ZEB) [1]. In most cases, the national and international bibliographical studies have focused their attention on the investigation of specific technical solutions to optimize building envelope strategies to reduce both cooling and heating energy consumptions respectively in summer and winter seasons, such as cool roofs [2-4], green roofs [5-8], dynamic windows [9] and so on; but sometimes planning important building retrofit strategies doesn't represent sustainable and sufficient solutions to achieve ZEB goals [10]. Today instead, the new frontiers are more and more involved in the development of integrated virtual environment [11, 12] and systems able to acquire, store and mine building data through the connection of Building Information Modeling (BIM) and the Internet of Things (IoT) [13]. While the BIM is the process related to the definition of digital representations of physical and functional characteristics of places [14], the IoT is essentially a network of connected and interconnected devices [15]. The spread of the IoT approach has allowed a proliferation of devices always connected in a communicating-actuating network, implemented following the "maker" movement and the Do-It-Yourself (DIY) philosophy, removing structural and technological obstacles [16]. Over the past years several shared projects and low-cost alternative technologies have appeared and developed, allowing end users to approach the electronics in a simple and fast way [17, 18, 19, 20, 21, 22]. The revolution of the DIY is the last in chronological order. After the agricultural and the industrial revolutions, the information age, the so-called Third Wave [23], draws upon the read/write functionality of the Internet and digitally-driven design/manufacture, to enable ordinary people to invent, design, make and, sometimes, sell goods and services [24]. Anybody at any location could carry out the principles of the DIY philosophy [25, 26, 27] through enabling technologies, for example Arduino or RaspberryPI.

The extreme flexibility of the technologies cited before allows their applications in different fields, like the Indoor Environmental Quality (IEQ) and energy consumption monitoring. As it is well known, the IEQ is a holistic concept including Indoor Air Quality (IAQ), Indoor Lighting Quality (ILQ) and indoor Acoustic comfort [28, 29, 30], besides the Indoor Climate Quality (ICQ). In addition these technologies could be fitted in common objects, transforming it in intelligent devices: in this sense the term "nearable object" (or nearable technology), used for the first time in 2014 as part of a marketing campaign, is now used to uniquely identify the idea of smart objects that can be equipped with a variety of sensors and can work as transmitters to broadcast digital data.

In the present article, the DIY approach has been applied to two nearable devices for the management of the IEQ and the related energy consumption. The ICQ, IAQ and ILQ are considered in the following scenarios. The devices were made using low-cost sensors, available on the market, wireless (IR and ZigBee) communication systems based on a LED IR and a XBee S2 communication modules, respectively. A 3D printer has been used for the implementation of the case. It implements Fused Deposition Modeling (FDM) technology [31] and uses polylactide (PLA) for printing. The PLA [32] is one of the most eco-friendly 3D printing materials available; it is made from annually renewable resources (corn-starch) and requires less energy to process than traditional (petroleum-based) plastics.

2. Application scenarios, hardware and software

2.1. Application scenarios

As evidence of the ability to apply and to adapt a nearable to the specific requirements by following the DIY approach, two different scenarios are considered corresponding to two different prototypes of a desk lamp, applied to the same case study aimed at optimizing different aspects of the IEQ. The former (Fig. 1a) in which the nearable tool is implemented and applied so as to optimize the ICQ. The latter (Fig. 1b) in which it is updated to optimize the IAQ and ILQ.

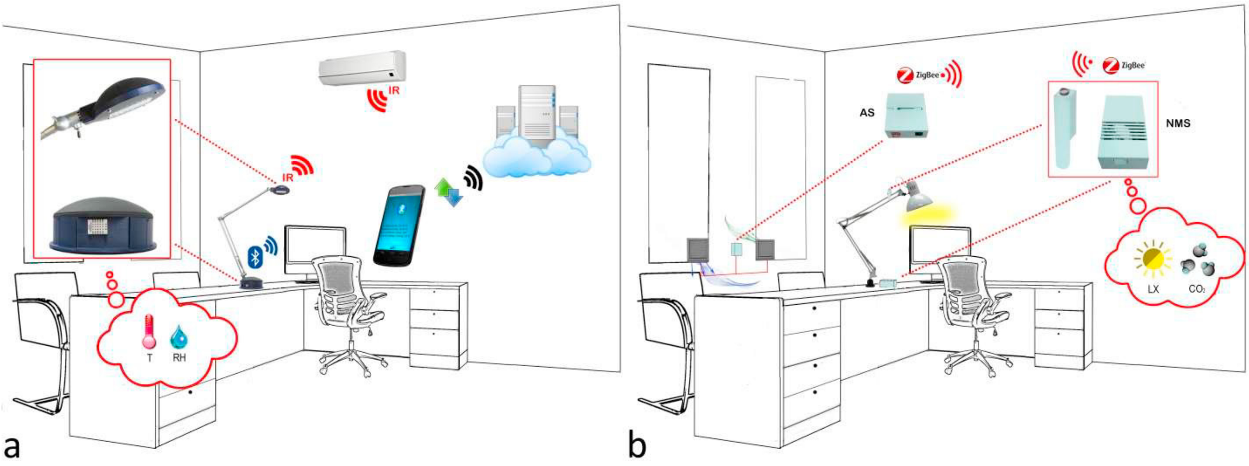

Fig. 1. Application scenarios: (a) 1st nearable for ICQ optimization; (b) 2nd nearable for IAQ and ILQ optimization.

The first nearable prototype (Fig. 1a) takes into account the monitored values of air temperature and relative humidity. The microcontroller provides the command to the air conditioner in the form of infrared code, on the basis of a the hypothesized control logics. The Bluetooth module allows to transfer the data to an Android device and the mobile app allow to send all the data to a cloud server.

The second nearable solution (Fig. 1b) allows to monitor the CO_2 concentration and illuminance values. Depending on these, the microcontroller provides the command of activation of the air exchange and lighting devices, through a ZigBee connection.

2.2. Hardware

The fundamental core of the hardware architecture of the first nearable, named "Smart lamp", released as a completely open source project [33], is a microcontroller, an integrated air temperature and relative humidity sensor (DHT22), an infrared (IR) led and a lighting element characterized by a "cold light" emitted by a 24 LEDs panel. The DHT22 sensor is placed into the base of the Smart lamp in a position so as not to be influenced either by the nearby overheated electronic components [34] or by the lighting appliance placed at a distance of about 50 cm from the base. The second nearable [35] (Fig. 1b) is composed by two elements:

- a monitoring station placed near the workstation (in Fig. 1b: NMS, nearable monitoring station) equipped with a XBee S2 module, a K30 CO_2 concentration sensor and a photoresistor;
- a receiving station (in Fig. 1b: AS, actuation station) wireless connected to the nearable monitoring station that manages the actuation of both the air exchange system and the lamp.

2.3. Software

The first nearable detects the air temperature (T) and the relative humidity (RH). Depending on the value, different scenarios and many useful settings are identified:

- If $T < 21$ °C then it sets the air conditioning system on the heating mode modifying the set point at 24 °C.
- If $21 \leq T < 22$ °C then it sets the air conditioning system on the heating mode modifying the set point at 22 °C.
- If $22 \leq T < 25$ °C and $RH > 60\%$ then it sets the air conditioning system on the dehumidification mode.
- If $22 \leq T < 25$ °C and $RH \leq 60\%$ then it turns off the air conditioning system.
- If $25 \leq T < 26$ °C then it sets the air conditioning system on the cooling mode modifying the set point at 25 °C.

- If T > 26 °C then it sets the air conditioning system on the cooling mode at modifying the set point at 23 °C.

In the present article 25 °C is considered as the limit value above which the air conditioning system works in cooling mode, taking into account the vertical thermal gradient between the air conditioner positioning (2.4 m above the floor) and the desk top (0.8 m above the floor). Indeed, it was experimentally observed (Fig. 3a) that at a 1.8-meter height, there is a vertical temperature difference with respect to the plane of the desk of more than 1 degree. For values higher than 26 °C, a lower cooling temperature (23 °C) and a different ventilation rate are considered because the installed air conditioning system provides an "On-Off" split type, without inverter.

The second nearable detects the carbon dioxide concentration (CO_2) and the illuminance level (LX). Depending on the value, it is possible to identify the following useful settings:

- If CO_2 > 900 ppm then it activates the air exchange system.
- If CO_2 ≤ 900 ppm then it deactivates the air exchange system.
- If LX > 500 lx then it deactivates the lighting system.
- If LX ≤ 500 lx then it activates the lighting system.

The devices are equipped with a Real Time Clock (RTC) module in order to take into account the seasons length. In particular, the heating season is considered equal to what provides by the national law and the cooling season is defined on the basis of the trend of the internal temperature. The RTC allows the heating and cooling periods to be fixed in an extremely flexible way.

3. Case study and method for comfort evaluation

3.1. Case study

Both systems were installed in the same office, located on the first and top floor of office building, with an area of about 42 m^2 (7.81 m × 5.37 m) normally occupied by four users (Fig. 2). Three integrated air temperature and relative humidity sensors (RHT1, RHT2 e RHT3), a globe thermometer (G), energy meters, variable in number, depending on configuration (Table1) ABB OD 1365 (EM), a carbon dioxide concentration sensor (CO_2) and a lux meter (LX) were installed in the office. All sensors are connected to a data logger (D). The RHT2, CO_2 and LX sensors were installed on the desktop close to the workplace where the thermal comfort, air and lighting quality are analyzed. The RHT1, RHT3 are located at 1.8 meter height.

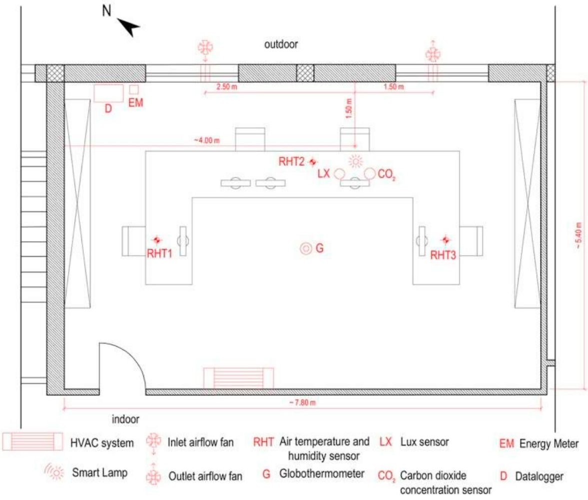

Fig. 2. Plan of the office with sensors position.

The data of the environmental variables are recorded every 10 seconds then averaged every minute and stored on a memory card. A total of 28 working days were considered divided in four distinct periods (Table 1).

Table 1. Weather data for the four configurations. The period of diurnal average of solar radiation is from 8.00 am to 9.00 pm.

Type of evaluation	Configuration	Air conditioning	Lighting	Ventilation	Period	External Temperature [°C]			Solar Radiation [W/m^2]	
						Min	Max	Avg	Max	Avg
ICQ	1.1	Manual control	No control	No control	I. 2015, June 30 - July 8	21.70	38.40	30.32	922	496
	1.2	Automatic control	No control	No control	II. 2015, July 9 – 17	21.13	38.60	29.91	949	498
ILQ, IAQ	2.1	No control	Manual control	Manual control	III. 2016, May 23 - 29	11.48	32.05	20.88	946	436
	2.2	No control	Automatic control	Automatic control	IV. 2016, May 30 – June 05	14.50	28.44	18.89	963	345

The EM sensor in configuration 1.1 and 1.2 (Table 1) was connected to the air conditioning system. In configuration 2.2 two EMs were considered, the former connected to the air exchange system, the latter connected to the lighting system. The air exchange system used just in the fourth test period consists of two fans: one introduces fresh air into the office, the other discharges the exhaust air. Both units have no filter or heat recovery system and are connected to the same relay of the receiving actuation station. The average air intake/discharge speed is equal to 2.5 m/s. Considering the diameter of the duct, equal to 0.15 m, its hourly flow rate results to be equal to 159 m^3/h. This value is greater than that defined by the Italian Standard UNI 10339:1995 which indicates a specific flow rate of air exchange equal to 11 l/s per person (equal to 39.6 m^3/h per person), for "single or open space" offices. By multiplying this value by the number of people in the office, a flow rate of 158.4 m^3/h is obtained, fulfilling the requirement.

3.2. Method for comfort evaluation

In order to evaluate the thermo-hygrometric comfort of an indoor environment the Predictive Mean Vote index (PMV, EN ISO 7730:2005) was applied.

The IAQ is assessed in relation to CO_2 concentration, expressed in ppm [36]. The Technical Standard addressing this issue is the EN 15251 that identifies air quality classes in relation to the difference in carbon dioxide concentration between indoor ($CO_{2,i}$) and outdoor air ($CO_{2,o}$).

The Reference Standard for the definition and the evaluation of visual comfort in indoor environments is the EN 12464-1 which defines the minimum required levels of illuminance for single indoor activities.

4. Experimentation results

Focusing attention on a summer typical day of the configuration 1.1 in manual control mode, (Fig. 3a) it is possible to observe the air temperature and relative humidity trends for the three workplaces from 9.00 am to 6.00 pm.

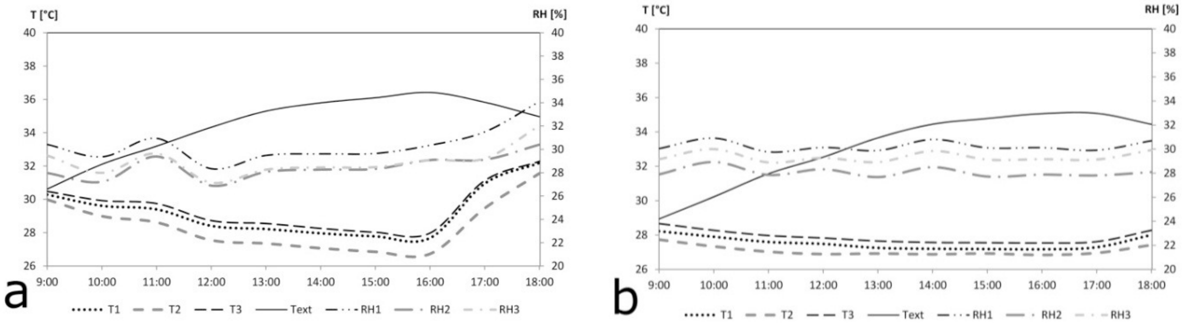

Fig. 3. Temperatures and relative humidity: (a) July 7th 2015, 9.00 am ÷ 6.00 pm, manual control; (b) July 16th 2015, 9.00 am ÷ 6.00 pm, automatic control.

The air conditioning system was set up with temperatures ranging between 23 °C and 26 °C. It could be noticed that the temperature variation during the working hours was very high, with values of 30 °C in the morning, decreasing to 27.4 °C in the afternoon and finally increasing up to 32 °C at 6.00 pm. The temperature trend detected by each sensor could be divided in three parts: a transient period from 9.00 am to 11.00 am which represents the thermal inertia necessary to achieve appropriate values of temperature and therefore of acceptable comfort levels, a steady-state period from 11.00 am to 4.00 pm, and a transient period from 4.00 pm onwards. The temperature difference of the absolute values recorded by sensors T1 and T3, placed at the same height, was less than 0.3 °C. By observing the difference between the measured values by these sensors and those measured by T2 a vertical difference of temperature at most equal to 1.2 °C can be noticed. The average value of outdoor temperature detected on this day was 32.5 °C. The minimum and maximum temperatures recorded were equal to 27.5 °C and 38.1 °C, respectively. As regards the relative humidity trends, the values were quite similar in the three workstations, with differences lower than 3% of the recorded value.

In configuration 1.2, in automatic control, after the installation of the 1st nearable, average hourly data of July 16th, 2015 were considered (Fig. 3b) for the preliminary analysis. This day is characterized by an average outdoor temperature of 31.6 °C, with minimum and maximum value equal to 25.9 °C and 38.6 °C, respectively.

At 9.00 am the temperature was slightly lower than 28 °C, at 4.00 pm slightly higher than 26.5 °C and finally, at 6.00 pm slightly lower than 28 °C. It may also be observed that the difference between the values recorded by T1 and T3 and those of sensor T2 are at most equal to approximately 0.9 °C, less marked than in the previous case. In this graph there are no transition zones because the overall temperature range is smaller than in the previous case and also the temperature trend is smoother. Finally, the relative humidity profile was quite stable, with a mean value for the three sensors of 30%. The difference between sensors data was less than 3 percentage points.

4.1. PMV index

The PMV index was calculated in accordance with the EN ISO 7730:2005. The average hourly values of the detected data recorded by the stations RHT2 and by the globe thermometer (G) were considered. The daily time interval considered was 9.00 am ÷ 6.00 pm. The remaining periods are in dark grey (Fig. 4a and Fig. 4b).

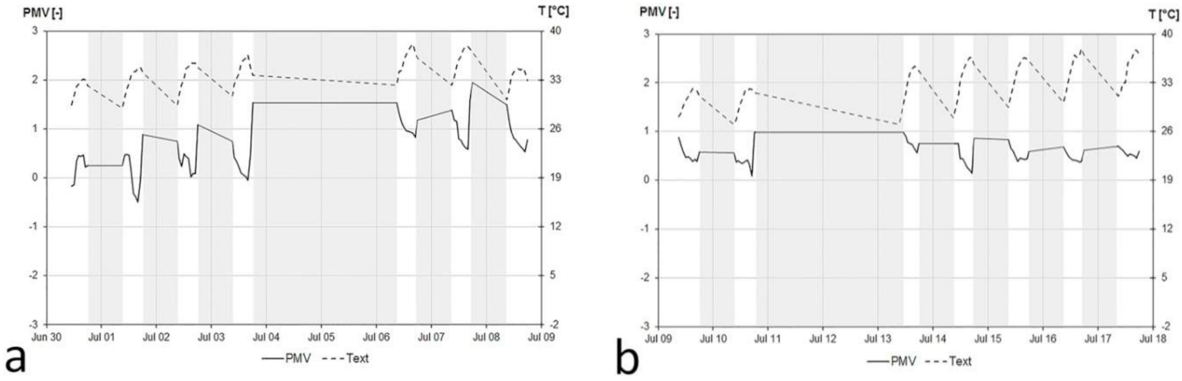

Fig. 4. PMV: (a) configuration 1.1 (manual control); (b) configuration 1.2 (automatic control). In white the hours of the day from 9.00 am to 6.00 pm. In grey the hours of the day from 6.00 pm to 9.00 am.

The chart (Fig. 4a) related to the 1st period (Table 1) shows a fairly fluctuating trend of comfort index with values close to neutrality, during days 1, 2, 3 and 4 with values corresponding to a slightly warm or warm sensation in the remaining days. A high variability can also be observed during the same day. After the installation of the 1st nearable, corresponding to the 2nd period of Table 1, the graph (Fig. 4b) shows an overall reduction of PMV index with values almost always less than 1, with a slower variability.

4.2. Air quality

In typical summer conditions, it is usual to keep windows and doors closed to prevent cool air from seeping out. This practice maintains acceptable levels of thermo-hygrometric comfort and electrical consumption but reduces air exchanges leading to an overall degradation of air quality in the indoor environment [37, 38, 39, 40].

Having fixed at 400 ppm the mean CO_2 concentration in the outdoor air and at 500 ppm of CO_2 the increment of the maximum permissible concentration of CO_2 to ensure a good level of air quality in indoor environments, the concentration value of CO_2 particles in indoor environments shall not exceed 900 ppm (CO_2 limit in Fig. 5).

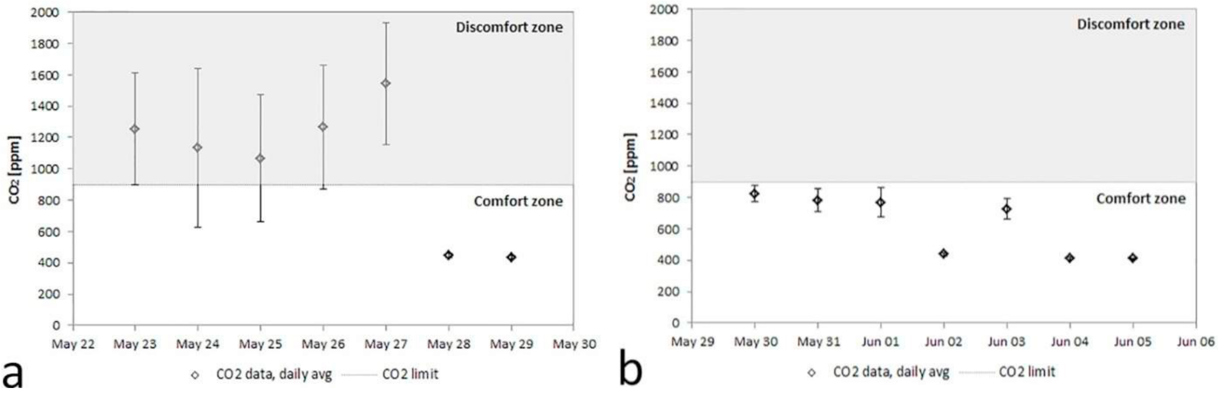

Fig. 5. CO_2 concentration: (a) configuration 2.1 (manual control); (b) configuration 2.2 (automatic control). The discomfort zone in grey; the comfort zone in white.

Considering the days of actual occupancy and the daily operating time frames (9.00 am ÷ 6.00 pm) it can be noticed that for most of the 3rd period (Table 1), the level of CO_2 concentration in the air was maintained well above the threshold value (Fig. 5a). The implementation of the mechanical ventilation system controlled by the 2nd nearable in the 4th period (Table 1), allows the CO_2 concentration levels to be maintained below the limit (Fig. 5b).

4.3. Lighting quality

The minimum illuminance levels required for activities related to writing, reading, typing and data processing should be 500 lx (illuminance limit in Fig. 6) according to EN 12464-1.

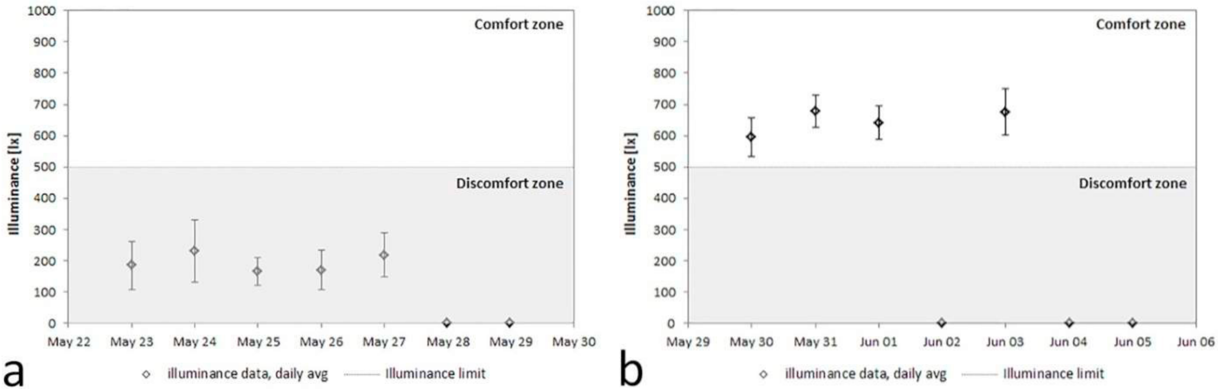

Fig. 6. Illuminance: (a) configuration 2.1 (manual control); (b) configuration 2.2 (automatic control). The discomfort zone in grey; the comfort zone in white.

Considering the days of actual occupancy and the daily operating time frames it could be observed that for most of the time of the third period, as identified in Table 1, the illuminance data are below the admissible value laid down in the technical regulation (Fig. 6a). In the 4th period the lighting levels are above the minimum required value (Fig. 6b).

4.4. Electrical consumption

By processing the data collected by the data logger connected with the energy meter, it was possible to verify the energy consumption associated with different configurations (Fig. 7). The electrical consumptions due to the use of the two nearables are not considered.

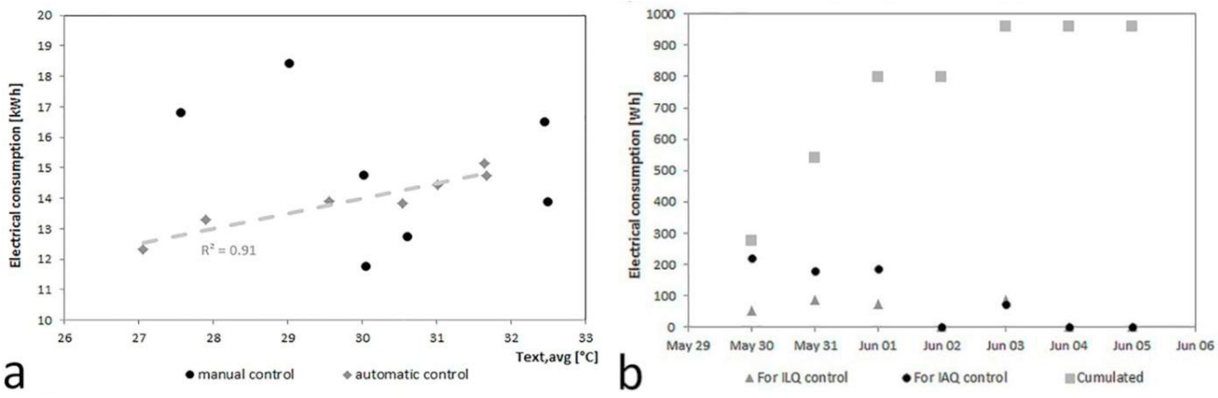

Fig. 7. Energy consumption: (a) configuration 1.1 (manual control) and 1.2 (automatic control); (b) configuration 2.2 (automatic control).

For configurations 1.1 and 1.2 (Table 1), related to the evaluation of the ICQ, Fig. 7a shows the distribution of the cumulated daily consumptions for cooling, as a function of the external daily average temperature. Over the testing period with automatic control (configuration 1.2), an overall saving over 7% was observed, with a linearity of the daily consumption compared to the average value of the external temperature confirmed by a correlation index R2 equal to 0.91. This means that consumption increases with the increase of the average outdoor temperature as it would be expected in summer [41, 42, 43, 44]. On the contrary, with manual control (configuration 1.1), the R^2 index was equal to 0.10, reflecting a distribution of limited relevance because it could be affected by many parameters, such as occupant behavior that is extremely stochastic.

For the 3rd and 4th period (Table 1) related to the evaluation of the IAQ and ILQ, only configuration 2.2 with automatic control is considered. The daily energy consumption due to the lighting is almost constant and below 100 Wh. The consumption related to the air exchange system is almost equal to 200 Wh for the first three days, then on June 3rd, when the office was occupied by only one person, the electrical consumption was halved.

5. Conclusions

The comparison of the data of the four monitoring periods clearly demonstrates the effectiveness of the automatic control systems implemented using the DIY approach and new pervasive technologies. As shown above with the two different scenarios, the advantages of implementing a system based on a DIY approach with respect to the commercial ones are associated with better customization and adaptation options. In this context, the user is not limited to the passive role of consumer, as he acts as prosumer, actively participating in the various phases of the management and improvement on the quality of the building where he lives, as indeed desirable in a ZEB.

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