A Cognitive Strategy for Renovation and Maintenance of Buildings through IoT Technology

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***Abstract*— Recently, designers of the home automation framework are looking to the Internet of Things (IoT) model to make it easier to deploy devices capable of gathering data from various plants. This situation is pushing a further evolution: from the conventional building automation, where the logic is determined by the installer or by the customer, to a cognitive system, capable of learning from the customers' preferences what the best plant configuration would be. The aim of this research work is to identify issues related to the implementation of cognitive solutions during the renovation process of buildings. The paper proposes a cognitive framework to help the operation and management phases of buildings, by means of the digitalization of the supply chain of the construction industry, from the single building aspect to the entire construction cycle. The paper presents the design of smart building elements with integrated capability to generate a massive amount of data for monitoring the energy and maintenance status of renovated buildings. The IoT paradigm has been used to link the physical word of building elements with the cognitive layer. The proposed approach has been applied and validated into a real test case.**

Keywords—Internet of Things; Building Automation; Konnex; fieldbus; cognitive building; Energy Efficiency; predictive maintenance.

I. Introduction

The recent technological innovations have been driving a transformation in a variety of application domains over the last decade. In particular, the Internet of Things (IoT) framework is one of the most effective technologies. This approach has made it much easier to overcome the information wall among the hierarchical domains on which conventional Information and Communication Technology (ICT) environment has been structured. This condition is no longer true thanks to the IoT model. It is now possible to share information between various application domains through the creation of specific data models and the use of web-based protocols to transmit this data and define the services each IoT device made available. Industrial automation was the first sectors able to completely leverage this approach: Industrial IoT (IIoT) [1] is one of the foundations of the so-called fourth industrial revolution, the data-driven revolution. The integration of intelligent devices with communication technologies [2][3] is the base of Industry4.0. The possibility of sharing data between different application areas is of particular interest in the context of Smart Cities, where the efficient management of resources (electricity, water, heat, waste) depends on the integration of heterogeneous infrastructures. In this context, IoT technologies are able to suggest innovative solutions to traditional problems of cities, such as the perceived level of security of citizens [4]. Focusing on the building assets, the construction sector industry has only recently fully acknowledged the advantages of digitalization. The first step in this process is the use of Building Information Modeling (BIM) [5] over the entire life cycle of the building, not just during the construction phase. Such an approach often completely changes the way buildings are used and treated, implying, for example, a pay to use approach [6]. The digitilization of the design, service and management phases of buildings is just the first step towards a data-driven approach. The need for building real-time data involves a large deployment of sensors [7][8], capable of collecting plant and infrastructure information and combining it with the rest of available data in BIM [9]. An extensive availability of data on buildings opens the way for creative solutions focused on Artificial Intelligence (AI) [10], for example, able to recognize the status of the building (i.e. predictive maintenance), its energy efficiency [11], the best use of renewable resources [12][13], and more. The use of massive data generated by sensors to feed AI algorithms able to automatically infer knowledge about the building and the needs of users is often referred in literature as Cognitive Building, a step beyond the conventional definition of building automation. The building itself is capable of self-defining its actions in order to maximize the tradeoff between energy efficiency and user comfort without human interaction. In addition, in the near future, the buildings must collaborate to improve the sustainability of the whole city: the collaborative neighborhood. Currently, to the knowledge of Authors, this approach has been applied only to experimental buildings [19], but an application on large scale has not yet been investigated.

The goal of this research work is to offer an approach to be extensively pursued during the renovation of buildings, to transform them by adding cognitive capabilities. Several countries are funding renovation programs to increase the energy efficiency of existing buildings. Such upgrades usually concentrate on replacing existing window units with more effective ones, installing external/internal thermal insulation coating, and upgrading existing electric and hydraulic plants. The ELISIR initiative, sponsored by Lombardy Region, Italy, aims to digitize the entire supply chain of the construction industry, from the building elements supplier, via the construction company to the final maintenance companies. Data is the link that connects each part of the supply chain: from generation to its elaboration. The concept behind the project is to incorporate "knowledge" into building elements that are often used during renovation: window units, hydraulic connection, electrical components, thermal and seismic coating. Upon installed, these elements continue to track the renovated building via the integrated sensors and, in some cases, can actuate command for maximizing the energy

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efficiency. In this way the costs of installing separate sensors and actuators can be reduced. The data generated by the integrated sensors are pushed to and processed through a cognitive layer [14], which automatically infer information about the state of the building and the behaviors and needs of the users to optimize the actions of the entire building in terms of energy efficiency and comfort. In particular, the papers focuses on the issues of the integration of these smart building objects by means of IoT solutions with the cognitive layer used to classify the users' behavior.

II. Cognitive Renovation: A Definition and Application

A. Cognitive Building

The cognitive building relies on cognitive computing [15], which is part of a complete system architecture that allows building management through data collection and processing. Data analysis makes it possible to improve management efficiency by automating the decision-making process. In addition, the improved use of building spaces and the personalized control of indoor conditions contribute to an increase in User eXperience (UX) while the building delivers a customized service. The building is transformed into a responsive environment that can adjust its indoor spaces according to changing user requests and desires, through a privacy-safe, personalized and real-time check. In the future, the business models of this innovative concept could disrupt traditional approaches, and key innovative revenues could be recorded. Data will be used to set modulation, scheduled or predictive maintenance, on-demand services that can complete and enhance process optimization. Machine-readable data includes energy consumption, water use, electricity for lighting, indoor environmental quality (IEQ), occupancy rate, people streams, maintenance sequences, Enterprise Resource Planning (ERP) systems, lease agreements and commercial information, IT equipment, communication setup, security and emergency coordination plans and the Building Management System (BMS) [16]. Cognitive management [17] is working on the establishment of a combined system that manages and assembles information in order to create a configuration capable of monitoring and controlling the specific purposes of the optimized processes of a given building. The information model is therefore the digital foundation that links, categorizes and foresees information by communicating [18] with simulation environments that are used for specific in-depth investigations, such as energy and structural analyses. The cognitive concept involves the realization of a building that can extract from user preferences and lifestyle a set of adjustments to be introduced in day-to-day management and can cooperate with sensors and actuators to make these adjustments. In addition, the services that can be provided to users on the basis of their preferences and habits will add value to life in and around the building in the connected environment. The objective of the Cognitive Building is to minimize energy consumption and, in the meantime, to enhance the comfort of users through a combined collaboration between the human and the asset (advanced man to the machine relationship). Increased indoor comfort conditions are not the only benefits that the building can deliver, as well-being and quality of life are a combination of physical satisfaction and psychological security, safety and entertainment. Typically, large public buildings have high energy consumption associated with the Heating, Ventilation and Air Conditioning (HVAC) needs provided by non-monitored systems and controls. In the context of the Cognitive Building approach, the static control of the average occupancy rate should be exceeded and the Energy Management System (EMS) plays an important role in reducing energy and increasing comfort [19]. The main strategy implemented by the EMS is based on the variable occupancy schedule and the percentages given by the predictive models that the user's habits have learned through data collection. Real-time Indoor Air Quality (IAQ) data that the IoT network [20] can provide enables HVAC to be modulated when an updated system is installed and improved indoor environmental quality can be achieved with the greatest satisfaction of the occupants.

B. ELISIR Project

The project ELISIR - Energy, LIfe styled & Seismic Innovation for Regenerated buildings [21] was funded the Lombardy Region under the Smart Living grant. The project partners covers the entire construction sector supply chain, from the producer of building components up to system integrators: University of Brescia, Politecnico di Milano, ESEB, Schneider Electric, Valsir, Harley & Dikkinson, Gexcel, Assini Costruzione, Deldossi, Delta Phoenix and Italserramenti. The project focused in depth on urban reconstruction and, in particular, building renovation, carrying out seismic and energy audits in the process of assessing and identifying optimal intervention, through standardized procedures and intervention monitoring systems with specific attention to pre-and post-intervention phases. The project's sustainability principle is the idea of coordinating a supply chain for the construction industry that will assess the quality of the transformed building at the level of health and well-being facilities, which will boost the housing standard that will interact directly with the occupant. This method identified the central importance of the user in the life-cycle of the (regenerated) work by inserting the data produced by the construction into an information flow that enables, the ability to identify informed decision-making processes assisted by the data used and processed by the AI during all phases of the process. Some choices may be semi-automated in this way, whereas other non-directly computable decision-making nodes may be evaluated for indicators derived from the analyzes themselves. Automation of computable processes optimizes the phases of service and decision-making by enabling an informed and cognitive framework with respect to user-introduced variables and project requirements. As a consequence, the project's priorities were: security; productivity and customization, assisted by the digitization, sensing and monitoring of building processes. However, the solution specifically focused on customer needs without making interactions between users and the internal condition control systems of the building more complicated. The potential of informative modeling allows the linking of a set of incoming data (Data obtained from existing structures, individual user needs, legislative enforcement criteria, performance criteria on voluntary software, etc.) with outgoing data (deviations from the quality thresholds, actual results, reduction of the gap between expectations and implementation, timing of the execution, control of the data collected). The added benefit of the program resides in the potential of collecting vast volumes of data during the various phases of buildings and urban renovation, both from sensors and social networks, in order to be able to detect in real time patterns in the performance of buildings and the behavior of their inhabitants. Smart building elements have been designed and realized to make easier, and cheap, the adoption of a cognitive solution during the renovation phase.

III. The Proposed Approach

A. Building Innovations of ELISIR project

The fundamental assumption underlying the ELISIR project refers to the production of large and heterogeneous data (Big Data), largely provided by the digitized design and execution processes and the sensors, which, suitably processed in terms of machine learning, allow, also thanks to self-learning processes, to semi-automate and improve the performance of the regenerated buildings. The sensor system that will be deployed, in addition to multi-functionality features, or integration of capture and actuation devices, has both a "widespread" and a "punctual" value, referring, for example, to the design of hydraulic or shading devices specifically sensorized in order to optimize their useful life and to provide for their replacement in a predictive way, transferring the costs, for example, to insurance companies. Three product innovations have been developed during the project and become precise, but not occasional, examples of systemic intervention: the high-performance plaster, the smart hydraulic manifold and the smart window frame. These elements invest the asset during its life cycle in a decisive way to increase durability, efficiency and management optimization. The first element, the *high performance plaster*, allows in the redevelopment of the building to increase the seismic performance of the construction by reinforcing the existing envelope and the partitions in and out of the floor. The property extends and improves its useful life with a maintenance investment that, however, generates quality and energy and social savings. The second element, the *smart hydraulic manifold*, becomes a sensorized and connected object, capable of evaluating water consumption (both in loading and unloading) through measurement systems that control the optimal operating parameters of the system (water consumption, leaks, malfunctioning problems) in order to promote conscious and sustainable behavior, also in terms of circular economy, and introduce the theme of predictive maintenance that does not generate additional costs resulting from emergency situations, with social, economic and environmental benefits, as well as insurance. This element is part of the maintenance section of the construction life cycle, identifying an optimization of costs at Facility Management level. The third element, the *smart window*, becomes a sensor and thermostat in the environmental conditions information system in order to manage the specific conditions of the individual rooms in an optimized way. The smart window proposes a distributed detection system in opposition to the traditional one, that usually takes place in a single point, and is not able to identify of all the energy flows required by the management and decision-making process (energy input, environmental pollutants, ventilation, humidity, temperature) for the setting of internal conditions.

From the communication of the conditions and the subsequent processing of data through machine learning, it is possible to infer predictive logics of adaptation and environmental compliance of the envelope systems that allow to reduce the plant engineering intervention, thus resulting in energy savings during the management phase (Operation & Maintenance). The proposed product innovations become icons of the entire supply chain.

B. The IoT infrastructures of ELISIR project

The design of sensorized building elements, and their adoption during the renovation of existing plants, requires a communication infrastructure able to collect the data from the integrated sensors and to transfer them to the layers responsible for their process. Since the main target of ELISIR project is a massive digitalization of the entire supply chain of construction industry, the communication system should be able to integrate heterogeneous devices, produced by different vendors, compatible with existing solutions and easily scalable. The IoT paradigm represents the obvious response to these requirements. Fig. 1 shows an example of architecture adopted for interfacing smart devices installed during the renovation. While the connection of building components at the field level can take the advantages of existing fieldbuses, such as KONNEX (KNX), which provide standard and future proof solutions, the connection with the cognitive layer necessarily requires the use of IoT protocols (e.g. HTTP webservices), in order to make easy the integration of heterogeneous solutions. In any case, it is always possible the direct data transmission from the sensors toward the cognitive layer. However, the use of edge computing has several benefits with the respect to a purely cloud approach: reduction of data traffic, fastest response, reliability in case of unstable connection, and many more. In the case of ELISIR project, a traditional home automation controller has been configured to interact with a remote intelligence. The local controller acquires the data from the smart elements installed in the building. As shown in Fig. 1, each of the installed devices can monitor more than a single parameters, with different sampling policy (e.g. event-based, periodic), which can be configured through the communication links. The local controller locally stores the data and applies control rules defined by the installer or by the user. Such an architecture looks similar to a traditional building automation architecture, thus simplifying the adoption from the installer. The local controller interact, using HTTP RESTFull Webservice with remote servers, which extends the capabilities of the local controller. In particular, the remote servers (cognitive cloud) are able to infer, using the information generated by the sensors and partially processed by the local controller, the best control which optimize the tradeoff between the user needs and the energy efficiency of the building. The rules defined by the cognitive cloud are sent to the local controller. Off-the-shelf controllers already made available remote services (Vendor Cloud), but typically it is limited to offer user interface for data visualization and controller configuration.

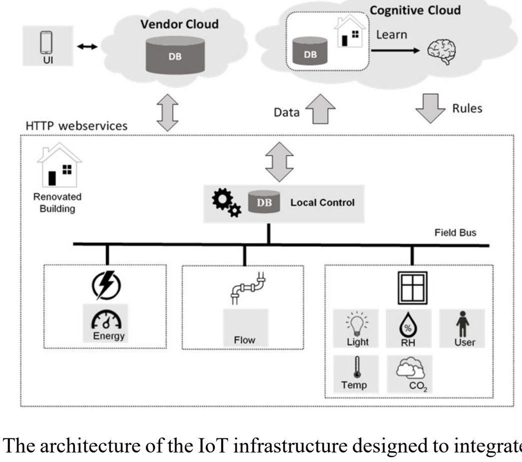

Fig. 1. The architecture of the IoT infrastructure designed to integrate smart building components.

IV. THE ELISIR TEST-CASE

Prototypes of the ELISIR installations has been engineered with the collaboration of project partners, using Schneider Electric's technologies for home automation. During initial phases, have been decided to use technologies with open communication protocols to ensure interoperability with different typologies of home automation systems. It has been selected the KONNEX (KNX) protocol [22], market leader for wired home automation open protocols.

During the ELISIR project, two innovation technologies have been implemented and tested: a smart water manifold and a smart window. Both the technologies have been connected to the central KNX controller Wiser for KNX [23]. This allow to create a house with a complete set of automation technologies (natural and artificial lights, Heating Ventilation and Air Conditioning (HVAC), access control, security, energy monitoring, weather monitoring, etc.) and include also the ELISIR smart objects. The main characteristics of the controller are summarized in TABLE I. Fig. 2 shows the test bench realized to testing the communication between the local controller and the ELISIR systems.

TABLE I. THE MAIN CHARACTERISTICS OF THE LOCAL CONTROLLER USED DURING THE TESTING PHASE.

Device	Wiser For KNX
Product ID	LSS100100
Features	Logic Controller for home automation solutions.
Field communication protocols supported	KNX, Modbus, BACnet and IP
High level communication protocols supported	Rest API, FTP

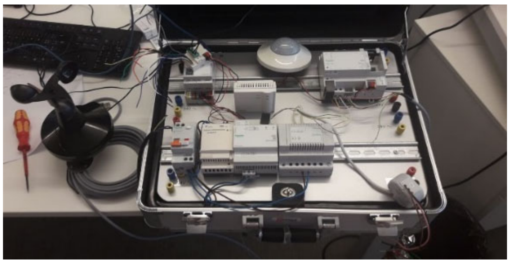

Fig. 2. Test Bench of communication between the ELISIR system technologies and the Wiser for KNX.

The smart manifold technology is based on a series of water meters provided by a third-party company (the main characteristics are summarized in Table II), which emits a number of pulses based on the amount of water passing through the pipe. This water meters are therefore connected to a KNX pulse counter which records home many pulses are sent. Meters are positioned both at the entrance of the water manifold and on each water stream, ensuring that can easily be identified if/where there is a leakage. The experimental set-up used to validated the feasibility of this approach and its integration with the cognitive layer is shown in Fig. 3. The user interface used to monitor the data generated by smart manifold is shown in Fig. 4. Through this interface it is possible to monitor the data generated by the sensors and set-up alarms when the values exceed a threshold, defined by the user.

TABLE II. THE MAIN CHARACTERISTICS OF SENSORS INTEGRATED IN THE SMART MANIFOLD.

Device	Product ID	Features	Connection
Inwall 6 In/2 Led Out module KNX	IO62D01KNX	6 DI, 2 LEDs outputs	KNX

Fig. 3. Test set for the smart manifold. A: Pump; B: Sensor for monitoring of general water supply; C: Valve to simulate water leakage; D: Manifold 1 hot water; E: Manifold 2 cold water; F: Mixing valve; G: Sensor for monitoring of hot water; H: Sensor for monitoring of cold water; I: Wiser for KNX; L: Water tank.

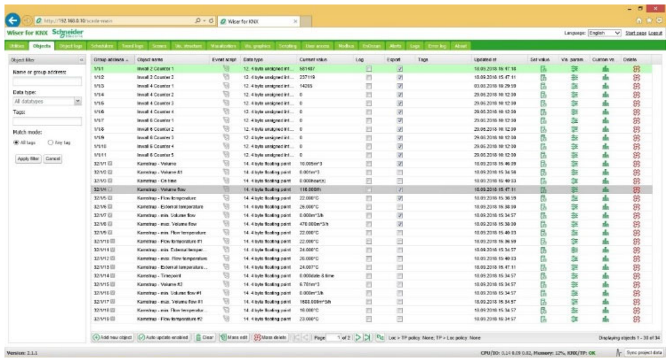

Fig. 4. Monitoring interface for the smart manifold.

Engineering of the smart window was carried out together with ELISIR partners to ensure proper monitoring of indoor/outdoor environmental condition in a very precise way. For example, the temperature is monitored at different heights, to ensure the value is correct even in stratified environments. Other than the temperatures, are monitored the total amount of CO_2, humidity, lux level and presence. The position of the sensors in the window frame is shown Fig. 5.

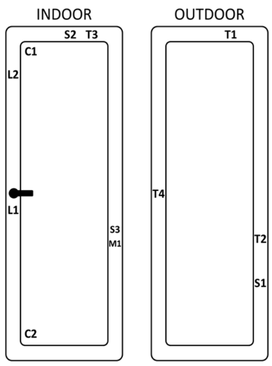

Fig. 5. The integration of sensors in the smart window. Tx: Temperature probe; Cx: Window contact sensor; Lx: LEDs; M1: KNX acquisition module (for Tx, Cx and Lx); S1: Illuminance sensor outdoor; S2: Illuminance sensor indoor; S3: Sensor humidity and CO2.

The main characteristics of each sensors are summarized in Table III. Based on these measurements, the window can control the blinds or turn on/off a led to advice the user to open the window when air quality is low (in case of a motorized window, it can be opened autonomously). The test and calibration of the window has been carried out with two windows installed in two offices of Politecnico di Milano, Milan, Italy. The final prototype (Fig. 6 shows the prototype during the final stage of production), installed in ELISIR demonstrator, is a French window with wooden frame.

TABLE III. THE MAIN CHARACTERISTICS OF SENSORS INTEGRATED IN THE SMART WINDOW.

Device	Product ID	Features	Conn.
Temperature probe	TS01A01ACC	NTC resistance tolerance: ± 3% Measure range: -20°C / 100°C	Analog sensor
Window contact sensor	PPCMACI00500	Magnetic contact sensor, normally closed	Digital contact
Inwall 8 Input / 4 Led Output Module	AD84A02KNX	Digital inputs to interface free potential contacts; 4 analog / digital inputs for free potential contacts or temperature sensors and 4 led outputs	KNX
KNX brightness and temperature sensor	MTN663991	Temperature: -25 ... +55 °C (±5% or ±1°C) Illuminance: 1 ... 100.000 lux (±20% or ±5 lux)	KNX
KNX ARGUS Presence 180/2.20 m flush-mounted	MTN630444	Temperature: -25 ... +55 °C (±5% or ±1°C) Illuminance: 10 ... 2.000 lux	KNX
KNX CO2, humidity and temperature sensor AP	MTN6005-0001	CO2: 300 – 9999 ppm Temperature: 0 ... +40 °C Humidity: linear 20% ... 100%	KNX

Fig. 6. Window prototype with inserted sensors.

V. RESULTS

The data generated by the smart window units is used by the cognitive layer to infer a number of information about the comfort conditions of each room and the behavior of the users. Each window unit is equipped with sensors for indoor and outdoor conditions monitoring. Two of the prototype smart window units have been installed in two offices of the Politecnico of Milan to monitor the comfort conditions. The smart windows were connected to the cognitive layer through the Schneider Electric controller. The indoor and outdoor conditions have been logged continuously for more than one year to collect training information for cognitive layer. As an example, Fig. 7 shows the data monitored by one of the window during the period from the 10 to 16 June 2019 to define the indoor comfort. The parameters logged from the window are: temperature, relative humidity and CO_2 concentration. While the temperature and the humidity trends follow, approximately, the different time of the day, the CO_2 concentration is affected by room occupancy and by the number of air changes. In order to customize the behavior of the HVAC plant with user' preference, the smart window is equipped with sensors to monitor the user' behavior. Fig. 8 shows, respectively, the state of the contacts of the window (from which is possible to infer the opening state) and the presence of person in the office in the period from the 10 to 16 June 2019. The smart window is used also to monitor the quality of lighting system, extremely important in working environment. As an example, the level of indoor and outdoor illuminance, monitored by the installed window during the period from 10 to 16 June 2019 is shown in Fig. 9. The opening and shading operations can be performed autonomously by the local controller, using static rules (based on international regulative EN16798-1), or which are defined by the cognitive layer on the basis of user' needs inferred by the sensor data using machine learning algorithm (based on Decision Tree algorithm [14]). For example, a large number of window openings under specific indoor conditions (e.g. the 15th of June in Fig. 8), could suggest the static rules defined on the base of EN16798-1 are not able to satisfy the user' comfort.

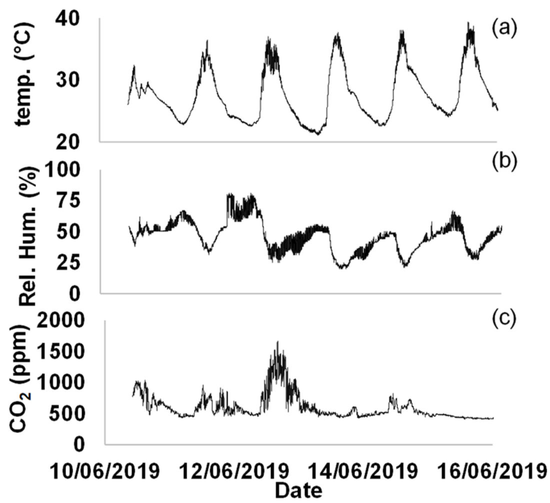

Fig. 7. Sensors installed on the window unit to infer information about indoor comfort. Data collected in the week from 10 June 2019 to 16 June 2019. (a) indoor temperature; (b) relative humidity; (c) CO_2 concentration.

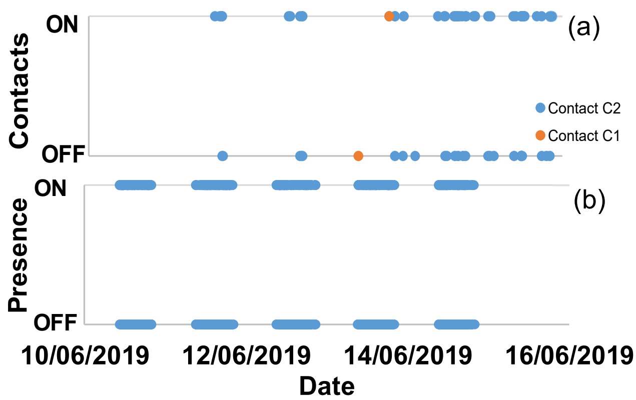

Fig. 8. Sensors installed on the window unit to infer information about users' behavior. Data collected in the week from 10 June 2019 to 16 June 2019. (a) The state of the window contacts; (b) people presence.

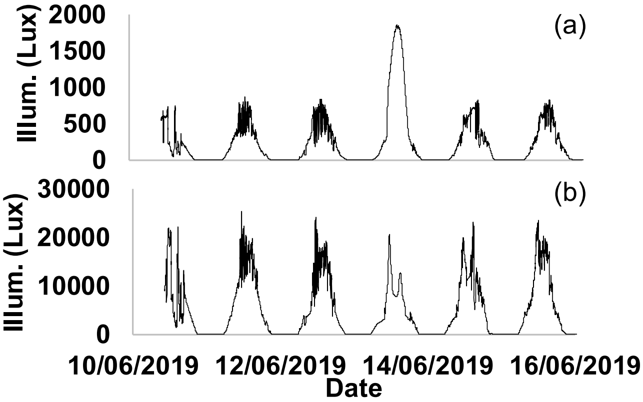

Fig. 9. Sensors installed on the window unit to infer information about illumination. Data collected in the week from 10 June 2019 to 16 June 2019. (a) Indoor illuminance; (b) Outdoor illuminance.

VI. CONCLUSIONS

The adoption of the IoT paradigm in the construction sector, in comparison to other sectors, is still at the beginning. The study explored the use of cognitive-based approaches during the renovation of buildings. The concept for this strategy is to design building components, used in the renovation process, with integrate sensing and connectivity capabilities. The components on which the ELISIR project focused were window units, thermal and seismic insulation coating, hydraulic manifold and electric plant. Knowledge created by these components is essential for the functioning and management of buildings during their life cycle. IoT protocols have been used to interconnect the smart building elements used during the renovation with a cognitive layer, responsible for the analysis of the generated data. Such an architecture is able to integrate also legacy building automation systems. During the projects, prototypes of smart window units and smart manifold has been designed, realized, and finally installed during the renovation of an existing building. The prototypes of elements have been integrated into a cognitive infrastructure and the validity of the proposed approach has been tested during renovation of a real building.

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