Lighting control and monitoring for energy efficiency: a case study focused on the interoperability of building management systems

Published Version:
Lighting control and monitoring for energy efficiency: a case study focused on the interoperability of building management systems / PELLEGRINO, Anna; LO VERSO, VALERIO ROBERTO MARIA; BLASO, LAURA; ACQUAVIVA, ANDREA; PATTI, EDOARDO; OSELLO, Anna. - In: IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS. - ISSN 0093-9994. - STAMPA. - 52:3(2016), pp. 7401012.2627-7401012.2637. [10.1109/TIA.2016.2526969]

This version is available at: https://hdl.handle.net/11585/818306 since: 2021-04-08

Published:

DOI: http://doi.org/10.1109/TIA.2016.2526969

*A. Pellegrino, V. R. M. Lo Verso, L. Blaso, A. Acquaviva, E. Patti and A. Osello, "**Lighting Control and Monitoring for Energy Efficiency: A Case Study Focused on the Interoperability of Building Management Systems**" in IEEE Transactions on Industry Applications, vol. 52, no. 3, pp. 2627-2637, May-June 2016*

Lighting Control and Monitoring for Energy Efficiency: A Case Study Focused on the Interoperability of Building Management Systems

Anna Pellegrino, Valerio R. M. Lo Verso, Laura Blaso, Andrea Acquaviva, Edoardo Patti, and Anna Osello

***Abstract*—This paper presents some results of a project that has been aimed at developing an event-driven user-centric middleware for the monitoring and management of energy consumption in already existing public buildings. One of the strengths of the designed system is that it allows an easy integration of heterogeneous technologies and their hardware-independent interoperability. This is a feature of great importance for existing buildings, where already existing controls could be integrated with new technologies to enhance the energy efficiency of a building. The functionality of the system has been tested in a number of representative spaces of already existing public buildings, where the already installed HVAC and lighting services have been equipped with monitoring and actuating systems designed and implemented using commercial off-the-shelf wired and wireless devices. This paper focuses on the energy aspects, which have been obtained by applying the designed system to monitor and control the electric lighting fixtures of different office spaces. The outcomes obtained from the monitored data have shown some significant differences from the expected and previously estimated energy saving results, and this paper offers some possible explanations. Some criticalities, in part related to the characteristics of the commercial off-the-shelf adopted devices and in part to the difficulties encountered in monitoring and analyzing the huge number of recorded data, are outlined.**

***Index Terms*—Energy efficiency, lighting-control strategies, lighting systems, long-term monitoring, middleware for embedded systems, smart buildings.**

I. INTRODUCTION

ENERGY saving and the development of information and communication technologies (ICT) are two of the main goals of European policies in the field of Research and Innovation to mitigate climate changes by reducing CO_2 emissions and to boost economic growth by accelerating the spread of innovative technological solutions [1], [2]. It is well known that the building sector is one of the main causes of the final global energy consumption: buildings consume nearly one-third of the final global energy and are responsible for about one-third of the total direct and indirect energy-related CO_2 emissions [3]. Several policy instruments have been devised to limit building pressure on the energy sector since the 1990s. Building energy codes were initially only focused on new residential buildings, but then they have progressively been expanded to include new nonresidential buildings and, more recently, to cover existing buildings when they undergo renovations or alterations [4]–[6].

At present, new building constructions represent a small volume in developed countries. Furthermore, more than half the current global building stock is still expected to be standing in 2050, and a building can generally last over 100 years. As a consequence, actions on existing private and public buildings have become a key instrument in achieving major reductions in energy consumption and CO_2 emissions [3]. Existing public buildings can consume large amounts of energy, due to a number of concurring factors, such as the presence of low-performance envelopes, old and scarcely efficient plant-engineering technologies, a lack of effective building management systems (BMS) or building automation and control (BCA), an irresponsible and unaware interaction of users toward the systems. A combined implementation of different intervention policies should be addressed and put into practice to achieve a smaller carbon footprint for existing buildings. One strategy, for instance, could concern building renovations through energy-conservation measures (ECMs), such as envelope optimization and the retrofitting of existing plants and appliances with new energy-efficient technologies and advanced controls (HVAC and lighting). Other strategies could rely on the use of renewable energies and on the integration of ICT solutions for the management of building energy use. Such ICT solutions could support Demand-Side Management in order to increase, through smart grids, the efficiency of building energy consumption. All these intervention policies have been regulated by the European Energy Efficiency Directive (EED 2012/27/EU) [7] and the related directives and national standards on the Energy Performance of Buildings (EPBD) [4], [5] as well as the Ecodesign and Energy Labeling of Energy-related Products (ErP) [8], [9].

Manuscript received August 26, 2015; revised December 19, 2015, January 7, 2016, and January 19, 2016; accepted January 19, 2016. Paper 2015-ILDC-0733.R3, presented at the 2015 IEEE International Conference on Environment and Electrical Engineering, Rome, Italy, June 10–13, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Industrial Lighting and Display Committee of the IEEE Industry Applications Society. This work was supported by the FP7 SEEMPubS research projects.

A. Pellegrino, V. R. M. Lo Verso, and L. Blaso are with the Department of Energy, Technology Energy Building Environment (TEBE) Research Group, Politecnico di Torino, 10129 Turin, Italy (e-mail: anna.pellegrino@polito.it; valerio.loverso@polito.it; laura.blaso@polito.it).

A. Acquaviva and E. Patti are with the Department of Control and Computer Engineering, Politecnico di Torino, 10129 Turin, Italy (e-mail: andrea.acquaviva@polito.it).

A. Osello is with the Department of Structural, Geotechnical, and Building Engineering, Politecnico di Torino, 10129 Turin, Italy (e-mail: anna.osello@polito.it).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TIA.2016.2526969

Nevertheless, several economic and noneconomic barriers are still encountered in the implementation of the measures needed to enhance the energy savings of existing buildings. These barriers are mainly concerned with aspects pertaining to higher initial costs, a lack of information, a lack of user awareness toward technologies and their potential energy savings, as well as to difficulties in the management operations. Among all the possible ECMs, upgrading system technologies—for instance, by replacing traditional lighting systems with new highly efficient LED solutions, or implementing and deploying ICT for building management and monitoring processes—could be a cost-effective solution for the renovation of existing buildings [10]–[12]. Solutions that are able to reduce the need for construction works are of particular value.

On this basis, a project named Smart Energy-Efficient Middleware for Public Spaces (SEEMPubS) has been designed and carried out, within the 7th European Research Framework Program, with the main objective of exploiting ICT-based monitoring and control systems to reduce energy usage and the CO_2 footprint in public buildings. Existing buildings are sometimes equipped with BMS for a coarse grain control of their systems, and new technologies, such as wireless sensors and actuator networks (WSAN), are nowadays available to achieve new systems or to extend existing ones. In both cases, the issue of interoperability should be addressed and solved so that these technologies can become widespread. The SEEMPubS project has led to the development of a middleware for embedded systems that is aimed at creating services and applications across heterogeneous devices in order to develop an energy-aware platform. This platform has been constructed to be open to future developments, in terms of further energy-efficiency measures or demand-side energy management through smart grids.

A number of representative spaces in some buildings belonging to the Politecnico di Torino, Italy, were chosen as case studies for demonstration purposes. The selected rooms are characterized by preexisting technical plants and in some cases also by existing BMS. The possibility of installing new BMS or implementing the existing ones has been explored within this project, and in particular, commercial off-the-shelf devices have been used to set up the new system or to integrate the existing BMS with new sensors and actuator networks. Both wired and wireless solutions were designed and tested.

In order to test the efficacy of the designed solutions, in terms of energy savings, the demonstration spaces were selected so as to have “pairs” of similar rooms: one room (reference room) was left with the existing plants and without a management system, while the system developed in the project was installed in the other room (test room). Each room was monitored throughout the whole project, and all the obtained data were transferred to a centralized database.

Within this frame, this paper presents the concept of the new Middleware that was developed and focuses on the approach and technical solutions used to plan the control of electric lighting. The results obtained from the monitoring activity during the October 2013–April 2014 period are discussed with respect to the use of lighting systems. A preliminary description of the study has been presented in [13].

II. MIDDLEWARE FOR AN EFFICIENT ENERGY MANAGEMENT OF BUILDINGS

The coexistence of several heterogeneous technologies and the lack of interoperability between them is a well-known issue. Devices such as OLE for process control unified architecture (OPC UA) try to solve these problems for classic BMS by providing abstraction layers. However, it should be considered that other technologies are also adopted in these buildings. A middleware approach has been adopted in the SEEMPubS project to handle the issues of interoperability and to be open toward future developments. The basis was the open-source LinkSmart middleware [14], which is a generic service-oriented middleware for Ubiquitous Computing. This was developed into a middleware for smart energy-efficient buildings. This middleware provides reusable and extensible components and concepts for reoccurring tasks and problems in future smart buildings, and the development implemented in the SEEMPubS project consists of a three-layered architecture with an *integration proxy layer*, a *service layer*, and an *application layer*.

A. Integration Proxy Layer

The infrastructure which has been developed relies upon an ICT infrastructure made up of heterogeneous monitoring and actuation devices, such as wireless sensor and actuator network (WSAN). In order to improve backward compatibility, the infrastructure also supports wired technologies that exploit different protocols (BACnet and LonWorks).

The Proxy is a concept that describes the integration of a specific technology in a LinkSmart application. A proxy acts as a bridge between the LinkSmart network and the underlying technology. It translates whatever kind of language the low-level technology speaks into LinkSmart Web Services, and the low-level technology can, therefore, be used transparently by any other LinkSmart component. This concept allows each low-level technology to be used transparently inside the LinkSmart network.

The integration proxy layer is the lowest layer of the developed Middleware for the efficient management of building energy. It integrates a specific technology with the middleware infrastructure by abstracting its functionalities and translating whatever kind of language the low-level device speaks into a web service. Exploiting this approach, interoperability between heterogeneous devices is enabled, and any other middleware component or application can use a specific technology transparently.

Different integration proxies have been developed to manage several types of WSANs (plugwise and ST Microelectronics Smart Plug commercial end node with ZigBee protocol; EnOcean protocol stack commercial end nodes). In addition, an integration proxy has been developed to allow interoperability with OPC UA, which incorporates all the functionalities provided by different standards, such as BACnet or LonWorks. Hence, backward compatibility with wired technologies is enabled and integrated in the new middleware. Because of the modularity achieved by means of the deployment of Integration

Proxies, the Middleware for the efficient management of building energy is suitable for integration and for extension of already existing BMS with new commercial off-the-shelf sensors and actuator networks.

B. *Service Layer*

Three main functionalities were implemented in the service layer of the Middleware.

1) Secure Communication: The middleware generates a peer-to-peer network in which web service calls are routed through the LinkSmart Network Manager, thus creating a simple object access protocol (SOAP) tunnel to the requested service endpoint. This concept allows direct communication among all the devices in the middleware network. Furthermore, the middleware provides components that enable message encryption and trust management [15].

2) Event-Based Communication: Building automation systems generally need to react to events that happen in a given building. Sensors publish events that lead to a certain reaction, such as switching lights on after an incoming motion event. The proposed middleware includes an Event Manager, which is a specific component that implements the published approach [16]. This allows loosely coupled event-based systems, which increase the scalability of the whole software infrastructure, to be developed. This mechanism is a key requirement for smart buildings, in which a high number of sensor events occur, to develop systems and applications.

3) Semantic Knowledge: The context and ontology frameworks are two complementary components, which together manage semantic knowledge about the application domain and the implemented system. This knowledge includes metadata on the sensors and actuators, but also on their relationship with the domain model objects, such as the appliances, buildings, and rooms. Moreover, the context framework provides a convenient entry point for application developers as it exposes a simple JavaScript Object Notation (JSON) API. Hence, developers can have access to any kind of information from a rich domain model.

C. *Application Layer*

The Application Layer is the highest layer in the proposed infrastructure. It is dedicated to developing distributed event-based user-centric applications in order to manage buildings and postprocess data obtained from the lower layers, thus providing a set of tools and a web service API. Interoperability between different devices is enabled at this level.

III. CASE STUDY

The new middleware, developed according to the LinkSmart system, has been adopted in various already existing buildings of the Politecnico di Torino. Both historical and contemporary buildings, constructed in different ages, were chosen to assess the potentials and drawbacks of using smart ICT-based systems in buildings with different features and constraints. This was done because one of the main goals of the SEEMPubS project was to define technologies that could be replicated in other already existing buildings in Europe with similar features. The buildings that were selected are located in three different sites in the city: 1) the historical campus building (The Valentino Castle), which dates back to the beginning of the 16th century; 2) the old campus site, which is still the main campus for the Engineering Faculties and was constructed in 1958; and 3) the modern campus site, which was created from a complex refurbishment of a former industrial area.

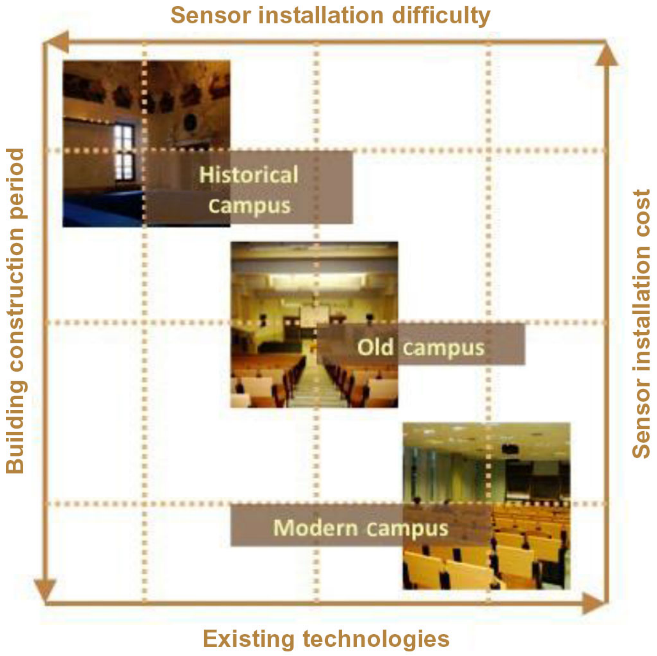

Fig. 1. Link between the construction age, costs, and difficulty in installing sensors for the different buildings considered as case studies.

Each building obviously required a specific solution for the installation of new sensors and controls for the HVAC and lighting systems [17]. The modern campus was already equipped with a basic BMS (Desigo by Siemens): new sensors and control rules were implemented to optimize energy use. New sensors were installed in the main campus in a wired system. The value of the paintings and stuccoes in the historical building made the installation of sensors a difficult task: in this case, each room required a specific solution, and only wireless sensors were considered.

The diagram in Fig. 1 shows the connection between the building construction period, the existing technologies, the sensor installation costs, and the difficulty in the installation of the sensors. A historical building is generally characterized by very few existing technologies as well as high construction work costs, related to the difficulty of installing the new technologies that are necessary to preserve any paintings, stuccos, or wood/marble floors. Instead, a new building can normally incorporate recent technologies: these can easily be integrated in the structure using false ceilings and floating floors. Moreover, there are also already existing buildings in which new technologies have to be improved significantly, and in this case, the costs and difficulties are closely related to the construction work that is required [18].

Some representative rooms were selected in the buildings in each campus in order to implement the BMS with the new sensor-network infrastructure. The rooms were chosen on the basis of the following criteria: ability to represent the Campus buildings and other Public buildings; energy-saving potential, according to the architectural, services, and occupancy characteristics. Both private and public spaces, such as classrooms, student offices, individual offices, and open plan offices, were selected.

The rooms were selected in pairs: one reference room (R), running with the present systems and with manual controls, and one similar test room (T), where automatic control and monitoring were implemented for the lighting, heating/cooling, and electrical appliances. In some rooms, the existing BMS was linked to the new middleware, while in other rooms, a new control and monitoring system, based on WSAN, was installed and managed by the middleware.

This paper focuses on the lighting control and monitoring that were carried out in two pairs of offices (Fig. 2).

1) The DITER offices, which are located in the historical building of the Valentino Castle. Both rooms are toplit by means of three skylights, but there are also two small west-/north-facing vertical windows, which provide a supplementary source of daylight. Two 2 × 35 W luminaires (T5 fluorescent lights) are installed in each room.
2) The ADMIN offices, which are located in a modern building of the main Politecnico campus. Both rooms have large west-facing windows. The R room is equipped with three ceiling-mounted 2 × 36 W luminaires (T8 fluorescent lamps). The T room has a different system, which consists of three suspended 2 × 35 W luminaires (T5 fluorescent lamps).

A. Lighting-Control Strategies

The recurrent lighting-control solutions for energy savings are time scheduling, daylight harvesting, occupancy control, or a combination of the previous three. Time scheduling allows the luminaires to be turned on and off automatically at scheduled times in order to avoid wasteful lighting outside working hours. Daylight harvesting entails the automatic adjustment of the light flux of luminaires (dimming) in order to maintain a predetermined illuminance in the room, taking the contribution of daylight into account. This strategy is especially effective in those rooms or buildings that are characterized by high daylight availability and all-day working hours. Occupancy control is based on the detection of the presence or absence of people in a space: lights are then switched on or off accordingly, in order to avoid energy waste produced by lights left on by users who have left the space. The control logic could involve either switching on and off (presence detection) or just off (absence detection). A lighting control based on presence detection would only be effective in spaces in which user absence is highly probable, or the users are not too motivated to pay attention to the use of light. Absence detection instead can be fruitfully used in all the spaces where people can forget to switch the lights off.

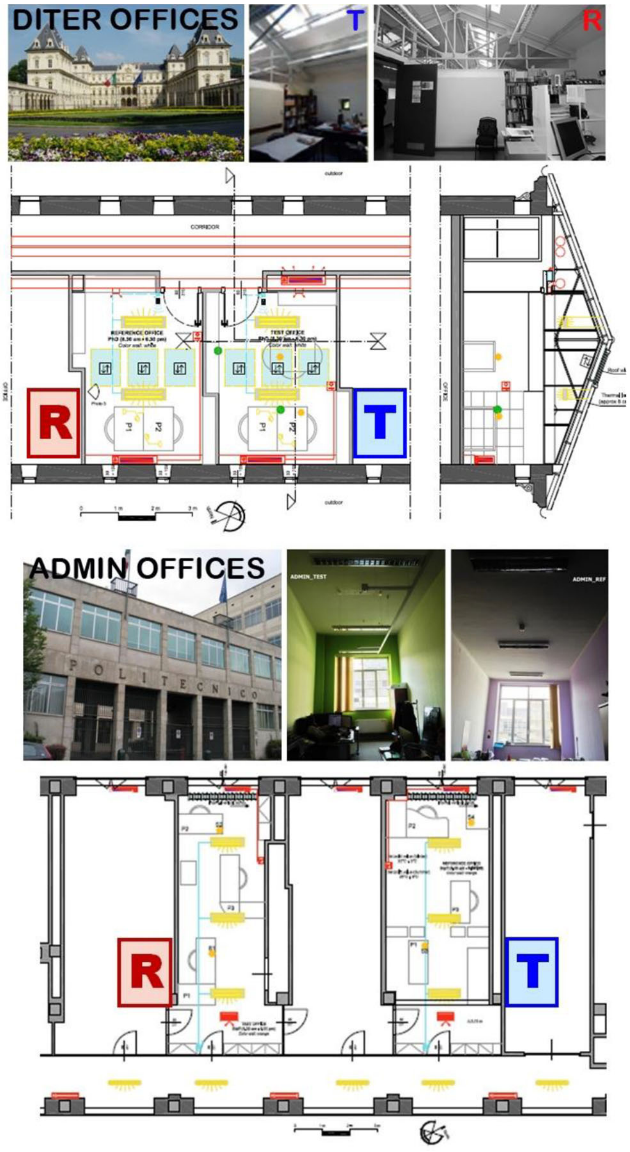

Fig. 2. Plans and views of the rooms used in the case study: DITER offices (top) and ADMIN offices (bottom).

Different lighting-control strategies were implemented in the T spaces, according to the features of the room [19]. Both daylight harvesting and occupancy control were implemented for spaces with high daylight availability and medium user-absence probability. The possibility of overriding the automatic control, via a manual command, was provided for all the different situations. The following strategies were implemented for the two pairs of rooms analyzed in detail in this paper (Fig. 3).

1) The *DITER offices*: in the R room, two 2 × 35 W luminaires are controlled manually through an on/off switch (the existing solution was maintained), while the same luminaires in the T room are controlled through a new WSAN, which includes a wireless switch, a photosensor, and an occupancy sensor. These are all connected to a wireless actuator, which communicates via Enocean

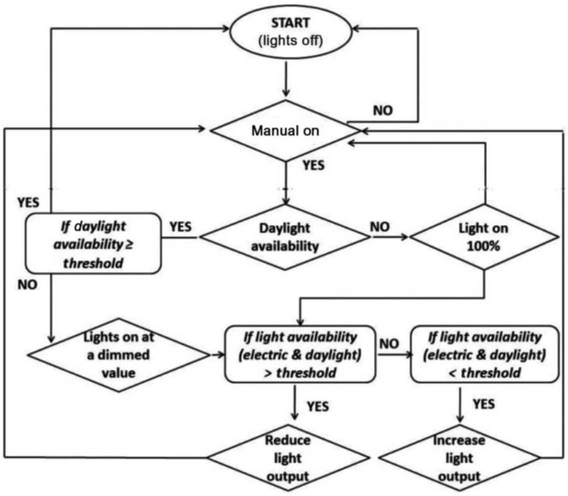

Fig. 3. Control logic implemented in the DITER and ADMIN test offices. In both cases, daylight harvesting and absence control were used because of the high annual daylight availability.

   protocol to the network access point. The following devices are used in the network:
   - a) Thermokon SR-MDS Solar sensors to control the lighting systems, to check the status of the system and to record the brightness and the occupancy;
   - b) an Eltako switch and an Eltako actuator;
   - c) an ST-Microlectronics smart-plug prototype to monitor the energy consumption (ZigBee) of both the luminaires and the actuator.
2) The *ADMIN offices*: three ceiling-mounted 2 × 36 W luminaires in the R room are controlled through a single on/off switch (preexistent solution), while three suspended 2 × 35 W luminaires are controlled in the T room through the already existing commercial BMS (Desigo by Siemens) with two wired photo-sensors and two occupancy sensors (one to control the area close to the windows and the other for the back part of the room). ST-Microlectronics prototypes of smart plugs were used to monitor the energy consumption. In this case, the luminaire consumption was only monitored by the energy meters. The Siemens Desigo system was integrated with the general middleware developed in the project.

As fluorescent light fittings have recently been installed in both the DITER and ADMIN spaces, it was decided not to replace them with LED systems. Furthermore, it should be recalled that the goal of the project was to demonstrate the effectiveness of the ICT-based management solution in improving the building energy efficiency rather than to estimate the savings achievable by retrofitting the lighting plants with new, more energy-efficient lamp technologies. Fig. 3 describes the control logic of the light strategy adopted in the ADMIN and DITER offices.

The use of electric lighting-control systems that can provide the required quantity of light to the right place and at the right time during operating hours is recognized as an ECM that can significantly reduce the consumption of electricity used for lighting [20]. A recent literature review, carried out within the international IEA Task 50 research on Advanced Lighting Solutions for Retrofitting Buildings [21], has outlined the saving results obtained in a large number of experimental or simulation studies focused on the implementation of electric lighting-control systems as a retrofitting measure to reduce energy use in buildings [22]. The saving potentials vary greatly, according to the context, the type of building, and the building features, such as daylight availability and occupancy profile. Furthermore, great differences have been found between simulation results and field studies: the former has overestimated the savings compared to the latter. The study has reported the following saving results with respect to the different possible lighting-control strategies: manual controls 23%–77%; time scheduling 12%; occupancy control 20%–93% (highly dependent on space occupancy and the time delay); daylight harvesting 10%–93%; combined daylight harvesting and occupancy 26%. According to another study [20], which has analyzed lighting energy savings from the literature—240 saving estimates from 88 papers and case studies, categorized as daylighting strategies, occupancy strategies, personal tuning, and institutional tuning—"the best estimates of average lighting energy-saving potential are 24% for occupancy, 28% for daylighting, 31% for personal tuning, 36% for institutional tuning, and 38% for multiple approaches." Again, it has been highlighted that "simulations significantly overestimate (by at least 10%) the average savings obtainable from daylighting in actual buildings."

A very wide range of saving potentials for each control strategy has also been confirmed in another extensive literature review carried out by a dedicated Technical Committee of the CIE Division 3 [23]. For instance, a large bandwidth of savings (20%–70%) has been pointed out for daylight harvesting strategies, while savings ranging from 28% to 60% have been reported for occupancy-sensing strategies.

In this project, the savings expected from the implementation of the proposed lighting-control strategies were first estimated through energy simulations and then evaluated by analyzing the data that were measured through the ICT-based management system.

IV. RESULTS

In this section, the main results concerning the energy consumption of lighting systems are summarized. The results of the energy simulation and of the monitoring have been separated, as have those of the two pairs of offices, DITER and ADMIN. The analysis period for the monitoring results was October 2013–April 2014, so as to take into account a period in which the use of electric lighting is more prevalent. In fact, it was observed that lights are almost always switched off during the operating hours in summer, due to the high daylight availability.

A. Results of the Energy Simulations Carried Out in the Early Stages of the Project

Lighting simulations were carried out in the early stages of the project in order to estimate and compare the electric lighting energy demand of the R and T rooms. The simulation results were then used to optimize the control strategy on the basis of the characteristics of the specific rooms.

Parametric 3-D models were imported into the Radiance and Daysim lighting simulation tools using the Ecotect software. Radiance and Daysim were used because of the interoperability between the software packages. Radiance was used to validate the models, while Daysim was adopted to estimate the energy demand for electric lighting and the savings that could be obtained with the proposed control strategies. Daysim allows an annual simulation to be run for a given site. Factors such as the specific dynamic climate conditions, the lighting power installed in the room, the type of lighting-control system, the occupancy profile, the lighting requirements (the target illuminance value), and the user behavior are taken into account in the simulation. An initial validation of the model has been conducted by comparing the output of the Radiance simulations (illuminance distribution) with the illuminance values measured in the corresponding rooms. After the validation phase, a set of simulations was run for each room using Daysim, in which the defined control strategies were introduced as input and the corresponding energy demand for lighting was calculated [in (kWh/m^{2}year)]. The simulations were initially carried out considering "mixed user behavior" (some users are active and some passive with respect to the use of electric lighting and blinds) and were then repeated considering only "active user behavior." The potential savings were estimated comparing the energy demand for the new control systems and the currently installed ones [24], [25].

The following savings were obtained from the simulations:

1) *the DITER offices:* 29% with mixed user behavior and 64% with active user behavior;
2) *the ADMIN offices:* 27% with mixed user behavior and 70% with active user behavior.

B. Results of the Monitoring Activity

1) DITER Offices: Fig. 4 and Table I show the main results (which were found) with regard to the lighting energy use in the T and R offices. Considering the whole analysis period, the T room showed higher absolute energy consumption for lighting than the R room [+47.5%, Fig. 4(a), continuous lines]. This unexpected performance appears to be due to the following combination of factors.

1) A high parasitic consumption, due to the stand-by power and sensor noise [Fig. 4(b) and (c)]. If this parasitic consumption was to be subtracted from the energy consumption of both the T and R rooms [a constant power of 4 W was subtracted for each time-step during which the lights are off, as this was found to be the value which occurred the most; see Fig. 6(a)], the absolute consumption for the two rooms would become comparable [+2.6% for the T room; see Fig. 4(a), dashed lines]. The power was calculated from the measured energies, for a resolution of the sensor of 4 Wh and an acquisition interval of 15 min (thus resulting in a power of 4 W per each 15 min).
2) The occupancy time in the T and R rooms is comparable (+6.4% for the T room for the whole analysis period), but the lights remain on for more hours in the T room (+58.5%).

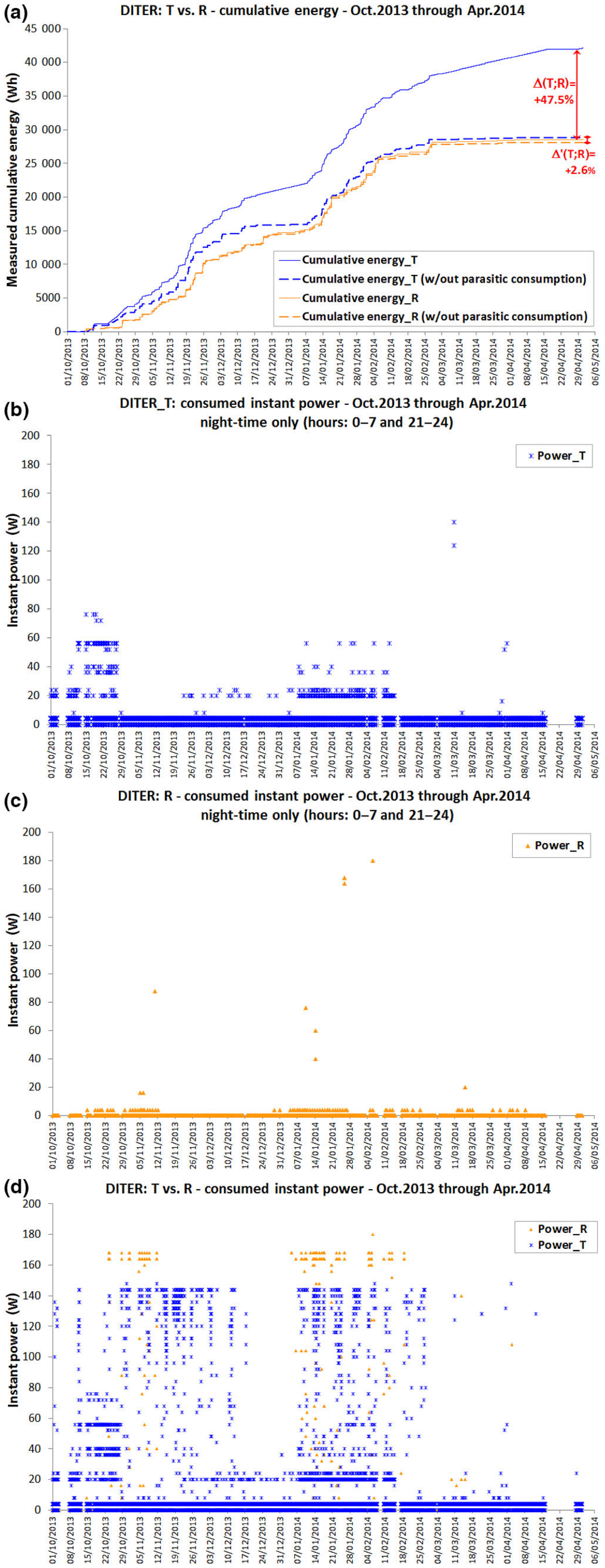

Fig. 4. Summary of the energy and power consumption for the DITER offices. F4:1

TABLE I
SUMMARY OF THE ENERGY RESULTS FOR THE DITER OFFICES

Analysis factor	*Δ(T;R)*^{a}
Total energy consumption	+47.5%
Total energy consumption (without parasitic consumption and sensor noise)	+2.6%
Number of occupancy hours	+6.4%
Number of hours with lights on	+58.5%
Total energy consumption (without sensor noise)/ number of occupancy hours	-4.8%
Total energy consumption (without sensor noise)/ number of hours with lights on	-36.1%

^{a}Calculated through the formula: $(T - R)/R$* 100.

3) During the periods when the lights are on in the T room, they are dimmed by the control system for 88.2% of the time, with a mean percent of dimming of 63.7%. Furthermore, the control system sets the luminaires at a maximum power, which is lower than the maximum value [Fig. 4(d)]. The control system seems to work effectively by dimming the light output in response to the natural environmental brightness.

It is worth stressing that this latter factor (dimming of the light output in the T room) is a positive aspect for the T room and should lead to a decrease in energy consumption, compared to the R room. Nevertheless, this positive performance is counterbalanced by the other previously described factors (sensor noise, stand-by power, occupancy profile, and hours during which the lights remain on). Among all these factors, the stand-by power and sensor noise play the most important roles on the final consumption. The energy consumed during the analysis period for each hour of lights on (without the sensor noise) was lower in the T room than in the R room (-36.1%), while the energy consumed for each hour of occupancy was similar for the two rooms (-4.8%). These data are more in line with the expected and simulated results.

2) ADMIN Offices: Fig. 5 and Table II show a summary of the results for the ADMIN T and R offices. Considering the whole analysis period, the T room showed a significantly lower energy consumption for lighting than the R office [-70.8%, Fig. 3(a), continuous line]. This performance, which was even better than could be expected, appears to be due to the following combination of factors.

1) The different characteristics of the lighting systems in the T and R rooms are as follows:
    a) the luminaires installed in the T room are newer and are suspended, which results in a better light flux Utilization Factor for the T room than for the R room;
    b) the illuminance over the work plane (E_{wp}) in the R room was 300 lx, while, in the T room, the performance requirements from the occupants were 500 lx for the desk close to the window (zone 2) and 300 lx for the desk at the back of the room (zone 1).
2) *The different behavior of the occupants:* The T room is occupied less than the R room (-22.2% for the whole heating period); consistently, lights are kept on for fewer hours (-26.6%).

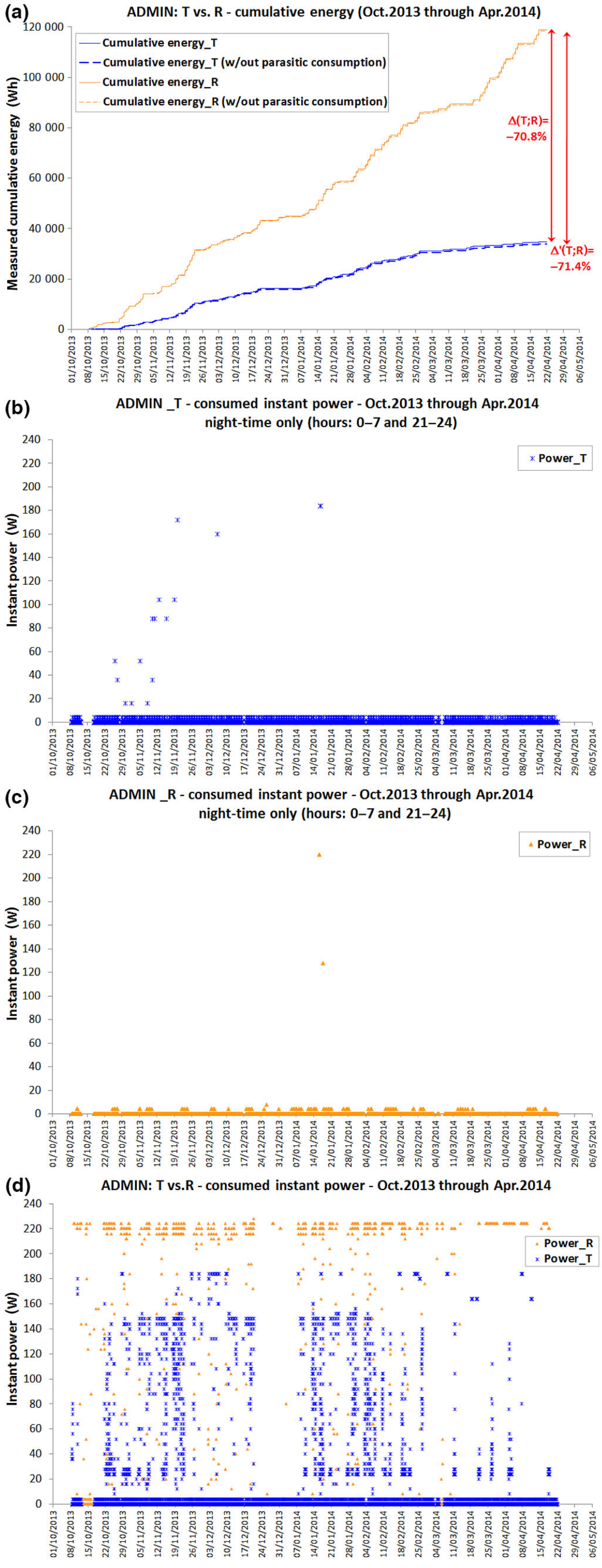

Fig. 5. Summary of the energy and power consumption for the ADMIN offices.

TABLE II
SUMMARY OF THE ENERGY RESULTS FOR THE ADMIN OFFICES

Analysis factor	*Δ(T;R)*[a]
Total energy consumption	-70.8%
Total energy consumption (without sensor noise)	-71.4%
Number of occupancy hours	-22.2%
Number of hours with lights on	-26.4%
Total energy consumption (without sensor noise) / number of occupancy hours	-64.3%
Total energy consumption (without sensor noise) / number of hours with lights on	-62.2%

[a] Calculated through the formula: $(T - R)/R$* 100.

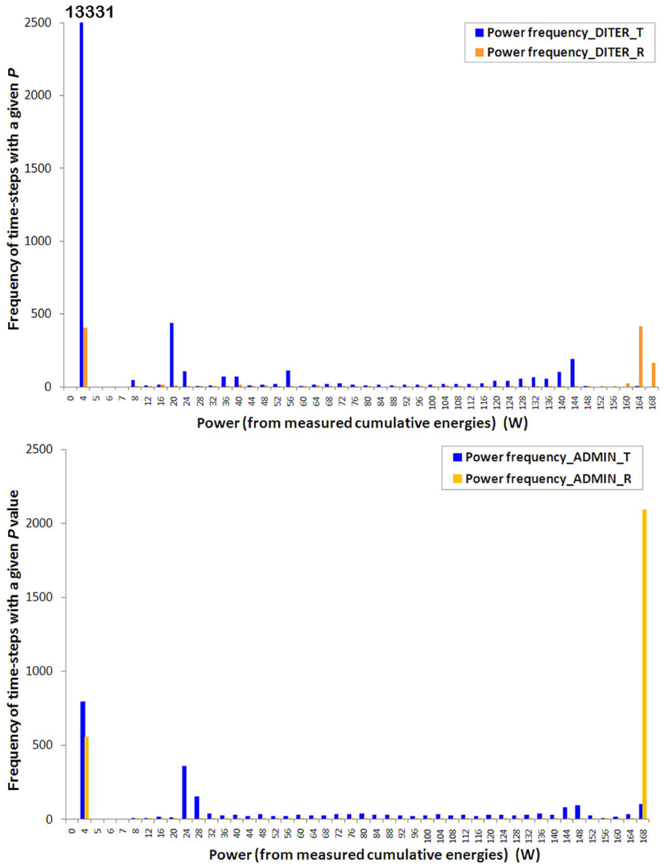

Fig. 6. Occurrence frequencies of the recorded power values in the DITER (top) and ADMIN (bottom) offices.

Furthermore, when the lights are on in the T room, they never reach the nominal maximum power, and they are dimmed by the photodimming control for 93.7% of the time [mean dimming = 40.6%, Fig. 5(d)]. The control system is therefore effective in dimming electric lights in response to the natural brightness.

A parasitic consumption, due to sensor noise, was also observed in the ADMIN offices, but this was found to have a limited impact on the energy consumption [Fig. 5(b) and (c)]. When the sensor noise was subtracted from the energy consumption in the T room [again, a constant power of 4 W was subtracted for each time-step during which the lights were off, as this was found to be the value which occurred the most; see Fig. 6(b)], the difference in the consumption for the T and R rooms was of the same magnitude [−71.4%, Fig. 5(a), dashed line].

On the whole, these results show that the control system in the T room (i.e., electric light management based on daylight levels and considering the absence of the occupants) led to rather remarkable energy savings. The global energy consumed (excluding the sensor noise) for each occupancy hour was found to be significantly lower in the T room than in the R room (−64.3%); the same applies if the energy consumption is expressed per number of hours with lights on (−62.2%). It should also be noted that the stand-by power of the sensors and actuators in the T room was not recorded by the ST smart plug as they were managed directly by the centralized Desigo system and could not be extrapolated from the overall data.

V. DISCUSSION AND CONCLUSION

The huge amount of data measured and managed in the SEEMPubS project has been used to analyze the impact of lighting-control strategies (photodimming and occupancy based), compared to simple manual on-off switches. The measured data were highly heterogeneous with regard to both the sensor type employed in the different rooms and to the different acquisition intervals recorded by each type of sensor (temperature, occupancy, brightness, and energy). All the data were "synchronized" to the same time interval (5 min) to allow a comparison to be made between the different datasets. One of the merits of the methodology presented in this paper is the "synchronization" algorithm, which allowed all the measured data to be aligned to the same time-steps.

On the other hand, some criticalities emerged from the data analysis and they need to be pointed out. Analyzing the results, a "performance gap" was found between the expected performance (based on the simulation results) and the actual performance observed in the real rooms. This was particularly evident for the DITER offices. The energy consumption of the test room was influenced to a great extent by the stand-by power of the actuators and lamp ballasts and by the sensor noise, as shown in Fig. 6, where the parasitic consumption is represented by the recurrent 4 W. This parasitic consumption represents more than 30% of the global energy consumed in the test room. This result is in line with what has been found in other researches [26], [27], but it also seems to have been influenced by the characteristics of the sensor, which was in fact designed to measure greater loads (not for a single office). Therefore, the minimum reading step is greater than the minimum power absorbed by the devices, which remain in stand-by throughout the whole 24 h. Furthermore, the sensor was a prototype and several false measurements (sensor noise) were recorded. The data recorded when the lights were off, particularly during the nighttime, in the rooms without stand-by loads, were considered as sensor noise (this is the case of both the R and T room in the ADMIN offices and of the R room in the DITER offices).

Furthermore, the data have shown that the control system in the T room actually dims the light output when the room is occupied [Fig. 4(d)], but the lights remain on for more hours (Table I). This could be ascribed to two aspects: a limited capacity of the photo-sensor in the T room to switch the lights off when there is sufficient daylight or a "low attitude" of the occupants of the R room to switch the lights on when there is insufficient daylight (with respect to the target illuminance used to set the dimming system in the T room). It has emerged, from an analysis of the monitored data, that both conditions could have occurred.

A "performance gap" was also found for the ADMIN offices, but to a lesser extent; in this case, energy savings were actually obtained, due to the photodimming and the implementation of occupancy sensors, but they appear to be higher than could be expected. This result is probably also due to the fact that the stand-by power of the sensors and actuators could not be recorded by the system that was implemented for the present project.

In general, it appears evident that the high number of variables that influence the final energy performance is hard to manage in the design stages, and large differences may be found between the expected and actual performance. One of the hardest variables to describe seems to be the occupants' behavior, in terms of actual occupancy profiles and attitude toward switching lights on and off. It is also worth noting that analyzing the energy performance, in terms of total energy consumption, may lead to results that are very different from those that are found when the absolute total energy consumption is "normalized," considering the number of actual monitored occupancy hours (which was adopted to overcome the problem of the quite different occupancy patterns in the T and R rooms) or considering the number of hours when lights were detected to be on (to account for the actual electric light use during the occupancy time). This was found to be particularly evident for the DITER offices: comparing the total energy consumption, in absolute terms, showed a higher consumption in the T room than in the R room ($+47.5\%$), while using the ratio of the consumption to the number of occupancy hours or the ratio of the consumption to the number of hours with lights on in the T room (after subtracting the parasitic power) shows a better performance than that of the R room (-4.8% and -36.1%, respectively).

This consideration becomes more evident if a disaggregated day-by-day analysis is carried out. As an example, Fig. 7 shows the data that were recorded for a single day (November 22): the profiles of occupancy, consumed power, and environmental brightness are plotted for both the T and R DITER rooms. The following results were obtained:

- hours of occupancy:	T: 5.58	R: 7.01
- hours with lights ON:	T: 4.83	R: 6.08
- hours with lights ON/occupancy:	T: 0.87	R: 0.87
- consumed energy (Wh):	T: 596.6	R: 987.6

These data show that, throughout the considered day, the occupancy profile and the duration time with the lights on are different for the T and R rooms, but when the hours with the lights on are compared to the hours during which the two offices were occupied, the result is the same (0.87), which makes the two rooms comparable. Under these conditions, the energy consumption was found to be lower in the T room (-38.1%) than in the R room. As a more general consideration, it is possible to state that although on one hand, the global consumption during the course of a year or throughout a season (heating or cooling) is an important metric for the energy manager of a facility; on the other hand, if the aim is to compare two different lighting-control technologies implemented in different rooms, different metrics could be more advantageous: for instance, the energy consumed per actual occupancy hour or the energy consumed per hour with lights on could be used for this purpose.

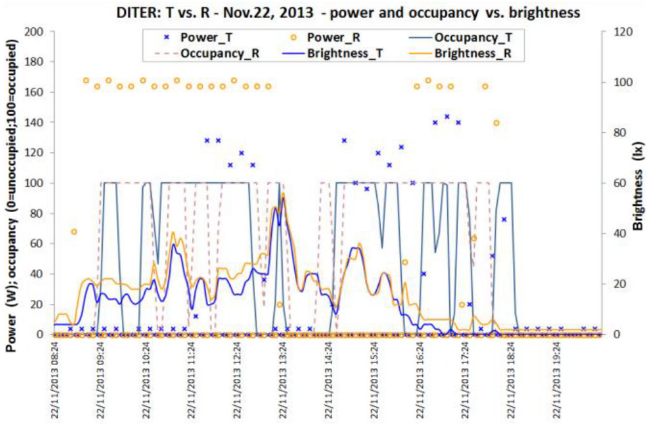

Fig. 7. Power, occupancy, and brightness profiles for a single day in the DITER offices.

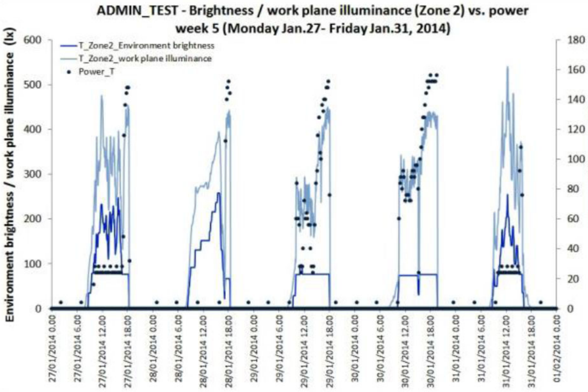

Fig. 8. ADMIN: example of the relationship between environment brightness E_{wp} and consumed power for the T room (back of the room).

Another criticality that was observed concerns the monitoring of the lighting amount on the working plane E_{wp} through the photosensor used to dim the lights. Owing to the features and position of the sensors (ceiling-mounted and suspended), the brightness data monitored in the four rooms were not always useful to verify the actual lighting condition over the work plane [28]. These sensors measured the environment brightness in the room, which was then converted into the corresponding E_{wp} value through a calibration process for each room. Fig. 8 shows the E_{wp} levels recorded by Gigahertz data loggers (which were used to calibrate the brightness sensor) compared to the ambient brightness measured by the SEEMPubS sensors. In the ADMIN offices, which are unilateral daylit spaces, the brightness responds to the variation in the daylighting levels (which hit the sensor more directly), but fails to correctly record the increase in horizontal illuminance when electric lights are switched on (which is measured indirectly).

In conclusion, the main results which have been obtained by comparing the energy consumption in the T and R rooms are as follows.

1) The measured energy is influenced by a parasitic power consumption, due to the stand-by power of the luminaires and to sensor noise. A somewhat similar behavior (increase in sensor noise during the night hours as the sensors falsely detected the presence of an individual when the room was actually empty) was also reported in a study by Gonzalez *et al.* [29]. In this case, and particularly for the DITER Test office, the parasitic consumption is also influenced to a great extent by the features of the sensor (larger minimum reading step than the actual stand-by power).
2) The energy performance of both the ADMIN and DITER offices observed in real rooms was influenced to a great extent by the occupants' behavior (especially concerning the attitude of individuals to switch lights on and to keep them on during the working hours). As a consequence, the consumption significantly differed from what was expected during the design stage (when all decisions were based on simulation results). This result is in line with what was observed in [30] and [31].
3) The choice of measuring the E_{wp} indirectly, by measuring the environment brightness through ceiling-mounted or suspended sensors, implied a complex calibration process. Installing illuminance sensors directly on the work plane seems to be a more reliable solution for future applications.

ACKNOWLEDGMENT

The authors would like to thank G. Carioni (Livinglab, Politecnico di Torino) for building the algorithm used to synchronize the recorded data.

REFERENCES

[1] Commission of the European Communities. (2009). *Commission Recommendation on mobilising Information and Communications Technologies to Facilitate the Transition to an Energy-Efficient, Low-Carbon Economy*, C(2009)7604 [Online]. Available: http://ec.europa.eu/information_society/activities/sustainable_growth/docs/recommendation_d_vista.pdf

Q2 [2] *ICT-03-2016:SSI—Smart System Integration* [Online]. Available: http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/5090-ict-03-2016.html

Q3 [3] International Energy Agency (IEA), *Transition to Sustainable Buildings. Strategies and Opportunities to 2050*. 2013.

[4] *Directive 2002/91/EC of the European Parliament on the Energy Performance of Building* [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32002L0091&from=EN

[5] *Directive 2010/31/EU, Recast of Energy Performance of Building* [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=URISERV:en0021&from=IT

[6] International Energy Agency (IEA), *Modernising Building Energy Codes to Secure Our Global Energy Future*. 2013.

[7] Energy Efficiency Directive 2012/27/EU.

[8] Ecodesign Directive 2009/125/EU, *Directive 2009/125/EC of the European Parliament and of the Council of 21/10/2009 Establishing a Framework for the Setting of Ecodesign Requirements for Energy-Related Products, Recast of Directive 2005/32/EC Amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council* [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/list_of_ecodesign_measures.pdf, accessed on Dec. 2015. Q4

[9] Directive 2010/30/EU of 19 May 2010 on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products.

[10] M. Magno, T. Polonelli, L. Benini, and E. Popovici, "A low cost, highly scalable wireless sensor network solution to achieve smart LED light control for green buildings," *IEEE Sensors J.*, vol. 15, no. 5, pp. 2963–2973, May 2015.

[11] E. Uken, G. Bevan, and R. Smith, "LED tube retrofits for fluorescent lighting in offices," in *Proc. 10th Ind. Commer. Use Energy Conf. (ICUE)*, 2013, pp. 1–4.

[12] T.-J. Park and S.-H. Hong, "Experimental case study of a BACnet-based lighting control system," *IEEE Trans. Autom. Sci. Eng.*, vol. 6, no. 2, pp. 322–333, Apr. 2009.

[13] A. Pellegrino, V. R. M. Lo Verso, L. Blaso, A. Acquaviva, E. Patti, and A. Osello, "Lighting control and monitoring for energy efficiency: A case study focused on the interoperability of building management systems," in *Proc. IEEE 15th Int. Conf. Environ. Elect. Eng. (EEEIC)*, Jun. 10–13, 2015, pp. 748–753.

[14] M. Eisenhauer, P. Rosengren, and P. Antolin, "A development platform for integrating wireless devices and sensors into ambient intelligence systems," in *Proc. 6th Annu. IEEE Commun. Soc. Conf. Sens. Mesh Ad Hoc Commun. Netw. Workshops (SECON Workshops '09)*, Jun. 2009, pp. 1–3.

[15] M. Hoffmann *et al.*, "Towards semantic resolution of security in ambient environments," in *Developing Ambient Intelligence*, 2008, pp. 13–22. Q5

[16] P. T. Eugster, P. A. Felber, R. Guerraoui, and A. M. Kermarrec, "The many faces of publish/subscribe," *ACM Comput. Surveys*, vol. 35, pp. 114–131, 2003.

[17] A. Acquaviva *et al.*, "From historical buildings to smart buildings via middleware and interoperability," in *Proc. Int. Conf. Comput. Civil Build. Eng. (ICCCBE2012)*, Jun. 27–29, 2012. Q6

[18] A. Acquaviva *et al.*, "Service oriented solution for interoperable networks in smart public spaces," in *Proc. Nat. AICA Smart Tech Smart Innov. La strada per costruire futuro*, Nov. 15–17, 2011.

[19] C. Aghemo *et al.*, "Management and monitoring of public buildings through ICT based systems: Control rules for energy saving with lighting and HVAC services," *Front. Archit. Res.*, vol. 2, pp. 147–161, 2013.

[20] A. Williams, B. Atkinson, K. Garbesi, E. Page, and F. Rubinstein, "Lighting controls in commercial buildings," *Leukos*, vol. 8, pp. 161–180, 2012.

[21] IEA Task 50, *Advanced Lighting Solution for Retrofitting Buildings* [Online]. Available: http://task50.iea-shc.org/

[22] M. C. Dubois *et al.*, "Retrofitting the electric lighting and daylighting systems to reduce energy use in buildings: A literature review," *Energy Res. J.*, vol. 6, pp. 25–41.

[23] CIE TC 3.49, *Decision Scheme for Lighting Controls for Tertiary Lighting in Buildings* [Online]. Available: http://div3.cie.co.at/?i_ca_id=573&pubid=349

[24] A. Acquaviva *et al.*, "Increasing energy efficiency in existing public buildings through the implementation of a Building Management System based on interoperable networks," in *Proc. 2nd Int. Conf. Build. Energy Environ. (COBEE)*, Boulder, CO, USA. Q7

[25] A. Osello *et al.*, "Energy saving in existing buildings by an intelligent use of interoperable ICTs," *Energy Effic.*, vol. 6, pp. 707–723, 2013.

[26] N. Gentile, T. Laike, and M. C. Dubois, "Lighting control system in peripheral offices rooms at high latitude: Measurements of electricity savings and users preferences," *Energy Procedia*, vol. 57, pp. 1987–1996, 2014.

[27] C. Aghemo, L. Blaso, and A. Pellegrino, "Building automation and control systems: A case study to evaluate the energy and environmental performances of a lighting control system in offices," *Autom. Constr.*, vol. 43, pp. 10–22, 2014.

[28] L. T. Doulos, A. Tsangrassoulis, and F. V. Topalis, "Optimizing the position and the field of view of photosensors in daylight responsive systems," in *Proc. 11th Lux Europa*, Istanbul, Turkey, Sep. 9–11, 2009.

[29] L. I. L. Gonzalez, U. Großekath, and O. Amft, "An intervention study on automated lighting control to save energy in open space offices," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun. Workshop*, San Louis, MO, USA, Mar. 23–25, 2015, pp. 317–322.

[30] G. Y. Yun, H. J. Kong, H. Kim, and J. T. Kim, “A field survey of visual comfort and lighting energy consumption in open plan offices,” *Energy Build.*, vol. 46, pp. 146–151, 2012.

[31] P. Correia da Silva, V. Leal, and M. Andersen, “Occupants interaction with electric lighting and shading systems in real single-occupied offices: Results from a monitoring campaign,” *Build. Environ.*, vol. 64, pp. 152–168, 2013.

Anna Pellegrino received the M.S. degree in architecture and the Ph.D. degree in energetics from the Politecnico di Torino, Turin, Italy.

She is an Associate Professor of Building Physics with the Politecnico di Torino. Since 1998, she has been carrying out her research activity in the Department of Energetics, Technology Energy Building Environment (TEBE) Group, Politecnico di Torino. Her research interests include different topics on lighting: from lighting and control technologies to applications and energy use, from lighting design to the issue of light and health, visual comfort and material damage, considering both daylighting and electric lighting.

Valerio R. M. Lo Verso received the M.S. degree in architecture and the Ph.D. degree in building physics from the Politecnico di Torino, Turin, Italy.

He is an Assistant Professor of Indoor Environment Physics with the Department of Energy, Politecnico di Torino. He has authored/coauthored over 70 international scientific papers. His research interests include daylighting/electric lighting for visual comfort and energy savings purposes through software simulations and field analyses; new materials for innovative façades. He was granted a Post-Doctoral position with the National Research Council, Ottawa, ON, Canada, on “daylighting for green buildings.”

Dr. Lo Verso is an Associate Editor of the *Journal of Daylighting*.

Laura Blaso received the M.S. degree in architecture and the Ph.D. degree in technological innovation for architecture and industrial design from the Politecnico di Torino, Turin, Italy, in 2003 and 2008, respectively.

She is a Researcher with the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA), Rome, Italy. Her research interests include various topics on lighting: from daylight to electric lighting, from visual comfort to energy saving, and from technologies to applications.

Dr. Blaso has been the Coordinator of the Italian Working Group “Energy performance of Buildings” UNI/CT023/GL10 of the Commission UNI/CT023 “Light and Lighting” since December 2015.

Andrea Acquaviva received the Ph.D. degree in electrical engineering from the University of Bologna, Bologna, Italy, in 2003.

He is an Associate Professor with the Politecnico di Torino, Turin, Italy. He was an Assistant Professor with the Università di Urbino, Urbino, Italy, and with the Università di Verona, Verona, Italy. Since 2008, he has been with the Department of Computer Engineering and Automation, Politecnico di Torino. He has authored or coauthored more than 150 scientific publications. His research interests include smart systems and cities, Internet of Things, parallel computing for distributed embedded systems, and bioinformatics.

Edoardo Patti received the B.Sc. degree in computer engineering from the University of Palermo, Palermo, Italy, and the M.Sc. degree in computer engineering from the Politecnico di Torino, Turin, Italy, in 2007 and 2010, respectively.

Since January 2011, he has been with the Department of Control and Computer Engineering, Politecnico di Torino, as a Ph.D. student first and then as a Postdoctoral Research Fellow. During the academic year 2014/2015, he was a Visiting Academic at the University of Manchester, Manchester, U.K. He is also involved in various European-funded projects focused on smart cities. His research interests include Internet of Things, smart systems and cities, distributed software architectures for smart environments, and software solutions for user awareness.

Anna Osello received the B.S. degree in building engineering from the Politecnico di Torino, Turin, Italy, and the Ph.D. degree in drawing and survey of buildings from the l’Università degli Studi la Sapienza, Rome, Italy, in 1992 and 1996, respectively.

Since 1999, she has been an Associate Professor of Drawing with the Politecnico di Torino, where she coordinates a laboratory denominated drawing to the future (http://www.drawingtothefuture.polito.it/) with the goal of carrying out theoretical and applied research on the issues of BIM and software interoperability. She is currently engaged in several research projects, including Smart Energy-Efficient Middleware for Public Spaces (SEEMPubS) and District Information Modeling and Management for Energy Reduction (DIMMER).

QUERIES

Q1: Please spell out “HVAC and OLE.”
Q2: Please provide name of author/organization and year of publication for Refs. [2], [4], and [5].
Q3: Please provide complete details for Refs. [3], [6], [7], and [9].
Q4: Please provide year of publication for Refs. [8], [21], [22], and [23].
Q5: Please provide publisher name and location for Ref. [15].
Q6: Please provide page range for Refs. [17], [18], and [28].
Q7: Please provide year of publication and page range for Ref. [24].
Q8: Please provide year of completion of the M.S. and Ph.D. degrees of the authors “Anna Pellegrino and Valerio R. M. Lo Verso.”
Q9: Please check and confirm whether the word “denominated” is correct at line number 904.
Q10: Please expand the term BIM in the biographies section.

Lighting Control and Monitoring for Energy Efficiency: A Case Study Focused on the Interoperability of Building Management Systems

Anna Pellegrino, Valerio R. M. Lo Verso, Laura Blaso, Andrea Acquaviva, Edoardo Patti, and Anna Osello

***Abstract*—This paper presents some results of a project that has been aimed at developing an event-driven user-centric middleware for the monitoring and management of energy consumption in already existing public buildings. One of the strengths of the designed system is that it allows an easy integration of heterogeneous technologies and their hardware-independent interoperability. This is a feature of great importance for existing buildings, where already existing controls could be integrated with new technologies to enhance the energy efficiency of a building. The functionality of the system has been tested in a number of representative spaces of already existing public buildings, where the already installed HVAC and lighting services have been equipped with monitoring and actuating systems designed and implemented using commercial off-the-shelf wired and wireless devices. This paper focuses on the energy aspects, which have been obtained by applying the designed system to monitor and control the electric lighting fixtures of different office spaces. The outcomes obtained from the monitored data have shown some significant differences from the expected and previously estimated energy saving results, and this paper offers some possible explanations. Some criticalities, in part related to the characteristics of the commercial off-the-shelf adopted devices and in part to the difficulties encountered in monitoring and analyzing the huge number of recorded data, are outlined.**

***Index Terms*—Energy efficiency, lighting-control strategies, lighting systems, long-term monitoring, middleware for embedded systems, smart buildings.**

I. INTRODUCTION

ENERGY saving and the development of information and communication technologies (ICT) are two of the main goals of European policies in the field of Research and Innovation to mitigate climate changes by reducing CO_2 emissions and to boost economic growth by accelerating the spread of innovative technological solutions [1], [2]. It is well known that the building sector is one of the main causes of the final global energy consumption: buildings consume nearly one-third of the final global energy and are responsible for about one-third of the total direct and indirect energy-related CO_2 emissions [3]. Several policy instruments have been devised to limit building pressure on the energy sector since the 1990s. Building energy codes were initially only focused on new residential buildings, but then they have progressively been expanded to include new nonresidential buildings and, more recently, to cover existing buildings when they undergo renovations or alterations [4]–[6].

At present, new building constructions represent a small volume in developed countries. Furthermore, more than half the current global building stock is still expected to be standing in 2050, and a building can generally last over 100 years. As a consequence, actions on existing private and public buildings have become a key instrument in achieving major reductions in energy consumption and CO_2 emissions [3]. Existing public buildings can consume large amounts of energy, due to a number of concurring factors, such as the presence of low-performance envelopes, old and scarcely efficient plant-engineering technologies, a lack of effective building management systems (BMS) or building automation and control (BCA), an irresponsible and unaware interaction of users toward the systems. A combined implementation of different intervention policies should be addressed and put into practice to achieve a smaller carbon footprint for existing buildings. One strategy, for instance, could concern building renovations through energy-conservation measures (ECMs), such as envelope optimization and the retrofitting of existing plants and appliances with new energy-efficient technologies and advanced controls (HVAC and lighting). Other strategies could rely on the use of renewable energies and on the integration of ICT solutions for the management of building energy use. Such ICT solutions could support Demand-Side Management in order to increase, through smart grids, the efficiency of building energy consumption. All these intervention policies have been regulated by the European Energy Efficiency Directive (EED 2012/27/EU) [7] and the related directives and national standards on the Energy Performance of Buildings (EPBD) [4], [5] as well as the Ecodesign and Energy Labeling of Energy-related Products (ErP) [8], [9].

Manuscript received August 26, 2015; revised December 19, 2015, January 7, 2016, and January 19, 2016; accepted January 19, 2016. Paper 2015-ILDC-0733.R3, presented at the 2015 IEEE International Conference on Environment and Electrical Engineering, Rome, Italy, June 10–13, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Industrial Lighting and Display Committee of the IEEE Industry Applications Society. This work was supported by the FP7 SEEMPubS research projects.

A. Pellegrino, V. R. M. Lo Verso, and L. Blaso are with the Department of Energy, Technology Energy Building Environment (TEBE) Research Group, Politecnico di Torino, 10129 Turin, Italy (e-mail: anna.pellegrino@polito.it; valerio.loverso@polito.it; laura.blaso@polito.it).

A. Acquaviva and E. Patti are with the Department of Control and Computer Engineering, Politecnico di Torino, 10129 Turin, Italy (e-mail: andrea.acquaviva@polito.it).

A. Osello is with the Department of Structural, Geotechnical, and Building Engineering, Politecnico di Torino, 10129 Turin, Italy (e-mail: anna.osello@polito.it).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TIA.2016.2526969

Nevertheless, several economic and noneconomic barriers are still encountered in the implementation of the measures needed to enhance the energy savings of existing buildings. These barriers are mainly concerned with aspects pertaining to higher initial costs, a lack of information, a lack of user awareness toward technologies and their potential energy savings, as well as to difficulties in the management operations. Among all the possible ECMs, upgrading system technologies—for instance, by replacing traditional lighting systems with new highly efficient LED solutions, or implementing and deploying ICT for building management and monitoring processes—could be a cost-effective solution for the renovation of existing buildings [10]–[12]. Solutions that are able to reduce the need for construction works are of particular value.

On this basis, a project named Smart Energy-Efficient Middleware for Public Spaces (SEEMPubS) has been designed and carried out, within the 7th European Research Framework Program, with the main objective of exploiting ICT-based monitoring and control systems to reduce energy usage and the CO_2 footprint in public buildings. Existing buildings are sometimes equipped with BMS for a coarse grain control of their systems, and new technologies, such as wireless sensors and actuator networks (WSAN), are nowadays available to achieve new systems or to extend existing ones. In both cases, the issue of interoperability should be addressed and solved so that these technologies can become widespread. The SEEMPubS project has led to the development of a middleware for embedded systems that is aimed at creating services and applications across heterogeneous devices in order to develop an energy-aware platform. This platform has been constructed to be open to future developments, in terms of further energy-efficiency measures or demand-side energy management through smart grids.

A number of representative spaces in some buildings belonging to the Politecnico di Torino, Italy, were chosen as case studies for demonstration purposes. The selected rooms are characterized by preexisting technical plants and in some cases also by existing BMS. The possibility of installing new BMS or implementing the existing ones has been explored within this project, and in particular, commercial off-the-shelf devices have been used to set up the new system or to integrate the existing BMS with new sensors and actuator networks. Both wired and wireless solutions were designed and tested.

In order to test the efficacy of the designed solutions, in terms of energy savings, the demonstration spaces were selected so as to have "pairs" of similar rooms: one room (reference room) was left with the existing plants and without a management system, while the system developed in the project was installed in the other room (test room). Each room was monitored throughout the whole project, and all the obtained data were transferred to a centralized database.

Within this frame, this paper presents the concept of the new Middleware that was developed and focuses on the approach and technical solutions used to plan the control of electric lighting. The results obtained from the monitoring activity during the October 2013–April 2014 period are discussed with respect to the use of lighting systems. A preliminary description of the study has been presented in [13].

II. MIDDLEWARE FOR AN EFFICIENT ENERGY MANAGEMENT OF BUILDINGS

The coexistence of several heterogeneous technologies and the lack of interoperability between them is a well-known issue. Devices such as OLE for process control unified architecture (OPC UA) try to solve these problems for classic BMS by providing abstraction layers. However, it should be considered that other technologies are also adopted in these buildings. A middleware approach has been adopted in the SEEMPubS project to handle the issues of interoperability and to be open toward future developments. The basis was the open-source LinkSmart middleware [14], which is a generic service-oriented middleware for Ubiquitous Computing. This was developed into a middleware for smart energy-efficient buildings. This middleware provides reusable and extensible components and concepts for reoccurring tasks and problems in future smart buildings, and the development implemented in the SEEMPubS project consists of a three-layered architecture with an *integration proxy layer*, a *service layer*, and an *application layer*.

A. Integration Proxy Layer

The infrastructure which has been developed relies upon an ICT infrastructure made up of heterogeneous monitoring and actuation devices, such as wireless sensor and actuator network (WSAN). In order to improve backward compatibility, the infrastructure also supports wired technologies that exploit different protocols (BACnet and LonWorks).

The Proxy is a concept that describes the integration of a specific technology in a LinkSmart application. A proxy acts as a bridge between the LinkSmart network and the underlying technology. It translates whatever kind of language the low-level technology speaks into LinkSmart Web Services, and the low-level technology can, therefore, be used transparently by any other LinkSmart component. This concept allows each low-level technology to be used transparently inside the LinkSmart network.

The integration proxy layer is the lowest layer of the developed Middleware for the efficient management of building energy. It integrates a specific technology with the middleware infrastructure by abstracting its functionalities and translating whatever kind of language the low-level device speaks into a web service. Exploiting this approach, interoperability between heterogeneous devices is enabled, and any other middleware component or application can use a specific technology transparently.

Different integration proxies have been developed to manage several types of WSANs (plugwise and ST Microelectronics Smart Plug commercial end node with ZigBee protocol; EnOcean protocol stack commercial end nodes). In addition, an integration proxy has been developed to allow interoperability with OPC UA, which incorporates all the functionalities provided by different standards, such as BACnet or LonWorks. Hence, backward compatibility with wired technologies is enabled and integrated in the new middleware. Because of the modularity achieved by means of the deployment of Integration

Proxies, the Middleware for the efficient management of building energy is suitable for integration and for extension of already existing BMS with new commercial off-the-shelf sensors and actuator networks.

B. Service Layer

Three main functionalities were implemented in the service layer of the Middleware.

1) Secure Communication: The middleware generates a peer-to-peer network in which web service calls are routed through the LinkSmart Network Manager, thus creating a simple object access protocol (SOAP) tunnel to the requested service endpoint. This concept allows direct communication among all the devices in the middleware network. Furthermore, the middleware provides components that enable message encryption and trust management [15].

2) Event-Based Communication: Building automation systems generally need to react to events that happen in a given building. Sensors publish events that lead to a certain reaction, such as switching lights on after an incoming motion event. The proposed middleware includes an Event Manager, which is a specific component that implements the published approach [16]. This allows loosely coupled event-based systems, which increase the scalability of the whole software infrastructure, to be developed. This mechanism is a key requirement for smart buildings, in which a high number of sensor events occur, to develop systems and applications.

3) Semantic Knowledge: The context and ontology frameworks are two complementary components, which together manage semantic knowledge about the application domain and the implemented system. This knowledge includes metadata on the sensors and actuators, but also on their relationship with the domain model objects, such as the appliances, buildings, and rooms. Moreover, the context framework provides a convenient entry point for application developers as it exposes a simple JavaScript Object Notation (JSON) API. Hence, developers can have access to any kind of information from a rich domain model.

C. Application Layer

The Application Layer is the highest layer in the proposed infrastructure. It is dedicated to developing distributed event-based user-centric applications in order to manage buildings and postprocess data obtained from the lower layers, thus providing a set of tools and a web service API. Interoperability between different devices is enabled at this level.

III. CASE STUDY

The new middleware, developed according to the LinkSmart system, has been adopted in various already existing buildings of the Politecnico di Torino. Both historical and contemporary buildings, constructed in different ages, were chosen to assess the potentials and drawbacks of using smart ICT-based systems in buildings with different features and constraints. This was done because one of the main goals of the SEEMPubS project was to define technologies that could be replicated in other already existing buildings in Europe with similar features. The buildings that were selected are located in three different sites in the city: 1) the historical campus building (The Valentino Castle), which dates back to the beginning of the 16th century; 2) the old campus site, which is still the main campus for the Engineering Faculties and was constructed in 1958; and 3) the modern campus site, which was created from a complex refurbishment of a former industrial area.

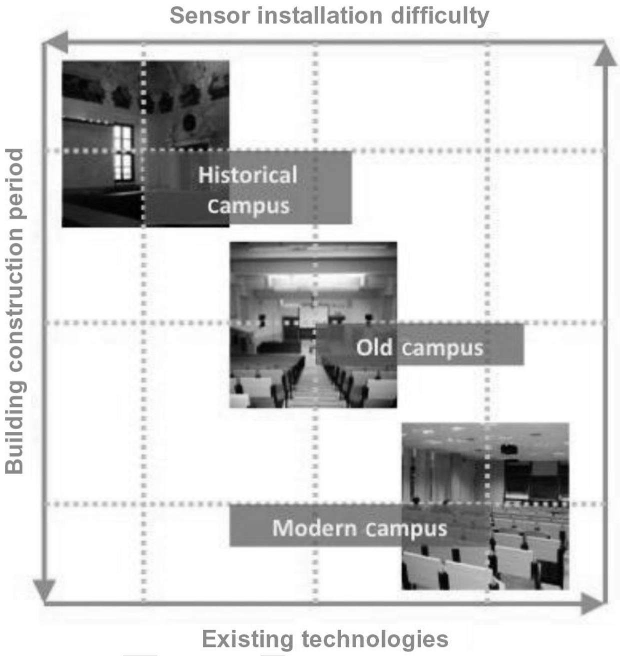

Fig. 1. Link between the construction age, costs, and difficulty in installing sensors for the different buildings considered as case studies.

Each building obviously required a specific solution for the installation of new sensors and controls for the HVAC and lighting systems [17]. The modern campus was already equipped with a basic BMS (Desigo by Siemens): new sensors and control rules were implemented to optimize energy use. New sensors were installed in the main campus in a wired system. The value of the paintings and stuccoes in the historical building made the installation of sensors a difficult task: in this case, each room required a specific solution, and only wireless sensors were considered.

The diagram in Fig. 1 shows the connection between the building construction period, the existing technologies, the sensor installation costs, and the difficulty in the installation of the sensors. A historical building is generally characterized by very few existing technologies as well as high construction work costs, related to the difficulty of installing the new technologies that are necessary to preserve any paintings, stuccos, or wood/marble floors. Instead, a new building can normally incorporate recent technologies: these can easily be integrated in the structure using false ceilings and floating floors. Moreover, there are also already existing buildings in which new technologies have to be improved significantly, and in this case, the costs and difficulties are closely related to the construction work that is required [18].

Some representative rooms were selected in the buildings in each campus in order to implement the BMS with the new sensor-network infrastructure. The rooms were chosen on the basis of the following criteria: ability to represent the Campus buildings and other Public buildings; energy-saving potential, according to the architectural, services, and occupancy characteristics. Both private and public spaces, such as classrooms, student offices, individual offices, and open plan offices, were selected.

The rooms were selected in pairs: one reference room (R), running with the present systems and with manual controls, and one similar test room (T), where automatic control and monitoring were implemented for the lighting, heating/cooling, and electrical appliances. In some rooms, the existing BMS was linked to the new middleware, while in other rooms, a new control and monitoring system, based on WSAN, was installed and managed by the middleware.

This paper focuses on the lighting control and monitoring that were carried out in two pairs of offices (Fig. 2).

1) The DITER offices, which are located in the historical building of the Valentino Castle. Both rooms are toplit by means of three skylights, but there are also two small west-/north-facing vertical windows, which provide a supplementary source of daylight. Two 2 × 35 W luminaires (T5 fluorescent lights) are installed in each room.
2) The ADMIN offices, which are located in a modern building of the main Politecnico campus. Both rooms have large west-facing windows. The R room is equipped with three ceiling-mounted 2 × 36 W luminaires (T8 fluorescent lamps). The T room has a different system, which consists of three suspended 2 × 35 W luminaires (T5 fluorescent lamps).

A. Lighting-Control Strategies

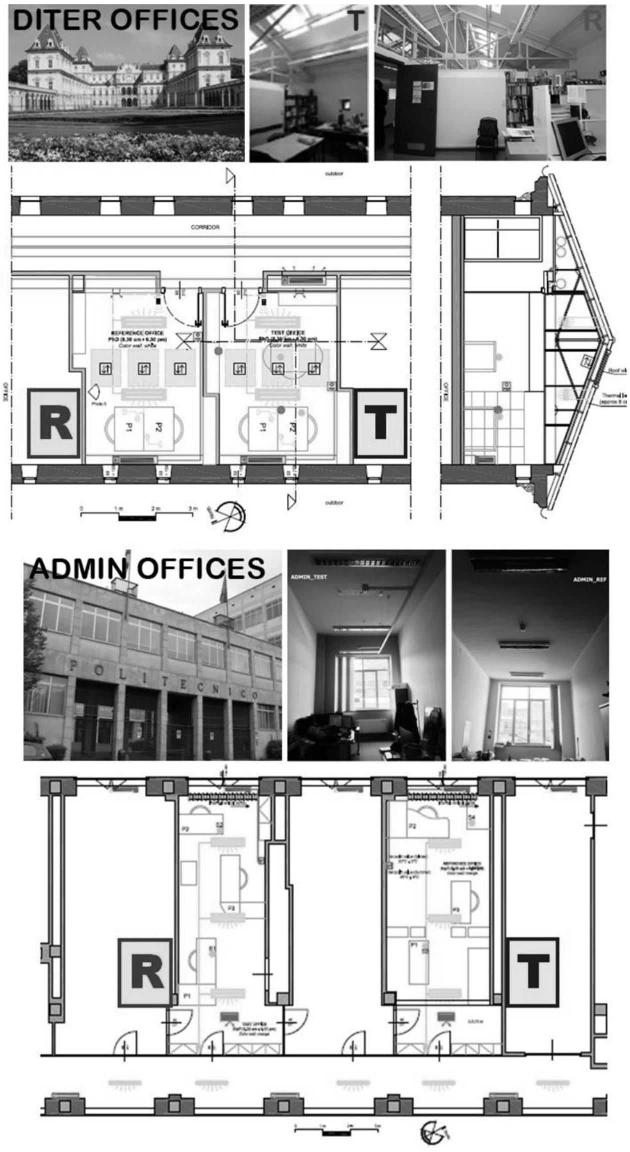

Fig. 2. Plans and views of the rooms used in the case study: DITER offices (top) and ADMIN offices (bottom).

The recurrent lighting-control solutions for energy savings are time scheduling, daylight harvesting, occupancy control, or a combination of the previous three. Time scheduling allows the luminaires to be turned on and off automatically at scheduled times in order to avoid wasteful lighting outside working hours. Daylight harvesting entails the automatic adjustment of the light flux of luminaires (dimming) in order to maintain a predetermined illuminance in the room, taking the contribution of daylight into account. This strategy is especially effective in those rooms or buildings that are characterized by high daylight availability and all-day working hours. Occupancy control is based on the detection of the presence or absence of people in a space: lights are then switched on or off accordingly, in order to avoid energy waste produced by lights left on by users who have left the space. The control logic could involve either switching on and off (presence detection) or just off (absence detection). A lighting control based on presence detection would only be effective in spaces in which user absence is highly probable, or the users are not too motivated to pay attention to the use of light. Absence detection instead can be fruitfully used in all the spaces where people can forget to switch the lights off. Different lighting-control strategies were implemented in the T spaces, according to the features of the room [19]. Both daylight harvesting and occupancy control were implemented for spaces with high daylight availability and medium user-absence probability. The possibility of overriding the automatic control, via a manual command, was provided for all the different situations. The following strategies were implemented for the two pairs of rooms analyzed in detail in this paper (Fig. 3).

1) The *DITER offices*: in the R room, two 2 × 35 W luminaires are controlled manually through an on/off switch (the existing solution was maintained), while the same luminaires in the T room are controlled through a new WSAN, which includes a wireless switch, a photosensor, and an occupancy sensor. These are all connected to a wireless actuator, which communicates via Enocean

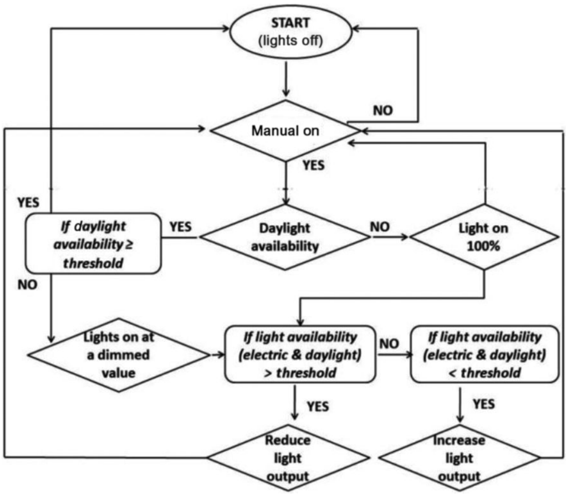

Fig. 3. Control logic implemented in the DITER and ADMIN test offices. In both cases, daylight harvesting and absence control were used because of the high annual daylight availability.

   protocol to the network access point. The following devices are used in the network:
   a) Thermokon SR-MDS Solar sensors to control the lighting systems, to check the status of the system and to record the brightness and the occupancy;
   b) an Eltako switch and an Eltako actuator;
   c) an ST-Microlectronics smart-plug prototype to monitor the energy consumption (ZigBee) of both the luminaires and the actuator.

2) The *ADMIN offices*: three ceiling-mounted 2 × 36 W luminaires in the R room are controlled through a single on/off switch (preexistent solution), while three suspended 2 × 35 W luminaires are controlled in the T room through the already existing commercial BMS (Desigo by Siemens) with two wired photo-sensors and two occupancy sensors (one to control the area close to the windows and the other for the back part of the room). ST-Microlectronics prototypes of smart plugs were used to monitor the energy consumption. In this case, the luminaire consumption was only monitored by the energy meters. The Siemens Desigo system was integrated with the general middleware developed in the project.

As fluorescent light fittings have recently been installed in both the DITER and ADMIN spaces, it was decided not to replace them with LED systems. Furthermore, it should be recalled that the goal of the project was to demonstrate the effectiveness of the ICT-based management solution in improving the building energy efficiency rather than to estimate the savings achievable by retrofitting the lighting plants with new, more energy-efficient lamp technologies. Fig. 3 describes the control logic of the light strategy adopted in the ADMIN and DITER offices.

The use of electric lighting-control systems that can provide the required quantity of light to the right place and at the right time during operating hours is recognized as an ECM that can significantly reduce the consumption of electricity used for lighting [20]. A recent literature review, carried out within the international IEA Task 50 research on Advanced Lighting Solutions for Retrofitting Buildings [21], has outlined the saving results obtained in a large number of experimental or simulation studies focused on the implementation of electric lighting-control systems as a retrofitting measure to reduce energy use in buildings [22]. The saving potentials vary greatly, according to the context, the type of building, and the building features, such as daylight availability and occupancy profile. Furthermore, great differences have been found between simulation results and field studies: the former has overestimated the savings compared to the latter. The study has reported the following saving results with respect to the different possible lighting-control strategies: manual controls 23%–77%; time scheduling 12%; occupancy control 20%–93% (highly dependent on space occupancy and the time delay); daylight harvesting 10%–93%; combined daylight harvesting and occupancy 26%. According to another study [20], which has analyzed lighting energy savings from the literature—240 saving estimates from 88 papers and case studies, categorized as daylighting strategies, occupancy strategies, personal tuning, and institutional tuning—"the best estimates of average lighting energy-saving potential are 24% for occupancy, 28% for daylighting, 31% for personal tuning, 36% for institutional tuning, and 38% for multiple approaches." Again, it has been highlighted that "simulations significantly overestimate (by at least 10%) the average savings obtainable from daylighting in actual buildings."

A very wide range of saving potentials for each control strategy has also been confirmed in another extensive literature review carried out by a dedicated Technical Committee of the CIE Division 3 [23]. For instance, a large bandwidth of savings (20%–70%) has been pointed out for daylight harvesting strategies, while savings ranging from 28% to 60% have been reported for occupancy-sensing strategies.

In this project, the savings expected from the implementation of the proposed lighting-control strategies were first estimated through energy simulations and then evaluated by analyzing the data that were measured through the ICT-based management system.

IV. RESULTS

In this section, the main results concerning the energy consumption of lighting systems are summarized. The results of the energy simulation and of the monitoring have been separated, as have those of the two pairs of offices, DITER and ADMIN. The analysis period for the monitoring results was October 2013–April 2014, so as to take into account a period in which the use of electric lighting is more prevalent. In fact, it was observed that lights are almost always switched off during the operating hours in summer, due to the high daylight availability.

A. Results of the Energy Simulations Carried Out in the Early Stages of the Project

Lighting simulations were carried out in the early stages of the project in order to estimate and compare the electric lighting energy demand of the R and T rooms. The simulation results were then used to optimize the control strategy on the basis of the characteristics of the specific rooms.

Parametric 3-D models were imported into the Radiance and Daysim lighting simulation tools using the Ecotect software. Radiance and Daysim were used because of the interoperability between the software packages. Radiance was used to validate the models, while Daysim was adopted to estimate the energy demand for electric lighting and the savings that could be obtained with the proposed control strategies. Daysim allows an annual simulation to be run for a given site. Factors such as the specific dynamic climate conditions, the lighting power installed in the room, the type of lighting-control system, the occupancy profile, the lighting requirements (the target illuminance value), and the user behavior are taken into account in the simulation. An initial validation of the model has been conducted by comparing the output of the Radiance simulations (illuminance distribution) with the illuminance values measured in the corresponding rooms. After the validation phase, a set of simulations was run for each room using Daysim, in which the defined control strategies were introduced as input and the corresponding energy demand for lighting was calculated [in (kWh/m^{2}year)]. The simulations were initially carried out considering "mixed user behavior" (some users are active and some passive with respect to the use of electric lighting and blinds) and were then repeated considering only "active user behavior." The potential savings were estimated comparing the energy demand for the new control systems and the currently installed ones [24], [25].

The following savings were obtained from the simulations:

1) *the DITER offices:* 29% with mixed user behavior and 64% with active user behavior;
2) *the ADMIN offices:* 27% with mixed user behavior and 70% with active user behavior.

B. Results of the Monitoring Activity

1) DITER Offices: Fig. 4 and Table I show the main results (which were found) with regard to the lighting energy use in the T and R offices. Considering the whole analysis period, the T room showed higher absolute energy consumption for lighting than the R room [+47.5%, Fig. 4(a), continuous lines]. This unexpected performance appears to be due to the following combination of factors.

1) A high parasitic consumption, due to the stand-by power and sensor noise [Fig. 4(b) and (c)]. If this parasitic consumption was to be subtracted from the energy consumption of both the T and R rooms [a constant power of 4 W was subtracted for each time-step during which the lights are off, as this was found to be the value which occurred the most; see Fig. 6(a)], the absolute consumption for the two rooms would become comparable [+2.6% for the T room; see Fig. 4(a), dashed lines]. The power was calculated from the measured energies, for a resolution of the sensor of 4 Wh and an acquisition interval of 15 min (thus resulting in a power of 4 W per each 15 min).
2) The occupancy time in the T and R rooms is comparable (+6.4% for the T room for the whole analysis period), but the lights remain on for more hours in the T room (+58.5%).

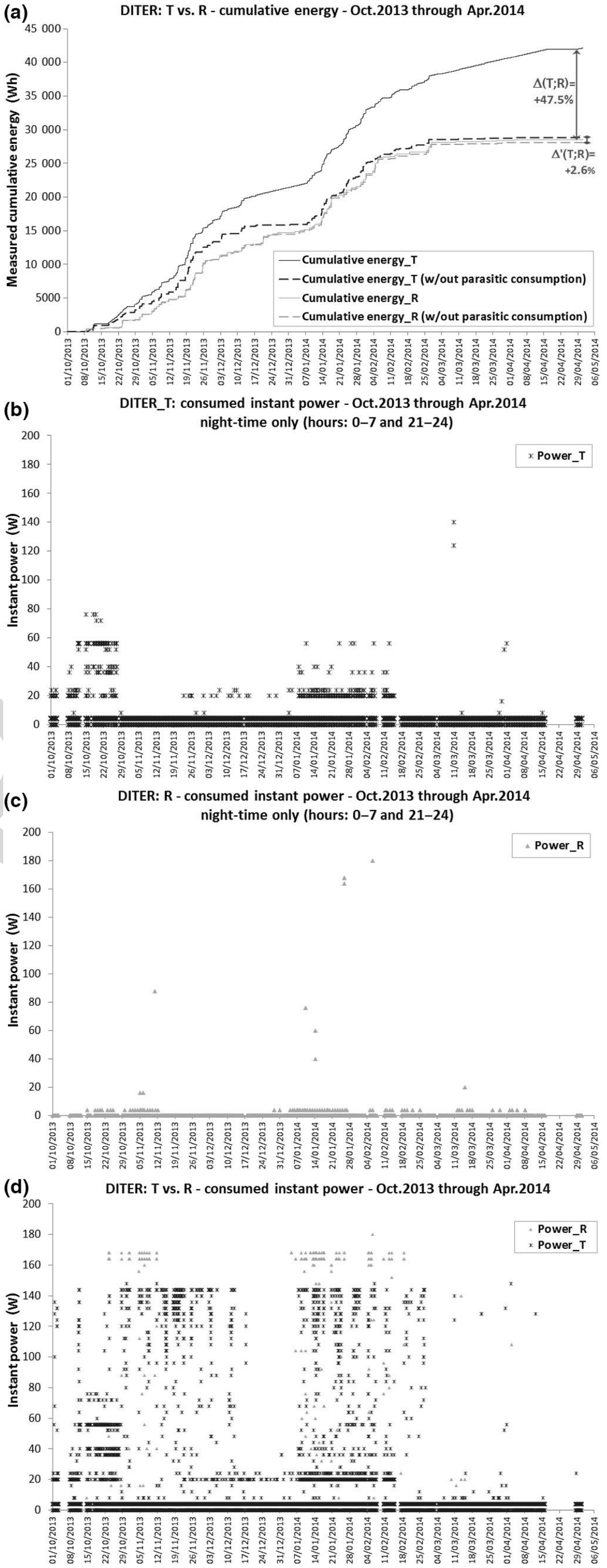

Fig. 4. Summary of the energy and power consumption for the DITER offices. F4:1

TABLE I

SUMMARY OF THE ENERGY RESULTS FOR THE DITER OFFICES

Analysis factor	*Δ(T;R)*[a]
Total energy consumption	+47.5%
Total energy consumption (without parasitic consumption and sensor noise)	+2.6%
Number of occupancy hours	+6.4%
Number of hours with lights on	+58.5%
Total energy consumption (without sensor noise)/ number of occupancy hours	–4.8%
Total energy consumption (without sensor noise)/ number of hours with lights on	–36.1%

[a] Calculated through the formula: $(T - R)/R$* 100.

3) During the periods when the lights are on in the T room, they are dimmed by the control system for 88.2% of the time, with a mean percent of dimming of 63.7%. Furthermore, the control system sets the luminaires at a maximum power, which is lower than the maximum value [Fig. 4(d)]. The control system seems to work effectively by dimming the light output in response to the natural environmental brightness.

It is worth stressing that this latter factor (dimming of the light output in the T room) is a positive aspect for the T room and should lead to a decrease in energy consumption, compared to the R room. Nevertheless, this positive performance is counterbalanced by the other previously described factors (sensor noise, stand-by power, occupancy profile, and hours during which the lights remain on). Among all these factors, the stand-by power and sensor noise play the most important roles on the final consumption. The energy consumed during the analysis period for each hour of lights on (without the sensor noise) was lower in the T room than in the R room (-36.1%), while the energy consumed for each hour of occupancy was similar for the two rooms (-4.8%). These data are more in line with the expected and simulated results.

2) ADMIN Offices: Fig. 5 and Table II show a summary of the results for the ADMIN T and R offices. Considering the whole analysis period, the T room showed a significantly lower energy consumption for lighting than the R office [-70.8%, Fig. 3(a), continuous line]. This performance, which was even better than could be expected, appears to be due to the following combination of factors.

1) The different characteristics of the lighting systems in the T and R rooms are as follows:
   a) the luminaires installed in the T room are newer and are suspended, which results in a better light flux Utilization Factor for the T room than for the R room;
   b) the illuminance over the work plane (E_{wp}) in the R room was 300 lx, while, in the T room, the performance requirements from the occupants were 500 lx for the desk close to the window (zone 2) and 300 lx for the desk at the back of the room (zone 1).

2) *The different behavior of the occupants:* The T room is occupied less than the R room (-22.2% for the whole heating period); consistently, lights are kept on for fewer hours (-26.6%).

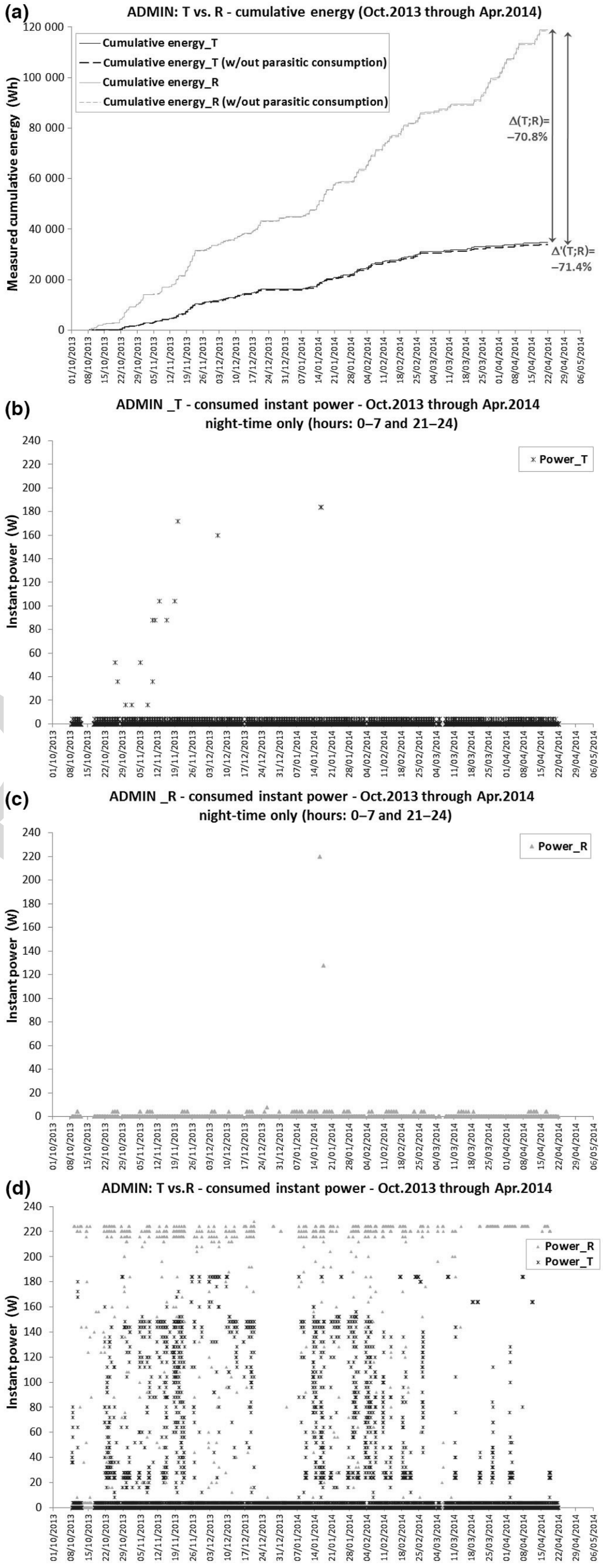

Fig. 5. Summary of the energy and power consumption for the ADMIN offices.

TABLE II
SUMMARY OF THE ENERGY RESULTS FOR THE ADMIN OFFICES

Analysis factor	Δ(T;R)[a]
Total energy consumption	–70.8%
Total energy consumption (without sensor noise)	–71.4%
Number of occupancy hours	–22.2%
Number of hours with lights on	–26.4%
Total energy consumption (without sensor noise) / number of occupancy hours	–64.3%
Total energy consumption (without sensor noise) / number of hours with lights on	–62.2%

[a] Calculated through the formula: $(T - R)/R^*$ 100.

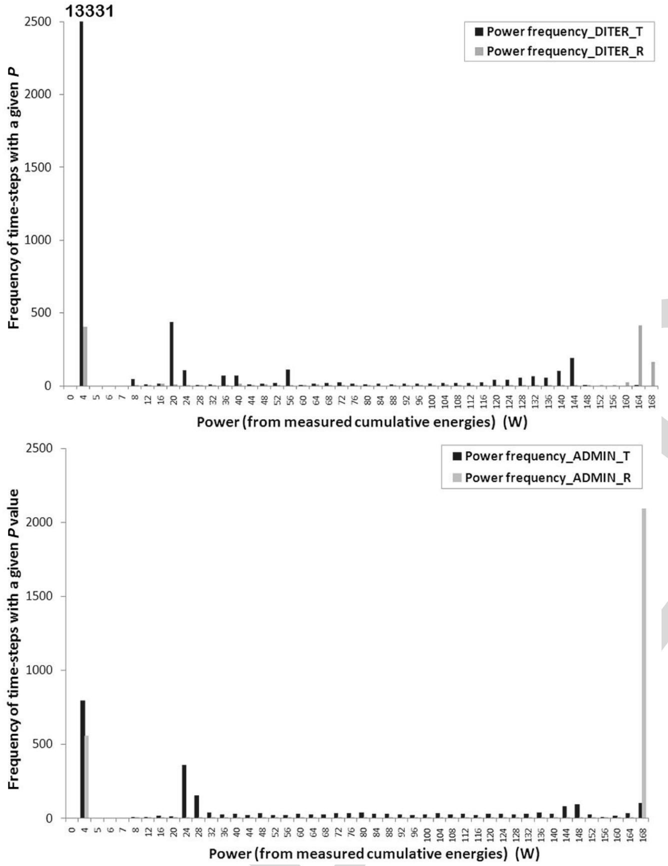

Fig. 6. Occurrence frequencies of the recorded power values in the DITER (top) and ADMIN (bottom) offices.

Furthermore, when the lights are on in the T room, they never reach the nominal maximum power, and they are dimmed by the photodimming control for 93.7% of the time [mean dimming = 40.6%, Fig. 5(d)]. The control system is therefore effective in dimming electric lights in response to the natural brightness.

A parasitic consumption, due to sensor noise, was also observed in the ADMIN offices, but this was found to have a limited impact on the energy consumption [Fig. 5(b) and (c)]. When the sensor noise was subtracted from the energy consumption in the T room [again, a constant power of 4 W was subtracted for each time-step during which the lights were off, as this was found to be the value which occurred the most; see Fig. 6(b)], the difference in the consumption for the T and R rooms was of the same magnitude [-71.4%, Fig. 5(a), dashed line].

On the whole, these results show that the control system in the T room (i.e., electric light management based on daylight levels and considering the absence of the occupants) led to rather remarkable energy savings. The global energy consumed (excluding the sensor noise) for each occupancy hour was found to be significantly lower in the T room than in the R room (-64.3%); the same applies if the energy consumption is expressed per number of hours with lights on (-62.2%). It should also be noted that the stand-by power of the sensors and actuators in the T room was not recorded by the ST smart plug as they were managed directly by the centralized Desigo system and could not be extrapolated from the overall data.

V. DISCUSSION AND CONCLUSION

The huge amount of data measured and managed in the SEEMPubS project has been used to analyze the impact of lighting-control strategies (photodimming and occupancy based), compared to simple manual on-off switches. The measured data were highly heterogeneous with regard to both the sensor type employed in the different rooms and to the different acquisition intervals recorded by each type of sensor (temperature, occupancy, brightness, and energy). All the data were "synchronized" to the same time interval (5 min) to allow a comparison to be made between the different datasets. One of the merits of the methodology presented in this paper is the "synchronization" algorithm, which allowed all the measured data to be aligned to the same time-steps.

On the other hand, some criticalities emerged from the data analysis and they need to be pointed out. Analyzing the results, a "performance gap" was found between the expected performance (based on the simulation results) and the actual performance observed in the real rooms. This was particularly evident for the DITER offices. The energy consumption of the test room was influenced to a great extent by the stand-by power of the actuators and lamp ballasts and by the sensor noise, as shown in Fig. 6, where the parasitic consumption is represented by the recurrent 4 W. This parasitic consumption represents more than 30% of the global energy consumed in the test room. This result is in line with what has been found in other researches [26], [27], but it also seems to have been influenced by the characteristics of the sensor, which was in fact designed to measure greater loads (not for a single office). Therefore, the minimum reading step is greater than the minimum power absorbed by the devices, which remain in stand-by throughout the whole 24 h. Furthermore, the sensor was a prototype and several false measurements (sensor noise) were recorded. The data recorded when the lights were off, particularly during the nighttime, in the rooms without stand-by loads, were considered as sensor noise (this is the case of both the R and T room in the ADMIN offices and of the R room in the DITER offices).

Furthermore, the data have shown that the control system in the T room actually dims the light output when the room is occupied [Fig. 4(d)], but the lights remain on for more hours (Table I). This could be ascribed to two aspects: a limited capacity of the photo-sensor in the T room to switch the lights off when there is sufficient daylight or a “low attitude” of the occupants of the R room to switch the lights on when there is insufficient daylight (with respect to the target illuminance used to set the dimming system in the T room). It has emerged, from an analysis of the monitored data, that both conditions could have occurred.

A “performance gap” was also found for the ADMIN offices, but to a lesser extent; in this case, energy savings were actually obtained, due to the photodimming and the implementation of occupancy sensors, but they appear to be higher than could be expected. This result is probably also due to the fact that the stand-by power of the sensors and actuators could not be recorded by the system that was implemented for the present project.

In general, it appears evident that the high number of variables that influence the final energy performance is hard to manage in the design stages, and large differences may be found between the expected and actual performance. One of the hardest variables to describe seems to be the occupants’ behavior, in terms of actual occupancy profiles and attitude toward switching lights on and off. It is also worth noting that analyzing the energy performance, in terms of total energy consumption, may lead to results that are very different from those that are found when the absolute total energy consumption is “normalized,” considering the number of actual monitored occupancy hours (which was adopted to overcome the problem of the quite different occupancy patterns in the T and R rooms) or considering the number of hours when lights were detected to be on (to account for the actual electric light use during the occupancy time). This was found to be particularly evident for the DITER offices: comparing the total energy consumption, in absolute terms, showed a higher consumption in the T room than in the R room ($+47.5\%$), while using the ratio of the consumption to the number of occupancy hours or the ratio of the consumption to the number of hours with lights on in the T room (after subtracting the parasitic power) shows a better performance than that of the R room (-4.8% and -36.1%, respectively).

This consideration becomes more evident if a disaggregated day-by-day analysis is carried out. As an example, Fig. 7 shows the data that were recorded for a single day (November 22): the profiles of occupancy, consumed power, and environmental brightness are plotted for both the T and R DITER rooms. The following results were obtained:

- hours of occupancy:	T: 5.58	R: 7.01
- hours with lights ON:	T: 4.83	R: 6.08
- hours with lights ON/occupancy:	T: 0.87	R: 0.87
- consumed energy (Wh):	T: 596.6	R: 987.6

These data show that, throughout the considered day, the occupancy profile and the duration time with the lights on are different for the T and R rooms, but when the hours with the lights on are compared to the hours during which the two offices were occupied, the result is the same (0.87), which makes the two rooms comparable. Under these conditions, the energy consumption was found to be lower in the T room (-38.1%) than in the R room. As a more general consideration, it is possible to state that although on one hand, the global consumption during the course of a year or throughout a season (heating or cooling) is an important metric for the energy manager of a facility; on the other hand, if the aim is to compare two different lighting-control technologies implemented in different rooms, different metrics could be more advantageous: for instance, the energy consumed per actual occupancy hour or the energy consumed per hour with lights on could be used for this purpose.

Another criticality that was observed concerns the monitoring of the lighting amount on the working plane E_{wp} through the photosensor used to dim the lights. Owing to the features and position of the sensors (ceiling-mounted and suspended), the brightness data monitored in the four rooms were not always useful to verify the actual lighting condition over the work plane [28]. These sensors measured the environment brightness in the room, which was then converted into the corresponding E_{wp} value through a calibration process for each room. Fig. 8 shows the E_{wp} levels recorded by Gigahertz data loggers (which were used to calibrate the brightness sensor) compared to the ambient brightness measured by the SEEMPubS sensors. In the ADMIN offices, which are unilateral daylit spaces, the

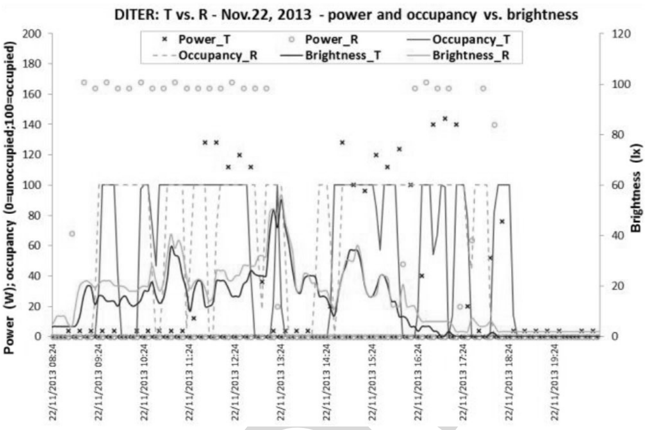

Fig. 7. Power, occupancy, and brightness profiles for a single day in the DITER offices.

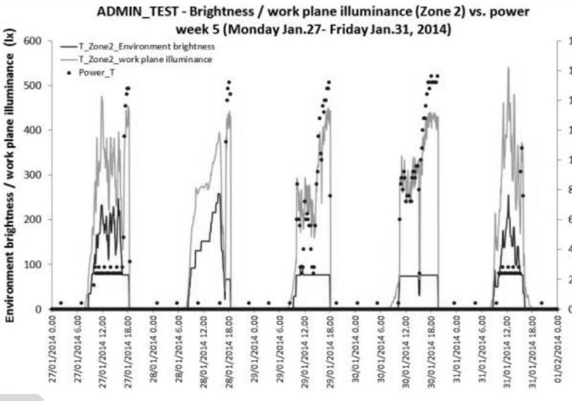

Fig. 8. ADMIN: example of the relationship between environment brightness E_{wp} and consumed power for the T room (back of the room).

brightness responds to the variation in the daylighting levels (which hit the sensor more directly), but fails to correctly record the increase in horizontal illuminance when electric lights are switched on (which is measured indirectly).

In conclusion, the main results which have been obtained by comparing the energy consumption in the T and R rooms are as follows.

1) The measured energy is influenced by a parasitic power consumption, due to the stand-by power of the luminaires and to sensor noise. A somewhat similar behavior (increase in sensor noise during the night hours as the sensors falsely detected the presence of an individual when the room was actually empty) was also reported in a study by Gonzalez *et al.* [29]. In this case, and particularly for the DITER Test office, the parasitic consumption is also influenced to a great extent by the features of the sensor (larger minimum reading step than the actual stand-by power).
2) The energy performance of both the ADMIN and DITER offices observed in real rooms was influenced to a great extent by the occupants' behavior (especially concerning the attitude of individuals to switch lights on and to keep them on during the working hours). As a consequence, the consumption significantly differed from what was expected during the design stage (when all decisions were based on simulation results). This result is in line with what was observed in [30] and [31].
3) The choice of measuring the E_{wp} indirectly, by measuring the environment brightness through ceiling-mounted or suspended sensors, implied a complex calibration process. Installing illuminance sensors directly on the work plane seems to be a more reliable solution for future applications.

ACKNOWLEDGMENT

The authors would like to thank G. Carioni (Livinglab, Politecnico di Torino) for building the algorithm used to synchronize the recorded data.

REFERENCES

[1] Commission of the European Communities. (2009). *Commission Recommendation on mobilising Information and Communications Technologies to Facilitate the Transition to an Energy-Efficient, Low-Carbon Economy*, C(2009)7604 [Online]. Available: http://ec.europa.eu/information_society/activities/sustainable_growth/docs/recommendation_d_vista.pdf

Q2 [2] *ICT-03-2016:SSI—Smart System Integration* [Online]. Available: http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/5090-ict-03-2016.html

Q3 [3] International Energy Agency (IEA), *Transition to Sustainable Buildings. Strategies and Opportunities to 2050*. 2013.

[4] *Directive 2002/91/EC of the European Parliament on the Energy Performance of Building* [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32002L0091&from=EN

[5] *Directive 2010/31/EU, Recast of Energy Performance of Building* [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=URISERV:en0021&from=IT

[6] International Energy Agency (IEA), *Modernising Building Energy Codes to Secure Our Global Energy Future*. 2013.

[7] Energy Efficiency Directive 2012/27/EU.

[8] Ecodesign Directive 2009/125/EU, *Directive 2009/125/EC of the European Parliament and of the Council of 21/10/2009 Establishing a Framework for the Setting of Ecodesign Requirements for Energy-Related Products, Recast of Directive 2005/32/EC Amending Council Directive 92/42/EEC and Directives 96/57/EC and 2000/55/EC of the European Parliament and of the Council* [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/list_of_ecodesign_measures.pdf, accessed on Dec. 2015. Q4

[9] Directive 2010/30/EU of 19 May 2010 on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products.

[10] M. Magno, T. Polonelli, L. Benini, and E. Popovici, "A low cost, highly scalable wireless sensor network solution to achieve smart LED light control for green buildings," *IEEE Sensors J.*, vol. 15, no. 5, pp. 2963–2973, May 2015.

[11] E. Uken, G. Bevan, and R. Smith, "LED tube retrofits for fluorescent lighting in offices," in *Proc. 10th Ind. Commer. Use Energy Conf. (ICUE)*, 2013, pp. 1–4.

[12] T.-J. Park and S.-H. Hong, "Experimental case study of a BACnet-based lighting control system," *IEEE Trans. Autom. Sci. Eng.*, vol. 6, no. 2, pp. 322–333, Apr. 2009.

[13] A. Pellegrino, V. R. M. Lo Verso, L. Blaso, A. Acquaviva, E. Patti, and A. Osello, "Lighting control and monitoring for energy efficiency: A case study focused on the interoperability of building management systems," in *Proc. IEEE 15th Int. Conf. Environ. Elect. Eng. (EEEIC)*, Jun. 10–13, 2015, pp. 748–753.

[14] M. Eisenhauer, P. Rosengren, and P. Antolin, "A development platform for integrating wireless devices and sensors into ambient intelligence systems," in *Proc. 6th Annu. IEEE Commun. Soc. Conf. Sens. Mesh Ad Hoc Commun. Netw. Workshops (SECON Workshops '09)*, Jun. 2009, pp. 1–3.

[15] M. Hoffmann *et al.*, "Towards semantic resolution of security in ambient environments," in *Developing Ambient Intelligence*, 2008, pp. 13–22. Q5

[16] P. T. Eugster, P. A. Felber, R. Guerraoui, and A. M. Kermarrec, "The many faces of publish/subscribe," *ACM Comput. Surveys*, vol. 35, pp. 114–131, 2003.

[17] A. Acquaviva *et al.*, "From historical buildings to smart buildings via middleware and interoperability," in *Proc. Int. Conf. Comput. Civil Build. Eng. (ICCCBE2012)*, Jun. 27–29, 2012. Q6

[18] A. Acquaviva *et al.*, "Service oriented solution for interoperable networks in smart public spaces," in *Proc. Nat. AICA Smart Tech Smart Innov. La strada per costruire futuro*, Nov. 15–17, 2011.

[19] C. Aghemo *et al.*, "Management and monitoring of public buildings through ICT based systems: Control rules for energy saving with lighting and HVAC services," *Front. Archit. Res.*, vol. 2, pp. 147–161, 2013.

[20] A. Williams, B. Atkinson, K. Garbesi, E. Page, and F. Rubinstein, "Lighting controls in commercial buildings," *Leukos*, vol. 8, pp. 161–180, 2012.

[21] IEA Task 50, *Advanced Lighting Solution for Retrofitting Buildings* [Online]. Available: http://task50.iea-shc.org/

[22] M. C. Dubois *et al.*, "Retrofitting the electric lighting and daylighting systems to reduce energy use in buildings: A literature review," *Energy Res. J.*, vol. 6, pp. 25–41.

[23] CIE TC 3.49, *Decision Scheme for Lighting Controls for Tertiary Lighting in Buildings* [Online]. Available: http://div3.cie.co.at/?i_ca_id=573&pubid=349

[24] A. Acquaviva *et al.*, "Increasing energy efficiency in existing public buildings through the implementation of a Building Management System based on interoperable networks," in *Proc. 2nd Int. Conf. Build. Energy Environ. (COBEE)*, Boulder, CO, USA. Q7

[25] A. Osello *et al.*, "Energy saving in existing buildings by an intelligent use of interoperable ICTs," *Energy Effic.*, vol. 6, pp. 707–723, 2013.

[26] N. Gentile, T. Laike, and M. C. Dubois, "Lighting control system in peripheral offices rooms at high latitude: Measurements of electricity savings and users preferences," *Energy Procedia*, vol. 57, pp. 1987–1996, 2014.

[27] C. Aghemo, L. Blaso, and A. Pellegrino, "Building automation and control systems: A case study to evaluate the energy and environmental performances of a lighting control system in offices," *Autom. Constr.*, vol. 43, pp. 10–22, 2014.

[28] L. T. Doulos, A. Tsangrassoulis, and F. V. Topalis, "Optimizing the position and the field of view of photosensors in daylight responsive systems," in *Proc. 11th Lux Europa*, Istanbul, Turkey, Sep. 9–11, 2009.

[29] L. I. L. Gonzalez, U. Großekath, and O. Amft, "An intervention study on automated lighting control to save energy in open space offices," in *Proc. IEEE Int. Conf. Pervasive Comput. Commun. Workshop*, San Louis, MO, USA, Mar. 23–25, 2015, pp. 317–322.

[30] G. Y. Yun, H. J. Kong, H. Kim, and J. T. Kim, "A field survey of visual comfort and lighting energy consumption in open plan offices," *Energy Build.*, vol. 46, pp. 146–151, 2012.

[31] P. Correia da Silva, V. Leal, and M. Andersen, "Occupants interaction with electric lighting and shading systems in real single-occupied offices: Results from a monitoring campaign," *Build. Environ.*, vol. 64, pp. 152–168, 2013.

Q8 **Anna Pellegrino** received the M.S. degree in architecture and the Ph.D. degree in energetics from the Politecnico di Torino, Turin, Italy.

She is an Associate Professor of Building Physics with the Politecnico di Torino. Since 1998, she has been carrying out her research activity in the Department of Energetics, Technology Energy Building Environment (TEBE) Group, Politecnico di Torino. Her research interests include different topics on lighting: from lighting and control technologies to applications and energy use, from lighting design to the issue of light and health, visual comfort and material damage, considering both daylighting and electric lighting.

Valerio R. M. Lo Verso received the M.S. degree in architecture and the Ph.D. degree in building physics from the Politecnico di Torino, Turin, Italy.

He is an Assistant Professor of Indoor Environment Physics with the Department of Energy, Politecnico di Torino. He has authored/coauthored over 70 international scientific papers. His research interests include daylighting/electric lighting for visual comfort and energy savings purposes through software simulations and field analyses; new materials for innovative façades. He was granted a Post-Doctoral position with the National Research Council, Ottawa, ON, Canada, on "daylighting for green buildings."

Dr. Lo Verso is an Associate Editor of the *Journal of Daylighting*.

Laura Blaso received the M.S. degree in architecture and the Ph.D. degree in technological innovation for architecture and industrial design from the Politecnico di Torino, Turin, Italy, in 2003 and 2008, respectively.

She is a Researcher with the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA), Rome, Italy. Her research interests include various topics on lighting: from daylight to electric lighting, from visual comfort to energy saving, and from technologies to applications.

Dr. Blaso has been the Coordinator of the Italian Working Group "Energy performance of Buildings" UNI/CT023/GL10 of the Commission UNI/CT023 "Light and Lighting" since December 2015.

Andrea Acquaviva received the Ph.D. degree in electrical engineering from the University of Bologna, Bologna, Italy, in 2003.

He is an Associate Professor with the Politecnico di Torino, Turin, Italy. He was an Assistant Professor with the Università di Urbino, Urbino, Italy, and with the Università di Verona, Verona, Italy. Since 2008, he has been with the Department of Computer Engineering and Automation, Politecnico di Torino. He has authored or coauthored more than 150 scientific publications. His research interests include smart systems and cities, Internet of Things, parallel computing for distributed embedded systems, and bioinformatics.

Edoardo Patti received the B.Sc. degree in computer engineering from the University of Palermo, Palermo, Italy, and the M.Sc. degree in computer engineering from the Politecnico di Torino, Turin, Italy, in 2007 and 2010, respectively.

Since January 2011, he has been with the Department of Control and Computer Engineering, Politecnico di Torino, as a Ph.D. student first and then as a Postdoctoral Research Fellow. During the academic year 2014/2015, he was a Visiting Academic at the University of Manchester, Manchester, U.K. He is also involved in various European-funded projects focused on smart cities. His research interests include Internet of Things, smart systems and cities, distributed software architectures for smart environments, and software solutions for user awareness.

Anna Osello received the B.S. degree in building engineering from the Politecnico di Torino, Turin, Italy, and the Ph.D. degree in drawing and survey of buildings from the l'Università degli Studi la Sapienza, Rome, Italy, in 1992 and 1996, respectively.

Since 1999, she has been an Associate Professor of Drawing with the Politecnico di Torino, where she coordinates a laboratory denominated drawing to Q9 the future (http://www.drawingtothefuture.polito.it/) with the goal of carrying out theoretical and applied research on the issues of BIM and software interoperability. She is cur- Q10 rently engaged in several research projects, including Smart Energy-Efficient Middleware for Public Spaces (SEEMPubS) and District Information Modeling and Management for Energy Reduction (DIMMER).

QUERIES

Q1: Please spell out "HVAC and OLE."
Q2: Please provide name of author/organization and year of publication for Refs. [2], [4], and [5].
Q3: Please provide complete details for Refs. [3], [6], [7], and [9].
Q4: Please provide year of publication for Refs. [8], [21], [22], and [23].
Q5: Please provide publisher name and location for Ref. [15].
Q6: Please provide page range for Refs. [17], [18], and [28].
Q7: Please provide year of publication and page range for Ref. [24].
Q8: Please provide year of completion of the M.S. and Ph.D. degrees of the authors "Anna Pellegrino and Valerio R. M. Lo Verso."
Q9: Please check and confirm whether the word "denominated" is correct at line number 904.
Q10: Please expand the term BIM in the biographies section.