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

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Abstract— The paper presents some results of a project carried out within the 7th European Research Framework Program, aimed at developing an event-driven user-centric middleware for monitoring and managing energy consumption in public buildings. One of the strengths of the designed system is to allow an easy integration of heterogeneous technologies and their hardware independent interoperability. This is a feature of great importance to existing buildings, where standing controls could be integrated with new technologies to enhance a greater building energy efficiency. The functionality of the system has been tested in some representative spaces of existing public buildings. Control strategies and hardware infrastructures have been defined to manage the operation of HVAC and lighting plants. The paper focuses on the results obtained by applying the designed system and control strategies to the electric lighting plants of different office spaces.

Keywords: *energy efficiency; smart buildings; middleware for embedded systems; lighting systems; lighting control strategies; long-term monitoring*

I. INTRODUCTION

Energy saving and development of ICT technologies are among the main goals of the European policies in the field of Research and Innovation. As far as energy consumption is concerned, the building sector is one of the main responsible. Existing public buildings can be highly energivorous, due to the use of old and scarcely efficient plant-engineering technologies, to the frequent lack of effective Building Management Systems (BMS) or Building Automation and Control (BCA) and sometimes to a not responsible and aware interaction of users towards systems.

With a small volume of new building constructions in the developed countries, major energy savings potentials can only be realized by retrofitting the building stock. By upgrading the systems technologies - for instance substituting the traditional lighting plants with new high efficient LED solutions, or by addressing the challenge of energy efficiency through the implementation and deployment of Information and

Communication Technologies (ICT) for building management and monitoring. Solutions able to reduce the need for construction works in retrofitting buildings are of great value.

On this basis, within the 7th European Research Framework Program a project named Smart Energy Efficient Middleware for Public Spaces (SEEMPubS) has been designed and carried out, with the main objective of exploiting ICT monitoring and control services to reduce energy usage and CO₂ footprint in public buildings. Existing buildings are sometimes equipped with BMS for a coarse grain control of systems, and new technologies such as Wireless Sensors and Actuators Network (WSAN) are nowadays available. Nevertheless the issue of interoperability should be addressed and solved to make these technologies actually widespread. The project led to the development of a middleware for embedded systems, aimed at creating services and applications across heterogeneous devices to develop an energy-aware platform.

The functionality of such a system from an energy saving viewpoint has been demonstrated using representative spaces in some buildings of the Politecnico di Torino, Italy, as case-study. The buildings were characterized by preexistent technical plants and in some cases also by existing BMS. Within the project the possibility to install new BMS or implement the existing ones was explored, with the idea of using commercial off-the-shelf devices and, where present, exploiting and integrating existing BMS with new sensors and actuator networks. Both wired and wireless solution were designed and tested.

To test the efficacy of the designed solutions in terms of energy savings, the demonstration spaces were selected in order to have “pairs” of similar rooms: one left with the existing plants and without management system the other one settled out with the system developed in the project. Each room was monitored during the whole project and all data achieved into an overall database.

The lighting plants were among the ones involved in the experimentation and this paper focuses on the method and

results obtained in managing electric lighting. Solutions to automatically control the lighting plants were compared to manual on/off systems, both in terms of energy consumption and environmental quality.

This paper presents the concept of the new Middleware which was developed and the approach and technical solutions used to plan the control of electric lighting and to elaborate the huge number of data achieved by the building management system through the designed middleware and reports the main results obtained. The monitoring activity carried out during the period October 2013 – April 2014 is presented, focusing on lighting and energy related aspects. The control strategies proposed for implementation (in the existing buildings) are described and a special focus is set on the procedure adopted to evaluate the effectiveness of the proposed control strategies.

II. THE MIDDLEWARE FOR BUILDINGS ENERGY EFFICIENT MANAGEMENT

The coexistence of several heterogeneous technologies and the lack of interoperability among them is a well-known issue. For classic BMS, efforts like OPC UA (OLE for Process Control Unified Architecture) try to solve these problems by providing abstraction layers, however it has to be considered that other technologies find their way into the buildings as well. A middleware approach was adopted in the project to handle the issues of interoperability and be open to future developments. The basis was the open source LinkSmart middleware [1], which is a generic service-oriented middleware for Ubiquitous Computing. This was further developed into a middleware for smart energy efficient buildings. This middleware provides reusable and extensible components and concepts for re-occurring 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 *Services Layer* and an *Application Layer*.

A. Integration Proxy Layer

The proposed infrastructure leverages upon an ICT infrastructure made of heterogeneous monitoring and actuation devices such as WSAN (Wireless Sensor and Actuator Network). In order to improve backwards compatibility, the infrastructure supports also wired technologies that exploit different protocols, such as BACnet, LonWorks, etc.

The Proxy is a concept that describes the integration of a specific technology into 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 so the low-level technology can be used transparently by any other LinkSmart component. This concept allows us to use each low-level technology transparently inside the LinkSmart network.

The Integration Proxy Layer is the lowest layer of the proposed Middleware for buildings energy efficient management. It integrates a specific technology into the middleware infrastructure by abstracting its functionalities and translating whatever kind of language the low-level device speaks into a Web Services. Exploiting this approach, the

interoperability between heterogeneous devices is enabled and any other middleware component or application can use a specific technology transparently.

Different Integration Proxies to manage several types of WSANs were developed (plugwise and ST Microelectronics Smart Plug commercial end-node with ZigBee protocol; EnOcean protocol stack commercial end-nodes, etc.). In addition, an Integration Proxy was developed to allow the interoperability with the OPC UA, which incorporates all the functionalities provided by different standards, such as BACnet or LonWorks. Hence, the backwards compatibility with wired technologies is enabled and integrated into the new middleware. Thanks to the modularity achieved with the Integration Proxies deployment, the Middleware for buildings energy efficient management is suitable for integration and extension of the already existing BMS with new commercial-off-the-shelf sensors and actuator networks.

B. Services Layer

Three main functionalities were implemented in the services 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 creating a SOAP (Simple Object Access Protocol) tunnel to the requested service endpoint. This concept allows direct communication among all devices into the middleware network. Furthermore, the middleware provides components for enabling message encryption and trust management [2].

2) Event-based communication

Building Automation systems typically need to react upon events happening in the building. Sensors publish events leading to a certain reaction, such as switching lights on upon an incoming motion event. The proposed middleware provides the Event Manager, which is a specific component that implements the publish/subscribe approach [3]. This allows the development of loosely-coupled event-based systems increasing the scalability of the whole software infrastructure. In smart buildings, where a high number of sensor events happens, this mechanism is a key requirement 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 includes meta-data about sensors and actuators but also their relation to domain model objects such as appliances, buildings and rooms. Moreover, for application developers the Context Framework provides a convenient entry point by exposing a simple JSON (JavaScript Object Notation) API. Hence, developers can query any kind of information from a rich domain model.

C. Application Layer

In the proposed infrastructure, the Application Layer represents the highest layer. It is dedicated to developing distributed event-based user-centric applications to manage

buildings and post process data coming from the lower layers, providing a set of tools and web service API. At that level the interoperability between different devices is enabled.

III. CASE STUDY

The new middleware developed based on the LinkSmart system was deployed in different buildings of the Politecnico di Torino. Some rooms from each building were selected as case-studies to demonstrate the effectiveness of the new system in reducing energy consumption, increasing occupant comfort and simplifying the activities facility managers [4].

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 was implemented for 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 WSN, was installed and managed through the middleware.

Within this paper a specific focus is done on the lighting control and monitoring carried out in two pairs of offices::

- DITER offices, located in a historical building (Valentino Castle 17th century). In R room 2 luminaires 2*35W are installed, controlled through an on/off switch, while T room has the same luminaires, but controlled through a new WSN: a wireless switch, a photosensor and an occupancy sensor were used
- ADMIN office, located in a modern building (Politecnico main campus, around 1965). R room is equipped with 3 ceiling mounted luminaires 2*36W, controlled through a single on/off switch. T room has a different system, consisting of 3 suspended 2*35W luminaires controlled through a commercial preexistent BMS with 2 wired photo-sensors and two occupancy sensors.

A. Lighting control strategies

Recurrent solutions of lighting controls for energy savings are: time switching; daylight harvesting; occupancy control; a combination of the previous. Time switching allows to turn automatically on and off luminaires at scheduled times to avoid useless lighting out of working hours. Daylight harvesting entails to automatically adjust luminaires light flux (dimming) 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 and lights are switched on or off accordingly. Once again the automatic control avoids energy waste produced by lights left on by users leaving the space. The control logic could provide for either switching on and off or for single off. A lighting control based only on presence detection would be effective in spaces where user absence is highly probable, where users are little motivated at paying attention to the use of light.

According to the rooms features, different lighting control logics were implemented in T spaces [5]. For spaces with high

daylight availability and medium user absence probability, a combination of daylight harvesting and occupancy control was proposed. In all cases, the possibility to override the automatic control via manual command is provided.

Fig. 1 describes the control logics corresponding to the strategy of ADMIN and DITER offices.

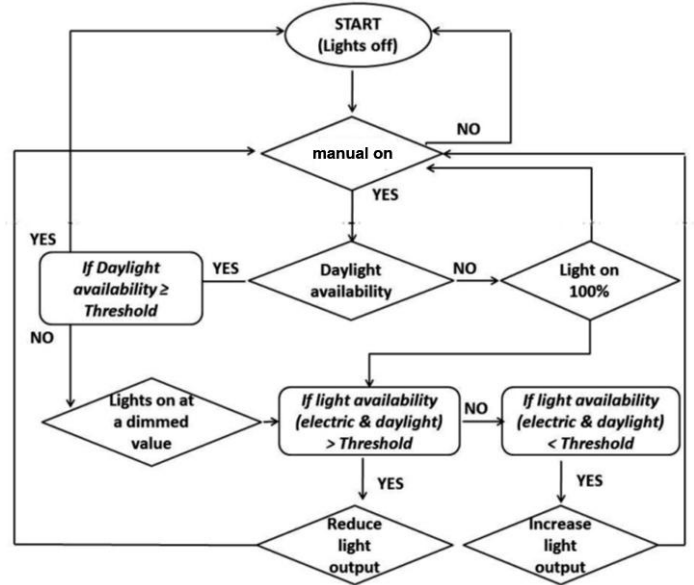


Fig. 1. Control logic in case of both daylight harvesting and occupancy control.

IV. RESULTS

In this section, the main results concerned with the energy consumption for lighting systems are summarized, separate for the two pairs of offices, DITER and ADMIN. The analysis period was October 2013 through April 2014.

A. DITER offices

Fig.2 shows the main results which were found with regard to the lighting energy use in the T and in the R offices. Considering the whole analysis period, T room showed a greater energy consumption for lighting than R room (+47.5%, Fig. 2a, continuous lines). This unexpected performance appears to be due to a combination of the following factors:

- high parasitic consumption due to the stand-by power and sensor noise (Fig 2b-c). If this parasitic consumption is ideally subtracted from the energy consumption of both T and R rooms (a constant power of 4W was subtracted for each time-step during which lights are off, as this was found to be value which occurred the most), the consumption for the two rooms becomes comparable (+2.6% for T room, see Fig. 2a, dashed lines). It is worth mentioning that powers were calculated from the measured energies; the resolution of the sensor was 4 Wh and the acquisition interval was 15 minutes (corresponding to a power of 4 W per each 15 minutes)
- the occupancy time in T and R rooms is comparable (+6.4% for T room for the whole analysis period), but in T

room lights remain on for a higher amount of hours (+58.5%)

- during the periods when lights are on in 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 to a maximum power which is lower than the maximum value (Fig. 2d). The control system seems to work effectively to dim the light output in response to the environmental brightness.

It is worth stressing that this latter factor (dimming of light output in T) is in favor of T room and should lead to a decrease in energy consumption compared to R room: nevertheless, this performance is overwhelmed by the other factors described earlier (sensor noise, occupancy profile and hours during which lights remain on). Among all these factor, the sensor noise plays the major role on the final consumption: referring to energy data without the sensor noise, it was calculated that the global energy consumed during the analysis period per each hour of lights on is lower in T than in R (-36.1%), while the energy consumed per each occupancy hours is comparable for the two rooms (-4.8%).

Table I summarizes the main results for DITER offices.

TABLE I. SUMMARY OF ENERGY RESULTS FOR DITER OFFICES

Analysis factor	$\Delta[T;R]^a$
Total energy consumption	+47.5%
Total energy consumption (without 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

B. ADMIN offices

Fig. 3 shows a summary of the results which were found for ADMIN T and R offices. Considering the whole analysis period, T room showed a significantly lower energy consumption for lighting than the R office (-70.8%, Fig. 3a, continuous line). This performance, even better than expected, appears to be due to a combination of the following factors, related to two aspects:

- different characteristics of the lighting systems in T and R:
 - the luminaires installed in T are newer and are suspended, which results in a better Utilization Factor for T room compared to R room
 - the illuminance over the work plane (E_{wp}) in R room was 300 lx, while in T room the performance requirements from the occupants were 500 lx for the desk close to window (zone 2) and to 300 lx for the desk in the back part of the room (zone 1)

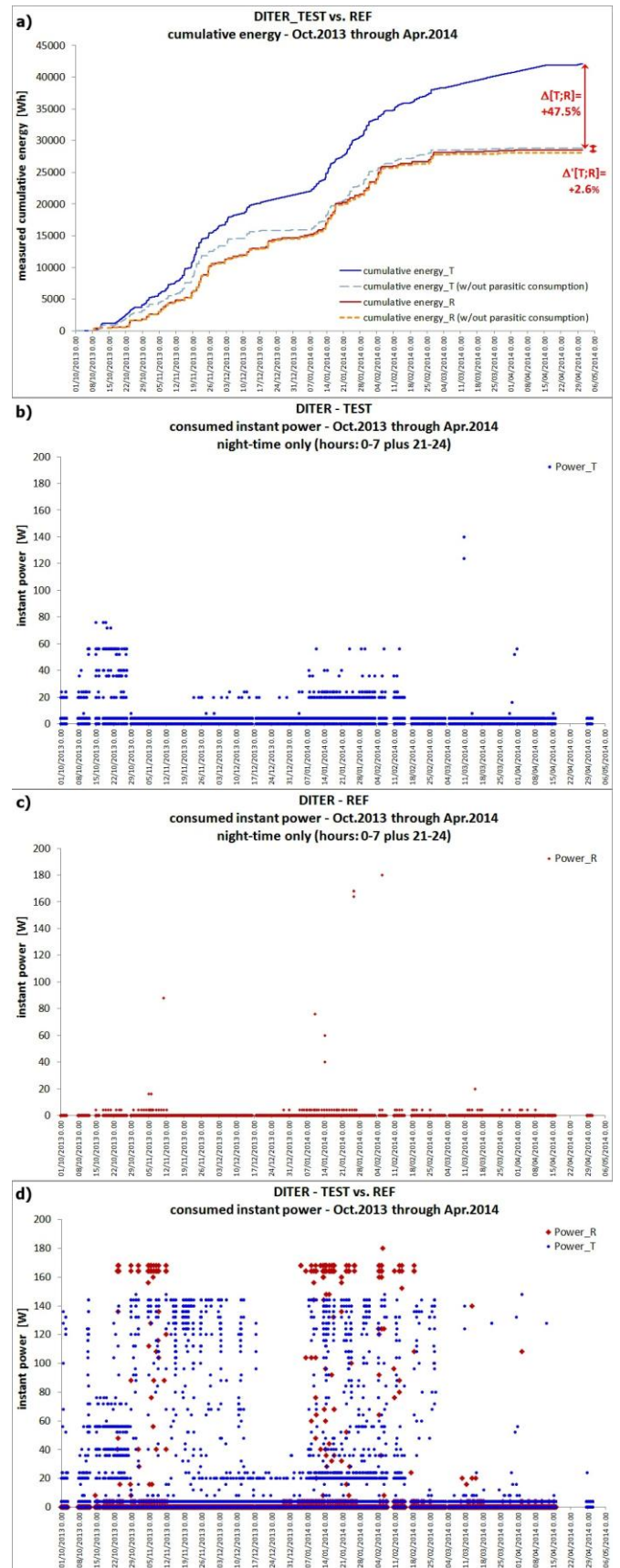


Fig. 2. Summary of energy and power consumption for DITER offices.

- a parasitic consumption, due to the stand-by power and to sensor noise, was observed, but this was found to have a low impact on the energy consumption (Fig. 3b-c). Ideally subtracting the sensor noise from the energy consumption in T room (a constant power of 4W was subtracted for each time-step during which lights are off, as this was found to be value which occurred the most) revealed that the difference in the consumption for T and R is of the same magnitude (-71.4%, Fig. 3a, dashed line).
- different behavior of occupants
 - T room is less occupied than R room (-22.2% for the whole heating period); consistently, lights are kept on for lower amount of hours (-26.6%)
 - furthermore, when lights are on in T room, they never reach the nominal maximum power and they are dimmed by the photodimming control for 93.7% of time (mean dimming = 40.6%, Fig. 3d). The control system is therefore effective in dimming electric lights in response to the brightness.

On the whole, results show that the control system in T room, managing electric lights based on daylight levels and on occupants' presence allowed achieving great energy savings: the global energy consumed (excluding the sensor noise) for each occupancy hour is significantly lower in T than in R (-64.3%); the same applies if the energy consumption is expressed per number of hours with lights on (-62.2%).

Table II summarizes the main results for ADMIN offices.

TABLE II. SUMMARY OF ENERGY RESULTS FOR ADMIN OFFICES

<i>Analysis factor</i>	<i>$\Delta T;R^b$</i>
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%

^b. Calculated through the formula: (T-R)/R*100

V. DISCUSSION AND CONCLUSIONS

The huge amount of data measured and processed in the SEEMPubS project were useful to analyze the impact of lighting control strategies (photodimming and occupancy based) compared to simple manual on-off switches. Measured data were highly heterogeneous with regard to both the sensor type employed in the different rooms and to the different acquisition interval recorded by each sensor type (temperature, occupancy, brightness, energy). All data were ‘synchronized’ to the same time interval (set to 5 minutes) to allow comparison between different data. One of the merit of the methodology presented in this paper is the ‘synchronization’ algorithm which allowed all measured data to be aligned to the same time-steps. On the other hand, some criticalities need to be stressed. Analyzing the results, a ‘performance gap’ was found between expected and actual performance in real rooms.

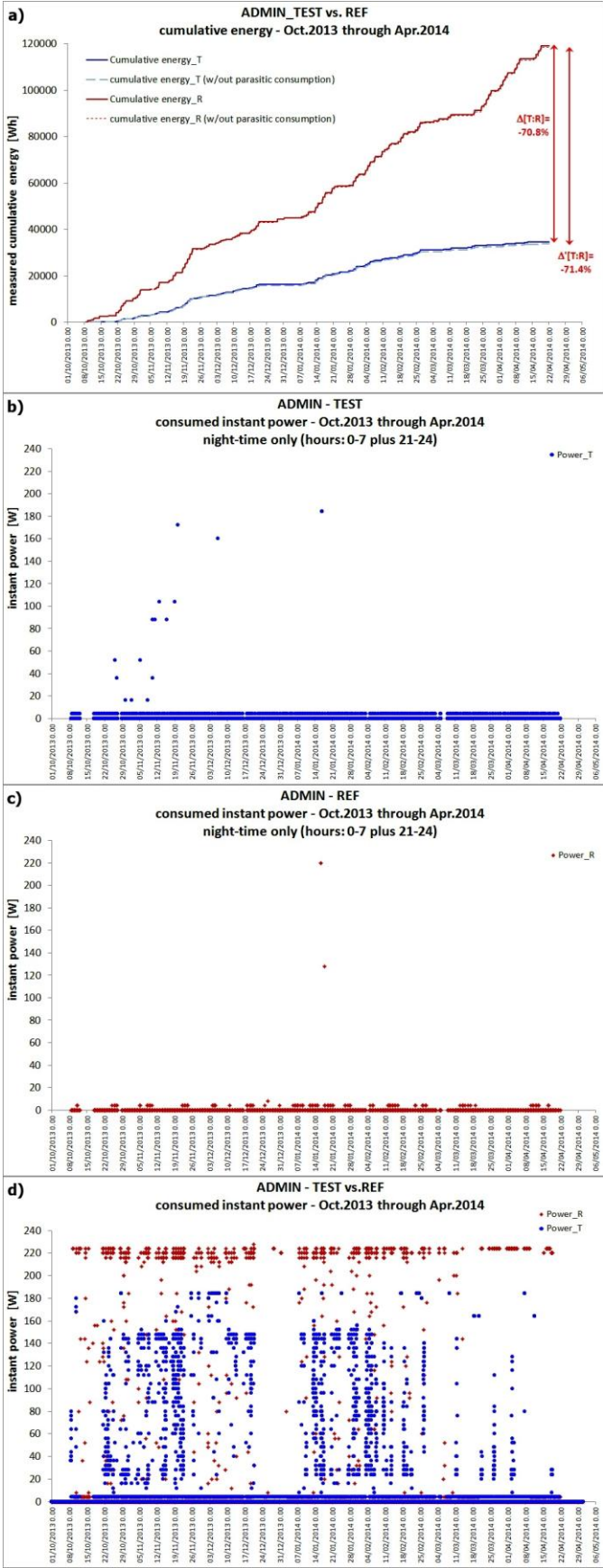


Fig. 3. Summary of energy and power consumption for ADMIN offices.

On the other hand, some criticalities need to be stressed. Analyzing the results, a ‘performance gap’ was found between expected and actual performance observed in real rooms. This was particularly evident for DITER offices. In T room, the control system actually dims the light output when the room is occupied, but lights remain on for a higher number of hours. This could be ascribed to two aspects: a low effectiveness of the photo-sensor in T room in switching lights off when daylight is sufficient or a ‘scarce attitude’ of R room’s occupants in switching lights on when daylight is insufficient.

To a lower extent, a ‘performance gap’ was also found for ADMIN offices: in this case, energy savings were actually obtained, thanks to the photodimming and occupancy sensors implemented, but even higher than expected.

It appears evident that the high number of variables influencing the final energy performance is hard to manage and to control during the design stages and big differences may be found between 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 towards switching lights on and off.

Another criticality concerned the monitoring of the E_{wp} , that is the set-point used to dim luminaires in T rooms. Due to sensors’ features and position (ceiling-mounted, suspended), the brightness data monitored in different rooms were not useful to verify the actual lighting condition over the work plane [6]. These sensors actually measured the environment brightness in the room, to be converted into a corresponding E_{wp} value through a calibration process for each room. Fig. 4 shows the E_{wp} levels recorded (using Gigahertz data-loggers, used to calibrate the brightness sensor) compared to the ambient brightness measured by the sensors. The brightness responds to the variation of daylighting levels (which hit the sensor directly), but fails to record the peak lighting levels when electric lights are switched on (which is measured indirectly). To replicate the SeemPUBS methodology to other buildings, using illuminance sensors installed on work planes would seem to guarantee more reliable readings (but they might interfere with occupants’ work activities).

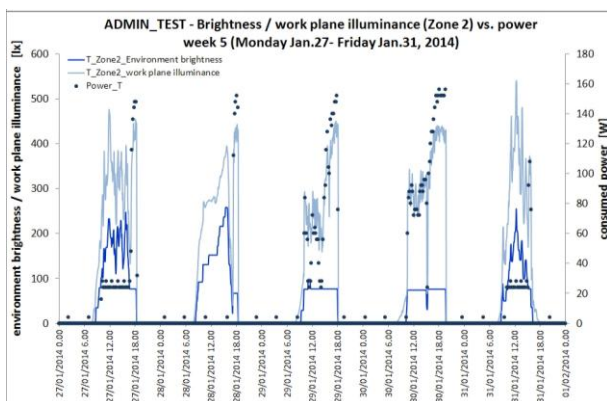


Fig. 4. ADMIN: example of the relation between environment brightness, E_{wp} and consumed power for T room (back of the room).

In conclusion, the main results which were obtained by comparing the energy consumption in T and R rooms are:

- the energy measured is influenced by a parasitic power consumption, due to the stand-by power of luminaires and to sensor noise. The different sensors installed in the two T rooms recorded a significantly different number of time-steps with a parasitic power. For the DITER offices, this produced a greater impact in T than in R room, resulting in a difference between T and R rooms up to 50%. Excluding this parasitic consumption from energy data, the two rooms have a comparable consumption. Differently, in ADMIN offices the effect of the parasitic consumption is comparable (and negligible) for T and R rooms
- for both ADMIN and DITER offices, the energy performance actually observed in real rooms is strongly influenced by occupants’ behavior (especially as for the attitude to switch lights on and to keep then on during the working hours). As a consequence, the consumption may significantly differ from what expected during the design stage (when all decisions are based on simulation results). This is in line with what observed in [7-8]
- 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.

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