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This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

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

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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

The final published version is available online at: https://doi.org/10.1109/TIA.2016.2526969

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# 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

5 Abstract—This paper presents some results of a project that has been aimed at developing an event-driven user-centric middle-6 7 ware for the monitoring and management of energy consumption in already existing public buildings. One of the strengths of the 8 9 designed system is that it allows an easy integration of heteroge-10 neous technologies and their hardware-independent interoperability. This is a feature of great importance for existing buildings, 11 12 where already existing controls could be integrated with new 13 technologies to enhance the energy efficiency of a building. The functionality of the system has been tested in a number of rep-14 resentative spaces of already existing public buildings, where the 15 16 already installed HVAC and lighting services have been equipped 17 with monitoring and actuating systems designed and implemented 18 using commercial off-the-shelf wired and wireless devices. This 19 paper focuses on the energy aspects, which have been obtained by 20 applying the designed system to monitor and control the electric 21 lighting fixtures of different office spaces. The outcomes obtained 22 from the monitored data have shown some significant differences from the expected and previously estimated energy saving results, 23 and this paper offers some possible explanations. Some criti-24 25 calities, in part related to the characteristics of the commercial off-the-shelf adopted devices and in part to the difficulties encoun-26 27 tered in monitoring and analyzing the huge number of recorded 28 data, are outlined.

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

### I. INTRODUCTION

**E** NERGY 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

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.

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Digital Object Identifier 10.1109/TIA.2016.2526969

Innovation to mitigate climate changes by reducing  $CO_2$  emis-36 sions and to boost economic growth by accelerating the spread 37 of innovative technological solutions [1], [2]. It is well known 38 that the building sector is one of the main causes of the final 39 global energy consumption: buildings consume nearly one-40 third of the final global energy and are responsible for about 41 one-third of the total direct and indirect energy-related  $CO_2$ 42 emissions [3]. Several policy instruments have been devised to 43 limit building pressure on the energy sector since the 1990s. 44 Building energy codes were initially only focused on new 45 residential buildings, but then they have progressively been 46 expanded to include new nonresidential buildings and, more 47 recently, to cover existing buildings when they undergo reno-48 vations or alterations [4]–[6]. 49

At present, new building constructions represent a small vol-50 ume in developed countries. Furthermore, more than half the 51 current global building stock is still expected to be standing 52 in 2050, and a building can generally last over 100 years. 53 As a consequence, actions on existing private and public 54 buildings have become a key instrument in achieving major 55 reductions in energy consumption and  $CO_2$  emissions [3]. 56 Existing public buildings can consume large amounts of energy, 57 due to a number of concurring factors, such as the pres-58 ence of low-performance envelopes, old and scarcely efficient 59 plant-engineering technologies, a lack of effective building 60 management systems (BMS) or building automation and con-61 trol (BCA), an irresponsible and unaware interaction of users 62 toward the systems. A combined implementation of different 63 intervention policies should be addressed and put into prac-64 tice to achieve a smaller carbon footprint for existing buildings. 65 One strategy, for instance, could concern building renova-66 tions through energy-conservation measures (ECMs), such as 67 envelope optimization and the retrofitting of existing plants 68 and appliances with new energy-efficient technologies and 69 advanced controls (HVAC and lighting). Other strategies could 70 rely on the use of renewable energies and on the integration 71 of ICT solutions for the management of building energy use. 72 Such ICT solutions could support Demand-Side Management 73 in order to increase, through smart grids, the efficiency of build-74 ing energy consumption. All these intervention policies have 75 been regulated by the European Energy Efficiency Directive 76 (EED 2012/27/EU) [7] and the related directives and national 77 standards on the Energy Performance of Buildings (EPBD) 78 [4], [5] as well as the Ecodesign and Energy Labeling of 79 Energy-related Products (ErP) [8], [9]. 80

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Nevertheless, several economic and noneconomic barriers 81 are still encountered in the implementation of the measures 82 needed to enhance the energy savings of existing buildings. 83 These barriers are mainly concerned with aspects pertaining to 84 higher initial costs, a lack of information, a lack of user aware-85 ness toward technologies and their potential energy savings, as 86 87 well as to difficulties in the management operations. Among all the possible ECMs, upgrading system technologies-for 88 instance, by replacing traditional lighting systems with new 89 90 highly efficient LED solutions, or implementing and deploying 91 ICT for building management and monitoring processes-92 could be a cost-effective solution for the renovation of existing 93 buildings [10]–[12]. Solutions that are able to reduce the need 94 for construction works are of particular value.

On this basis, a project named Smart Energy-Efficient 95 Middleware for Public Spaces (SEEMPubS) has been designed 96 97 and carried out, within the 7th European Research Framework 98 Program, with the main objective of exploiting ICT-based mon-99 itoring and control systems to reduce energy usage and the  $CO_2$  footprint in public buildings. Existing buildings are some-100 times equipped with BMS for a coarse grain control of their 101 systems, and new technologies, such as wireless sensors and 102 actuator networks (WSAN), are nowadays available to achieve 103 new systems or to extend existing ones. In both cases, the 104 issue of interoperability should be addressed and solved so that 105 106 these technologies can become widespread. The SEEMPubS project has led to the development of a middleware for embed-107 108 ded systems that is aimed at creating services and applications across heterogeneous devices in order to develop an energy-109 aware platform. This platform has been constructed to be open 110 111 to future developments, in terms of further energy-efficiency 112 measures or demand-side energy management through smart 113 grids.

114 A number of representative spaces in some buildings belonging to the Politecnico di Torino, Italy, were chosen as case 115 studies for demonstration purposes. The selected rooms are 116 117 characterized by preexisting technical plants and in some cases also by existing BMS. The possibility of installing new BMS or 118 implementing the existing ones has been explored within this 119 project, and in particular, commercial off-the-shelf devices have 120 been used to set up the new system or to integrate the existing 121 122 BMS with new sensors and actuator networks. Both wired and 123 wireless solutions were designed and tested.

In order to test the efficacy of the designed solutions, in terms 124 125 of energy savings, the demonstration spaces were selected so as to have "pairs" of similar rooms: one room (reference room) 126 127 was left with the existing plants and without a management sys-128 tem, while the system developed in the project was installed in 129 the other room (test room). Each room was monitored throughout the whole project, and all the obtained data were transferred 130 to a centralized database. 131

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 139 MANAGEMENT OF BUILDINGS 140

The coexistence of several heterogeneous technologies and 141 the lack of interoperability between them is a well-known 142 issue. Devices such as OLE for process control unified archi-143 tecture (OPC UA) try to solve these problems for classic 144 BMS by providing abstraction layers. However, it should be 145 considered that other technologies are also adopted in these 146 buildings. A middleware approach has been adopted in the 147 SEEMPubS project to handle the issues of interoperability and 148 to be open toward future developments. The basis was the 149 open-source LinkSmart middleware [14], which is a generic 150 service-oriented middleware for Ubiquitous Computing. This 151 was developed into a middleware for smart energy-efficient 152 buildings. This middleware provides reusable and extensible 153 components and concepts for reoccurring tasks and problems in 154 future smart buildings, and the development implemented in the 155 SEEMPubS project consists of a three-layered architecture with 156 an integration proxy layer, a service layer, and an application 157 layer. 158

### A. Integration Proxy Layer

The infrastructure which has been developed relies upon an 160 ICT infrastructure made up of heterogeneous monitoring and 161 actuation devices, such as wireless sensor and actuator net- 162 work (WSAN). In order to improve backward compatibility, 163 the infrastructure also supports wired technologies that exploit 164 different protocols (BACnet and LonWorks). 165

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The Proxy is a concept that describes the integration of a 166 specific technology in a LinkSmart application. A proxy acts as 167 a bridge between the LinkSmart network and the underlying 168 technology. It translates whatever kind of language the low-169 level technology speaks into LinkSmart Web Services, and the 170 low-level technology can, therefore, be used transparently by 171 any other LinkSmart component. This concept allows each low-172 level technology to be used transparently inside the LinkSmart 173 network. 174

The integration proxy layer is the lowest layer of the devel-175 oped Middleware for the efficient management of building 176 energy. It integrates a specific technology with the middleware 177 infrastructure by abstracting its functionalities and translat-178 ing whatever kind of language the low-level device speaks 179 into a web service. Exploiting this approach, interoperability 180 between heterogeneous devices is enabled, and any other mid-181 dleware component or application can use a specific technology 182 transparently. 183

Different integration proxies have been developed to manage 184 several types of WSANs (plugwise and ST Microelectronics 185 Smart Plug commercial end node with ZigBee protocol; 186 EnOcean protocol stack commercial end nodes). In addition, an 187 integration proxy has been developed to allow interoperability 188 with OPC UA, which incorporates all the functionalities pro-189 vided by different standards, such as BACnet or LonWorks. 190 Hence, backward compatibility with wired technologies is 191 enabled and integrated in the new middleware. Because of the 192 modularity achieved by means of the deployment of Integration 193 194 Proxies, the Middleware for the efficient management of building energy is suitable for integration and for extension of 195 already existing BMS with new commercial off-the-shelf sen-196 sors and actuator networks. 197

#### B. Service Layer 198

Three main functionalities were implemented in the service 199 layer of the Middleware. 200

201 1) Secure Communication: The middleware generates a 202 peer-to-peer network in which web service calls are routed through the LinkSmart Network Manager, thus creating a sim-203 ple object access protocol (SOAP) tunnel to the requested 204 service endpoint. This concept allows direct communication 205 among all the devices in the middleware network. Furthermore, 206 the middleware provides components that enable message 207 208 encryption and trust management [15].

2) Event-Based Communication: Building automation sys-209 tems generally need to react to events that happen in a given 210 building. Sensors publish events that lead to a certain reaction, 211 such as switching lights on after an incoming motion event. 212 The proposed middleware includes an Event Manager, which is 213 a specific component that implements the published approach 214 [16]. This allows loosely coupled event-based systems, which 215 increase the scalability of the whole software infrastructure, to 216 be developed. This mechanism is a key requirement for smart 217 buildings, in which a high number of sensor events occur, to 218 219 develop systems and applications.

3) Semantic Knowledge: The context and ontology frame-220 221 works are two complementary components, which together manage semantic knowledge about the application domain and 222 223 the implemented system. This knowledge includes metadata on 224 the sensors and actuators, but also on their relationship with the domain model objects, such as the appliances, buildings, 225 and rooms. Moreover, the context framework provides a con-226 venient entry point for application developers as it exposes a 227 228 simple JavaScript Object Notation (JSON) API. Hence, developers can have access to any kind of information from a rich 229 domain model. 230

#### C. Application Layer 231

232 The Application Layer is the highest layer in the proposed infrastructure. It is dedicated to developing distributed event-233 based user-centric applications in order to manage buildings 234 and postprocess data obtained from the lower layers, thus pro-235 236 viding a set of tools and a web service API. Interoperability 237 between different devices is enabled at this level.

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### **III. CASE STUDY**

239 The new middleware, developed according to the LinkSmart system, has been adopted in various already existing buildings 240of the Politecnico di Torino. Both historical and contemporary 241 buildings, constructed in different ages, were chosen to assess 242 the potentials and drawbacks of using smart ICT-based systems 243 in buildings with different features and constraints. This was 244 done because one of the main goals of the SEEMPubS project 245



Sensor installation difficulty

Historical

**Existing technologies** 

Fig. 1. Link between the construction age, costs, and difficulty in installing F1:1 sensors for the different buildings considered as case studies. F1:2

was to define technologies that could be replicated in other 246 already existing buildings in Europe with similar features. The 247 buildings that were selected are located in three different sites 248 in the city: 1) the historical campus building (The Valentino 249 Castle), which dates back to the beginning of the 16th cen-250 tury; 2) the old campus site, which is still the main campus 251 for the Engineering Faculties and was constructed in 1958; and 252 3) the modern campus site, which was created from a complex 253 refurbishment of a former industrial area. 254

Each building obviously required a specific solution for the 255 installation of new sensors and controls for the HVAC and light-256 ing systems [17]. The modern campus was already equipped 257 with a basic BMS (Desigo by Siemens): new sensors and 258 control rules were implemented to optimize energy use. New 259 sensors were installed in the main campus in a wired system. 260 The value of the paintings and stuccoes in the historical build-261 ing made the installation of sensors a difficult task: in this 262 case, each room required a specific solution, and only wireless 263 sensors were considered. 264

The diagram in Fig. 1 shows the connection between the 265 building construction period, the existing technologies, the sen-266 sor installation costs, and the difficulty in the installation of 267 the sensors. A historical building is generally characterized 268 by very few existing technologies as well as high construc-269 tion work costs, related to the difficulty of installing the 270 new technologies that are necessary to preserve any paint- 271 ings, stuccos, or wood/marble floors. Instead, a new building 272 can normally incorporate recent technologies: these can easily 273 be integrated in the structure using false ceilings and floating 274 floors. Moreover, there are also already existing buildings in 275 which new technologies have to be improved significantly, and 276 in this case, the costs and difficulties are closely related to the 277 construction work that is required [18]. 278

279 Some representative rooms were selected in the buildings 280 in each campus in order to implement the BMS with the new sensor-network infrastructure. The rooms were chosen on the 281 basis of the following criteria: ability to represent the Campus 282283 buildings and other Public buildings; energy-saving potential, according to the architectural, services, and occupancy charac-284 teristics. Both private and public spaces, such as classrooms, 285 student offices, individual offices, and open plan offices, were 286 287 selected.

288 The rooms were selected in pairs: one reference room (R), 289 running with the present systems and with manual controls, and one similar test room (T), where automatic control and moni-290 291 toring were implemented for the lighting, heating/cooling, and electrical appliances. In some rooms, the existing BMS was 292 linked to the new middleware, while in other rooms, a new con-293 294 trol and monitoring system, based on WSAN, was installed and managed by the middleware. 295

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.

3052) The ADMIN offices, which are located in a modern build-306ing of the main Politecnico campus. Both rooms have307large west-facing windows. The R room is equipped with308three ceiling-mounted  $2 \times 36$  W luminaires (T8 fluores-309cent lamps). The T room has a different system, which310consists of three suspended  $2 \times 35$  W luminaires (T5311fluorescent lamps).

### 312 A. Lighting-Control Strategies

The recurrent lighting-control solutions for energy savings 313 are time scheduling, daylight harvesting, occupancy control, or 314 a combination of the previous three. Time scheduling allows 315 the luminaires to be turned on and off automatically at sched-316 uled times in order to avoid wasteful lighting outside working 317 318 hours. Daylight harvesting entails the automatic adjustment of 319 the light flux of luminaires (dimming) in order to maintain a predetermined illuminance in the room, taking the contribution 320 321 of daylight into account. This strategy is especially effective in those rooms or buildings that are characterized by high daylight 322 323 availability and all-day working hours. Occupancy control is 324 based on the detection of the presence or absence of people in a 325 space: lights are then switched on or off accordingly, in order to avoid energy waste produced by lights left on by users who have 326 left the space. The control logic could involve either switching 327 328 on and off (presence detection) or just off (absence detection). A lighting control based on presence detection would only be 329 effective in spaces in which user absence is highly probable, 330 or the users are not too motivated to pay attention to the use 331 of light. Absence detection instead can be fruitfully used in 332 333 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 F2:1 (top) and ADMIN offices (bottom). F2:2

Different lighting-control strategies were implemented in the 334 T spaces, according to the features of the room [19]. Both 335 daylight harvesting and occupancy control were implemented 336 for spaces with high daylight availability and medium userabsence probability. The possibility of overriding the automatic 338 control, via a manual command, was provided for all the different situations. The following strategies were implemented 340 for the two pairs of rooms analyzed in detail in this paper 341 (Fig. 3). 342

1) The *DITER offices*: in the R room, two  $2 \times 35$  W luminaires are controlled manually through an on/off switch 344 (the existing solution was maintained), while the same 345 luminaires in the T room are controlled through a new 346 WSAN, which includes a wireless switch, a photosensor, and an occupancy sensor. These are all connected 348 to a wireless actuator, which communicates via Enocean 349



F3:1 Fig. 3. Control logic implemented in the DITER and ADMIN test offices. InF3:2 both cases, daylight harvesting and absence control were used because of theF3:3 high annual daylight availability.

protocol to the network access point. The followingdevices are used in the network:

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- 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 mon itor the energy consumption (ZigBee) of both the
   luminaires and the actuator.
- 2) The ADMIN offices: three ceiling-mounted  $2 \times 36$  W 359 luminaires in the R room are controlled through a sin-360 gle on/off switch (preexistent solution), while three sus-361 pended 2  $\times$  35 W luminaires are controlled in the 362 363 T room through the already existing commercial BMS 364 (Desigo by Siemens) with two wired photo-sensors and 365 two occupancy sensors (one to control the area close to the windows and the other for the back part of 366 the room). ST-Microlectronics prototypes of smart plugs 367 were used to monitor the energy consumption. In this 368 case, the luminaire consumption was only monitored by 369 370 the energy meters. The Siemens Desigo system was integrated with the general middleware developed in the 371 372 project.

373 As fluorescent light fittings have recently been installed in both the DITER and ADMIN spaces, it was decided not to 374 replace them with LED systems. Furthermore, it should be 375 376 recalled that the goal of the project was to demonstrate the effectiveness of the ICT-based management solution in improv-377 ing the building energy efficiency rather than to estimate the 378 savings achievable by retrofitting the lighting plants with new, 379 more energy-efficient lamp technologies. Fig. 3 describes the 380 control logic of the light strategy adopted in the ADMIN and 381 DITER offices. 382

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 388 Lighting Solutions for Retrofitting Buildings [21], has outlined 389 the saving results obtained in a large number of experimen-390 tal or simulation studies focused on the implementation of 391 electric lighting-control systems as a retrofitting measure to 392 reduce energy use in buildings [22]. The saving potentials 393 vary greatly, according to the context, the type of building, 394 and the building features, such as daylight availability and 395 occupancy profile. Furthermore, great differences have been 396 found between simulation results and field studies: the former 397 has overestimated the savings compared to the latter. The study 398 has reported the following saving results with respect to the 399 different possible lighting-control strategies: manual controls 400 23%–77%; time scheduling 12%; occupancy control 20%–93% 401 (highly dependent on space occupancy and the time delay); 402 daylight harvesting 10%–93%; combined daylight harvesting 403 and occupancy 26%. According to another study [20], which 404 has analyzed lighting energy savings from the literature—240 405 saving estimates from 88 papers and case studies, categorized 406 as daylighting strategies, occupancy strategies, personal tun-407 ing, and institutional tuning—"the best estimates of average 408 lighting energy-saving potential are 24% for occupancy, 28% 409 for daylighting, 31% for personal tuning, 36% for institutional 410 tuning, and 38% for multiple approaches." Again, it has been 411 highlighted that "simulations significantly overestimate (by at 412 least 10%) the average savings obtainable from daylighting in 413 actual buildings." 414

A very wide range of saving potentials for each control strategy has also been confirmed in another extensive literature 416 review carried out by a dedicated Technical Committee of the 417 CIE Division 3 [23]. For instance, a large bandwidth of savings (20%–70%) has been pointed out for daylight harvesting 419 strategies, while savings ranging from 28% to 60% have been 420 reported for occupancy-sensing strategies. 421

In this project, the savings expected from the implementation 422 of the proposed lighting-control strategies were first estimated 423 through energy simulations and then evaluated by analyzing the data that were measured through the ICT-based management 425 system. 426

In this section, the main results concerning the energy consumption of lighting systems are summarized. The results of the 429 energy simulation and of the monitoring have been separated, as 430 have those of the two pairs of offices, DITER and ADMIN. The 431 analysis period for the monitoring results was October 2013– April 2014, so as to take into account a period in which the use 433 of electric lighting is more prevalent. In fact, it was observed 434 that lights are almost always switched off during the operating 435 hours in summer, due to the high daylight availability. 436

### A. Results of the Energy Simulations Carried Out in the Early 437 Stages of the Project 438

Lighting simulations were carried out in the early stages of 439 the project in order to estimate and compare the electric lighting 440 energy demand of the R and T rooms. The simulation results 441 were then used to optimize the control strategy on the basis of 442 the characteristics of the specific rooms. 443

444 Parametric 3-D models were imported into the Radiance and 445 Daysim lighting simulation tools using the Ecotect software. Radiance and Daysim were used because of the interoperability 446 between the software packages. Radiance was used to vali-447 448 date the models, while Daysim was adopted to estimate the energy demand for electric lighting and the savings that could 449 be obtained with the proposed control strategies. Daysim allows 450 an annual simulation to be run for a given site. Factors such 451 452 as the specific dynamic climate conditions, the lighting power 453 installed in the room, the type of lighting-control system, the 454 occupancy profile, the lighting requirements (the target illuminance value), and the user behavior are taken into account in 455 the simulation. An initial validation of the model has been con-456 ducted by comparing the output of the Radiance simulations 457 (illuminance distribution) with the illuminance values mea-458 sured in the corresponding rooms. After the validation phase, 459 a set of simulations was run for each room using Daysim, in 460 which the defined control strategies were introduced as input 461 and the corresponding energy demand for lighting was calcu-462 lated [in (kWh/m<sup>2</sup>year)]. The simulations were initially carried 463 out considering "mixed user behavior" (some users are active 464 and some passive with respect to the use of electric lighting and 465 blinds) and were then repeated considering only "active user 466 467 behavior." The potential savings were estimated comparing the energy demand for the new control systems and the currently 468 469 installed ones [24], [25].

470 The following savings were obtained from the simulations:

471 1) *the DITER offices:* 29% with mixed user behavior and
472 64% with active user behavior;

473 2) *the ADMIN offices:* 27% with mixed user behavior and
474 70% with active user behavior.

### 475 B. Results of the Monitoring Activity

476 *1) DITER Offices:* Fig. 4 and Table I show the main results 477 (which were found) with regard to the lighting energy use in the 478 T and R offices. Considering the whole analysis period, the T 479 room showed higher absolute energy consumption for lighting 480 than the R room [+47.5%, Fig. 4(a), continuous lines]. This 481 unexpected performance appears to be due to the following 482 combination of factors.

483 1) A high parasitic consumption, due to the stand-by power 484 and sensor noise [Fig. 4(b) and (c)]. If this parasitic consumption was to be subtracted from the energy con-485 486 sumption of both the T and R rooms [a constant power of 4 W was subtracted for each time-step during which 487 488 the lights are off, as this was found to be the value 489 which occurred the most; see Fig. 6(a)], the absolute consumption for the two rooms would become comparable 490 491 [+2.6% for the T room; see Fig. 4(a), dashed lines]. The power was calculated from the measured energies, for a 492 493 resolution of the sensor of 4 Wh and an acquisition interval of 15 min (thus resulting in a power of 4 W per each 494 15 min). 495

496 2) The occupancy time in the T and R rooms is comparable
497 (+6.4% for the T room for the whole analysis period),
498 but the lights remain on for more hours in the T room
499 (+58.5%).



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

T1:1 TABLE I T1:2 Summary of the Energy Results for the DITER Offices

Analysis factor	$\Delta(T;R)^a$
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%

<sup>a</sup>Calculated through the formula:  $(T - R)/R^*$  100.

500 3) During the periods when the lights are on in the T room, they are dimmed by the control system for 88.2% of 501 the time, with a mean percent of dimming of 63.7%. 502 Furthermore, the control system sets the luminaires at a 503 maximum power, which is lower than the maximum value 504 [Fig. 4(d)]. The control system seems to work effectively 505 506 by dimming the light output in response to the natural environmental brightness. 507

It is worth stressing that this latter factor (dimming of the 508 light output in the T room) is a positive aspect for the T room 509 and should lead to a decrease in energy consumption, com-510 511 pared to the R room. Nevertheless, this positive performance is 512 counterbalanced by the other previously described factors (sensor noise, stand-by power, occupancy profile, and hours during 513 514 which the lights remain on). Among all these factors, the standby power and sensor noise play the most important roles on the 515 final consumption. The energy consumed during the analysis 516 517 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 518 energy consumed for each hour of occupancy was similar for 519 the two rooms (-4.8%). These data are more in line with the 520 expected and simulated results. 521

*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.

529 1) The different characteristics of the lighting systems in the530 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).
- 540 2) *The different behavior of the occupants:* The T room is
  541 occupied less than the R room (-22.2% for the whole
  542 heating period); consistently, lights are kept on for fewer
  543 hours (-26.6%).



Fig. 5. Summary of the energy and power consumption for the ADMIN offices. F5:1

T2:1 TABLE II T2:2 Summary of the Energy Results for the ADMIN Offices

Analysis factor	$\Delta(T;R)^a$
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%

<sup>a</sup>Calculated through the formula:  $(T - R)/R^*$  100.



F6:1 Fig. 6. Occurrence frequencies of the recorded power values in the DITER F6:2 (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 556 rooms was of the same magnitude [-71.4%, Fig. 5(a), dashed 557 line].

On the whole, these results show that the control system 559 in the T room (i.e., electric light management based on day-560 light levels and considering the absence of the occupants) led 561 to rather remarkable energy savings. The global energy con-562 sumed (excluding the sensor noise) for each occupancy hour 563 was found to be significantly lower in the T room than in the 564 R room (-64.3%); the same applies if the energy consumption 565 is expressed per number of hours with lights on (-62.2%). It 566 should also be noted that the stand-by power of the sensors and 567 actuators in the T room was not recorded by the ST smart plug 568 as they were managed directly by the centralized Desigo system 569 and could not be extrapolated from the overall data. 570

### V. DISCUSSION AND CONCLUSION 571

The huge amount of data measured and managed in the 572 SEEMPubS project has been used to analyze the impact 573 of lighting-control strategies (photodimming and occupancy 574 based), compared to simple manual on-off switches. The mea-575 sured data were highly heterogeneous with regard to both the 576 sensor type employed in the different rooms and to the different 577 acquisition intervals recorded by each type of sensor (temper-578 ature, occupancy, brightness, and energy). All the data were 579 "synchronized" to the same time interval (5 min) to allow a 580 comparison to be made between the different datasets. One of 581 the merits of the methodology presented in this paper is the 582 "synchronization" algorithm, which allowed all the measured 583 data to be aligned to the same time-steps. 584

On the other hand, some criticalities emerged from the 585 data analysis and they need to be pointed out. Analyzing the 586 results, a "performance gap" was found between the expected 587 performance (based on the simulation results) and the actual 588 performance observed in the real rooms. This was particularly 589 evident for the DITER offices. The energy consumption of the 590 test room was influenced to a great extent by the stand-by power 591 of the actuators and lamp ballasts and by the sensor noise, as 592 shown in Fig. 6, where the parasitic consumption is represented 593 by the recurrent 4 W. This parasitic consumption represents 594 more than 30% of the global energy consumed in the test 595 room. This result is in line with what has been found in other 596 researches [26], [27], but it also seems to have been influenced 597 by the characteristics of the sensor, which was in fact designed 598 to measure greater loads (not for a single office). Therefore, 599 the minimum reading step is greater than the minimum power 600 absorbed by the devices, which remain in stand-by throughout 601 the whole 24 h. Furthermore, the sensor was a prototype and 602 several false measurements (sensor noise) were recorded. The 603 data recorded when the lights were off, particularly during the 604 nighttime, in the rooms without stand-by loads, were consid-605 ered as sensor noise (this is the case of both the R and T room 606 in the ADMIN offices and of the R room in the DITER offices). 607

Furthermore, the data have shown that the control system in 608 the T room actually dims the light output when the room is 609 occupied [Fig. 4(d)], but the lights remain on for more hours 610 (Table I). This could be ascribed to two aspects: a limited 611 612 capacity of the photo-sensor in the T room to switch the lights 613 off when there is sufficient daylight or a "low attitude" of the 614 occupants of the R room to switch the lights on when there is 615 insufficient daylight (with respect to the target illuminance used 616 to set the dimming system in the T room). It has emerged, from 617 an analysis of the monitored data, that both conditions could 618 have occurred.

A "performance gap" was also found for the ADMIN offices, 619 but to a lesser extent; in this case, energy savings were actu-620 621 ally obtained, due to the photodimming and the implementation 622 of occupancy sensors, but they appear to be higher than could 623 be expected. This result is probably also due to the fact that the stand-by power of the sensors and actuators could not be 624 625 recorded by the system that was implemented for the present project. 626

In general, it appears evident that the high number of vari-627 ables that influence the final energy performance is hard to 628 manage in the design stages, and large differences may be found 629 between the expected and actual performance. One of the hard-630 est variables to describe seems to be the occupants' behavior, in 631 terms of actual occupancy profiles and attitude toward switch-632 ing lights on and off. It is also worth noting that analyzing the 633 energy performance, in terms of total energy consumption, may 634 635 lead to results that are very different from those that are found when the absolute total energy consumption is "normalized," 636 637 considering the number of actual monitored occupancy hours (which was adopted to overcome the problem of the quite dif-638 639 ferent occupancy patterns in the T and R rooms) or considering 640 the number of hours when lights were detected to be on (to account for the actual electric light use during the occupancy 641 642 time). This was found to be particularly evident for the DITER offices: comparing the total energy consumption, in absolute 643 terms, showed a higher consumption in the T room than in the 644 R room (+47.5%), while using the ratio of the consumption to 645 the number of occupancy hours or the ratio of the consumption 646 to the number of hours with lights on in the T room (after sub-647 648 tracting the parasitic power) shows a better performance than that of the R room (-4.8% and -36.1%, respectively). 649

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



Fig. 7. Power, occupancy, and brightness profiles for a single day in the DITER F7:1 offices. F7:2



Fig. 8. ADMIN: example of the relationship between environment brightness F8:1  $E_{\rm wp}$  and consumed power for the T room (back of the room). F8:2

two rooms comparable. Under these conditions, the energy con-661 sumption was found to be lower in the T room (-38.1%) than 662 in the R room. As a more general consideration, it is possible to 663 state that although on one hand, the global consumption during 664 the course of a year or throughout a season (heating or cooling) 665 is an important metric for the energy manager of a facility; on 666 the other hand, if the aim is to compare two different lighting-667 control technologies implemented in different rooms, different 668 metrics could be more advantageous: for instance, the energy 669 consumed per actual occupancy hour or the energy consumed 670 per hour with lights on could be used for this purpose. 671

Another criticality that was observed concerns the monitor-672 ing of the lighting amount on the working plane  $E_{\rm wp}$  through 673 the photosensor used to dim the lights. Owing to the features 674 and position of the sensors (ceiling-mounted and suspended), 675 the brightness data monitored in the four rooms were not always 676 useful to verify the actual lighting condition over the work 677 plane [28]. These sensors measured the environment brightness 678 in the room, which was then converted into the correspond- 679 ing  $E_{\rm wp}$  value through a calibration process for each room. 680 Fig. 8 shows the  $E_{wp}$  levels recorded by Gigahertz data loggers 681 (which were used to calibrate the brightness sensor) compared 682 to the ambient brightness measured by the SEEMPubS sensors. 683 In the ADMIN offices, which are unilateral daylit spaces, the 684 685 brightness responds to the variation in the daylighting levels (which hit the sensor more directly), but fails to correctly record 686 the increase in horizontal illuminance when electric lights are 687

switched on (which is measured indirectly). 688

- 689 In conclusion, the main results which have been obtained by comparing the energy consumption in the T and R rooms are as 690 691 follows.
- 1) The measured energy is influenced by a parasitic power 692 693 consumption, due to the stand-by power of the luminaires and to sensor noise. A somewhat similar behavior 694 695 (increase in sensor noise during the night hours as the sensors falsely detected the presence of an individual when 696 697 the room was actually empty) was also reported in a study by Gonzalez et al. [29]. In this case, and particularly for 698 the DITER Test office, the parasitic consumption is also 699 700 influenced to a great extent by the features of the sen-701 sor (larger minimum reading step than the actual stand-by 702 power).
- 2) The energy performance of both the ADMIN and DITER 703 offices observed in real rooms was influenced to a great 704 extent by the occupants' behavior (especially concern-705 ing the attitude of individuals to switch lights on and to 706 keep them on during the working hours). As a conse-707 quence, the consumption significantly differed from what 708 was expected during the design stage (when all decisions 709 were based on simulation results). This result is in line 710 with what was observed in [30] and [31]. 711
- 3) The choice of measuring the  $E_{wp}$  indirectly, by measur-712 ing the environment brightness through ceiling-mounted 713 714 or suspended sensors, implied a complex calibration process. Installing illuminance sensors directly on the work 715 716 plane seems to be a more reliable solution for future
- 717 applications.

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### ACKNOWLEDGMENT

The authors would like to thank G. Carioni (Livinglab, 719 Politecnico di Torino) for building the algorithm used to syn-720

chronize the recorded data. 721

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# 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

5 Abstract—This paper presents some results of a project that has been aimed at developing an event-driven user-centric middle-6 7 ware for the monitoring and management of energy consumption in already existing public buildings. One of the strengths of the 8 9 designed system is that it allows an easy integration of heteroge-10 neous technologies and their hardware-independent interoperability. This is a feature of great importance for existing buildings, 11 12 where already existing controls could be integrated with new 13 technologies to enhance the energy efficiency of a building. The 14 functionality of the system has been tested in a number of representative spaces of already existing public buildings, where the 15 16 already installed HVAC and lighting services have been equipped with monitoring and actuating systems designed and implemented 17 using commercial off-the-shelf wired and wireless devices. This 18 19 paper focuses on the energy aspects, which have been obtained by 20 applying the designed system to monitor and control the electric 21 lighting fixtures of different office spaces. The outcomes obtained 22 from the monitored data have shown some significant differences 23 from the expected and previously estimated energy saving results, and this paper offers some possible explanations. Some criti-24 25 calities, in part related to the characteristics of the commercial 26 off-the-shelf adopted devices and in part to the difficulties encoun-27 tered in monitoring and analyzing the huge number of recorded 28 data, are outlined.

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

### I. INTRODUCTION

Big NERGY 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

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.

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Digital Object Identifier 10.1109/TIA.2016.2526969

Innovation to mitigate climate changes by reducing CO<sub>2</sub> emis-36 sions and to boost economic growth by accelerating the spread 37 of innovative technological solutions [1], [2]. It is well known 38 that the building sector is one of the main causes of the final 39 global energy consumption: buildings consume nearly one-40 third of the final global energy and are responsible for about 41 one-third of the total direct and indirect energy-related CO2 42 emissions [3]. Several policy instruments have been devised to 43 limit building pressure on the energy sector since the 1990s. 44 Building energy codes were initially only focused on new 45 residential buildings, but then they have progressively been 46 expanded to include new nonresidential buildings and, more 47 recently, to cover existing buildings when they undergo reno-48 vations or alterations [4]–[6]. 49

At present, new building constructions represent a small vol-50 ume in developed countries. Furthermore, more than half the 51 current global building stock is still expected to be standing 52 in 2050, and a building can generally last over 100 years. 53 As a consequence, actions on existing private and public 54 buildings have become a key instrument in achieving major 55 reductions in energy consumption and  $CO_2$  emissions [3]. 56 Existing public buildings can consume large amounts of energy, 57 due to a number of concurring factors, such as the pres-58 ence of low-performance envelopes, old and scarcely efficient 59 plant-engineering technologies, a lack of effective building 60 management systems (BMS) or building automation and con-61 trol (BCA), an irresponsible and unaware interaction of users 62 toward the systems. A combined implementation of different 63 intervention policies should be addressed and put into prac-64 tice to achieve a smaller carbon footprint for existing buildings. 65 One strategy, for instance, could concern building renova-66 tions through energy-conservation measures (ECMs), such as 67 envelope optimization and the retrofitting of existing plants 68 and appliances with new energy-efficient technologies and 69 advanced controls (HVAC and lighting). Other strategies could 70 rely on the use of renewable energies and on the integration 71 of ICT solutions for the management of building energy use. 72 Such ICT solutions could support Demand-Side Management 73 in order to increase, through smart grids, the efficiency of build-74 ing energy consumption. All these intervention policies have 75 been regulated by the European Energy Efficiency Directive 76 (EED 2012/27/EU) [7] and the related directives and national 77 standards on the Energy Performance of Buildings (EPBD) 78 [4], [5] as well as the Ecodesign and Energy Labeling of 79 Energy-related Products (ErP) [8], [9]. 80

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Nevertheless, several economic and noneconomic barriers 81 are still encountered in the implementation of the measures 82 needed to enhance the energy savings of existing buildings. 83 These barriers are mainly concerned with aspects pertaining to 84 85 higher initial costs, a lack of information, a lack of user awareness toward technologies and their potential energy savings, as 86 well as to difficulties in the management operations. Among 87 all the possible ECMs, upgrading system technologies-for 88 89 instance, by replacing traditional lighting systems with new 90 highly efficient LED solutions, or implementing and deploying 91 ICT for building management and monitoring processes-92 could be a cost-effective solution for the renovation of existing 93 buildings [10]-[12]. Solutions that are able to reduce the need 94 for construction works are of particular value.

On this basis, a project named Smart Energy-Efficient 95 Middleware for Public Spaces (SEEMPubS) has been designed 96 97 and carried out, within the 7th European Research Framework 98 Program, with the main objective of exploiting ICT-based mon-99 itoring and control systems to reduce energy usage and the  $CO_2$  footprint in public buildings. Existing buildings are some-100 101 times equipped with BMS for a coarse grain control of their systems, and new technologies, such as wireless sensors and 102 actuator networks (WSAN), are nowadays available to achieve 103 new systems or to extend existing ones. In both cases, the 104 issue of interoperability should be addressed and solved so that 105 106 these technologies can become widespread. The SEEMPubS project has led to the development of a middleware for embed-107 108 ded systems that is aimed at creating services and applications across heterogeneous devices in order to develop an energy-109 aware platform. This platform has been constructed to be open 110 111 to future developments, in terms of further energy-efficiency 112 measures or demand-side energy management through smart 113 grids.

114 A number of representative spaces in some buildings belonging to the Politecnico di Torino, Italy, were chosen as case 115 studies for demonstration purposes. The selected rooms are 116 117 characterized by preexisting technical plants and in some cases also by existing BMS. The possibility of installing new BMS or 118 implementing the existing ones has been explored within this 119 project, and in particular, commercial off-the-shelf devices have 120 been used to set up the new system or to integrate the existing 121 122 BMS with new sensors and actuator networks. Both wired and 123 wireless solutions were designed and tested.

In order to test the efficacy of the designed solutions, in terms 124 125 of energy savings, the demonstration spaces were selected so as to have "pairs" of similar rooms: one room (reference room) 126 127 was left with the existing plants and without a management sys-128 tem, while the system developed in the project was installed in 129 the other room (test room). Each room was monitored throughout the whole project, and all the obtained data were transferred 130 to a centralized database. 131

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 139 MANAGEMENT OF BUILDINGS 140

The coexistence of several heterogeneous technologies and 141 the lack of interoperability between them is a well-known 142 issue. Devices such as OLE for process control unified archi-143 tecture (OPC UA) try to solve these problems for classic 144 BMS by providing abstraction layers. However, it should be 145 considered that other technologies are also adopted in these 146 buildings. A middleware approach has been adopted in the 147 SEEMPubS project to handle the issues of interoperability and 148 to be open toward future developments. The basis was the 149 open-source LinkSmart middleware [14], which is a generic 150 service-oriented middleware for Ubiquitous Computing. This 151 was developed into a middleware for smart energy-efficient 152 buildings. This middleware provides reusable and extensible 153 components and concepts for reoccurring tasks and problems in 154 future smart buildings, and the development implemented in the 155 SEEMPubS project consists of a three-layered architecture with 156 an integration proxy layer, a service layer, and an application 157 layer. 158

### A. Integration Proxy Layer

The infrastructure which has been developed relies upon an 160 ICT infrastructure made up of heterogeneous monitoring and 161 actuation devices, such as wireless sensor and actuator net- 162 work (WSAN). In order to improve backward compatibility, 163 the infrastructure also supports wired technologies that exploit 164 different protocols (BACnet and LonWorks). 165

159

The Proxy is a concept that describes the integration of a 166 specific technology in a LinkSmart application. A proxy acts as 167 a bridge between the LinkSmart network and the underlying 168 technology. It translates whatever kind of language the low-169 level technology speaks into LinkSmart Web Services, and the 170 low-level technology can, therefore, be used transparently by 171 any other LinkSmart component. This concept allows each low-172 level technology to be used transparently inside the LinkSmart 173 network. 174

The integration proxy layer is the lowest layer of the devel-175 oped Middleware for the efficient management of building 176 energy. It integrates a specific technology with the middleware 177 infrastructure by abstracting its functionalities and translat-178 ing whatever kind of language the low-level device speaks 179 into a web service. Exploiting this approach, interoperability 180 between heterogeneous devices is enabled, and any other mid-181 dleware component or application can use a specific technology 182 transparently. 183

Different integration proxies have been developed to manage 184 several types of WSANs (plugwise and ST Microelectronics 185 Smart Plug commercial end node with ZigBee protocol; 186 EnOcean protocol stack commercial end nodes). In addition, an 187 integration proxy has been developed to allow interoperability 188 with OPC UA, which incorporates all the functionalities pro-189 vided by different standards, such as BACnet or LonWorks. 190 Hence, backward compatibility with wired technologies is 191 enabled and integrated in the new middleware. Because of the 192 modularity achieved by means of the deployment of Integration 193 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.

### 198 B. Service Layer

Three main functionalities were implemented in the servicelayer of the Middleware.

201 1) Secure Communication: The middleware generates a 202 peer-to-peer network in which web service calls are routed through the LinkSmart Network Manager, thus creating a sim-203 ple object access protocol (SOAP) tunnel to the requested 204 service endpoint. This concept allows direct communication 205 among all the devices in the middleware network. Furthermore, 206 207 the middleware provides components that enable message 208 encryption and trust management [15].

2) Event-Based Communication: Building automation sys-209 tems generally need to react to events that happen in a given 210 building. Sensors publish events that lead to a certain reaction, 211 such as switching lights on after an incoming motion event. 212 The proposed middleware includes an Event Manager, which is 213 a specific component that implements the published approach 214 [16]. This allows loosely coupled event-based systems, which 215 increase the scalability of the whole software infrastructure, to 216 217 be developed. This mechanism is a key requirement for smart buildings, in which a high number of sensor events occur, to 218 219 develop systems and applications.

3) Semantic Knowledge: The context and ontology frame-220 221 works are two complementary components, which together manage semantic knowledge about the application domain and 222 223 the implemented system. This knowledge includes metadata on 224 the sensors and actuators, but also on their relationship with the domain model objects, such as the appliances, buildings, 225 and rooms. Moreover, the context framework provides a con-226 venient entry point for application developers as it exposes a 227 228 simple JavaScript Object Notation (JSON) API. Hence, developers can have access to any kind of information from a rich 229 domain model. 230

### 231 C. Application Layer

The Application Layer is the highest layer in the proposed infrastructure. It is dedicated to developing distributed eventbased 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.

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### 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



Fig. 1. Link between the construction age, costs, and difficulty in installing F1:1 sensors for the different buildings considered as case studies. F1:2

was to define technologies that could be replicated in other 246 already existing buildings in Europe with similar features. The 247 buildings that were selected are located in three different sites 248 in the city: 1) the historical campus building (The Valentino 249 Castle), which dates back to the beginning of the 16th century; 2) the old campus site, which is still the main campus 251 for the Engineering Faculties and was constructed in 1958; and 252 3) the modern campus site, which was created from a complex 253 refurbishment of a former industrial area. 254

Each building obviously required a specific solution for the 255 installation of new sensors and controls for the HVAC and light-256 ing systems [17]. The modern campus was already equipped 257 with a basic BMS (Desigo by Siemens): new sensors and 258 control rules were implemented to optimize energy use. New 259 sensors were installed in the main campus in a wired system. 260 The value of the paintings and stuccoes in the historical build-261 ing made the installation of sensors a difficult task: in this 262 case, each room required a specific solution, and only wireless 263 sensors were considered. 264

The diagram in Fig. 1 shows the connection between the 265 building construction period, the existing technologies, the sen-266 sor installation costs, and the difficulty in the installation of 267 the sensors. A historical building is generally characterized 268 by very few existing technologies as well as high construc-269 tion work costs, related to the difficulty of installing the 270 new technologies that are necessary to preserve any paint- 271 ings, stuccos, or wood/marble floors. Instead, a new building 272 can normally incorporate recent technologies: these can easily 273 be integrated in the structure using false ceilings and floating 274 floors. Moreover, there are also already existing buildings in 275 which new technologies have to be improved significantly, and 276 in this case, the costs and difficulties are closely related to the 277 construction work that is required [18]. 278

3



Sensor installation difficulty

279 Some representative rooms were selected in the buildings in each campus in order to implement the BMS with the new 280 sensor-network infrastructure. The rooms were chosen on the 281 basis of the following criteria: ability to represent the Campus 282283 buildings and other Public buildings; energy-saving potential, according to the architectural, services, and occupancy charac-284 teristics. Both private and public spaces, such as classrooms, 285 student offices, individual offices, and open plan offices, were 286 287 selected.

288 The rooms were selected in pairs: one reference room (R), 289 running with the present systems and with manual controls, and one similar test room (T), where automatic control and moni-290 291 toring were implemented for the lighting, heating/cooling, and electrical appliances. In some rooms, the existing BMS was 292 linked to the new middleware, while in other rooms, a new con-293 294 trol and monitoring system, based on WSAN, was installed and 295 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.
- 3052) The ADMIN offices, which are located in a modern build-306ing of the main Politecnico campus. Both rooms have307large west-facing windows. The R room is equipped with308three ceiling-mounted  $2 \times 36$  W luminaires (T8 fluores-309cent lamps). The T room has a different system, which310consists of three suspended  $2 \times 35$  W luminaires (T5311fluorescent lamps).

### 312 A. Lighting-Control Strategies

The recurrent lighting-control solutions for energy savings 313 are time scheduling, daylight harvesting, occupancy control, or 314 a combination of the previous three. Time scheduling allows 315 the luminaires to be turned on and off automatically at sched-316 uled times in order to avoid wasteful lighting outside working 317 318 hours. Daylight harvesting entails the automatic adjustment of 319 the light flux of luminaires (dimming) in order to maintain a predetermined illuminance in the room, taking the contribution 320 321 of daylight into account. This strategy is especially effective in those rooms or buildings that are characterized by high daylight 322 323 availability and all-day working hours. Occupancy control is 324 based on the detection of the presence or absence of people in a 325 space: lights are then switched on or off accordingly, in order to 326 avoid energy waste produced by lights left on by users who have left the space. The control logic could involve either switching 327 328 on and off (presence detection) or just off (absence detection). 329 A lighting control based on presence detection would only be effective in spaces in which user absence is highly probable, 330 or the users are not too motivated to pay attention to the use 331 of light. Absence detection instead can be fruitfully used in 332 333 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 F2:1 (top) and ADMIN offices (bottom). F2:2

Different lighting-control strategies were implemented in the 334 T spaces, according to the features of the room [19]. Both 335 daylight harvesting and occupancy control were implemented 336 for spaces with high daylight availability and medium userabsence probability. The possibility of overriding the automatic 338 control, via a manual command, was provided for all the different situations. The following strategies were implemented 340 for the two pairs of rooms analyzed in detail in this paper 341 (Fig. 3). 342

1) The *DITER offices*: in the R room, two  $2 \times 35$  W luminaires are controlled manually through an on/off switch 344 (the existing solution was maintained), while the same 345 luminaires in the T room are controlled through a new 346 WSAN, which includes a wireless switch, a photosensor, and an occupancy sensor. These are all connected 348 to a wireless actuator, which communicates via Enocean 349



F3:1 Fig. 3. Control logic implemented in the DITER and ADMIN test offices. In
F3:2 both cases, daylight harvesting and absence control were used because of the
F3:3 high annual daylight availability.

350	protocol to	the network	access	point.	The	following
351	devices are	used in the ne	twork:			

- 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;

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- c) an ST-Microlectronics smart-plug prototype to mon itor the energy consumption (ZigBee) of both the
   luminaires and the actuator.
- 2) The ADMIN offices: three ceiling-mounted  $2 \times 36$  W 359 luminaires in the R room are controlled through a sin-360 gle on/off switch (preexistent solution), while three sus-361 pended 2  $\times$  35 W luminaires are controlled in the 362 363 T room through the already existing commercial BMS 364 (Desigo by Siemens) with two wired photo-sensors and 365 two occupancy sensors (one to control the area close to the windows and the other for the back part of 366 the room). ST-Microlectronics prototypes of smart plugs 367 were used to monitor the energy consumption. In this 368 case, the luminaire consumption was only monitored by 369 370 the energy meters. The Siemens Desigo system was integrated with the general middleware developed in the 371 372 project.

As fluorescent light fittings have recently been installed in 373 both the DITER and ADMIN spaces, it was decided not to 374 375 replace them with LED systems. Furthermore, it should be 376 recalled that the goal of the project was to demonstrate the effectiveness of the ICT-based management solution in improv-377 ing the building energy efficiency rather than to estimate the 378 savings achievable by retrofitting the lighting plants with new, 379 more energy-efficient lamp technologies. Fig. 3 describes the 380 control logic of the light strategy adopted in the ADMIN and 381 DITER offices. 382

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 388 Lighting Solutions for Retrofitting Buildings [21], has outlined 389 the saving results obtained in a large number of experimen-390 tal or simulation studies focused on the implementation of 391 electric lighting-control systems as a retrofitting measure to 392 reduce energy use in buildings [22]. The saving potentials 393 vary greatly, according to the context, the type of building, 394 and the building features, such as daylight availability and 395 occupancy profile. Furthermore, great differences have been 396 found between simulation results and field studies: the former 397 has overestimated the savings compared to the latter. The study 398 has reported the following saving results with respect to the 399 different possible lighting-control strategies: manual controls 400 23%–77%; time scheduling 12%; occupancy control 20%–93% 401 (highly dependent on space occupancy and the time delay); 402 daylight harvesting 10%–93%; combined daylight harvesting 403 and occupancy 26%. According to another study [20], which 404 has analyzed lighting energy savings from the literature—240 405 saving estimates from 88 papers and case studies, categorized 406 as daylighting strategies, occupancy strategies, personal tun-407 ing, and institutional tuning—"the best estimates of average 408 lighting energy-saving potential are 24% for occupancy, 28% 409 for daylighting, 31% for personal tuning, 36% for institutional 410 tuning, and 38% for multiple approaches." Again, it has been 411 highlighted that "simulations significantly overestimate (by at 412 least 10%) the average savings obtainable from daylighting in 413 actual buildings." 414

A very wide range of saving potentials for each control strategy has also been confirmed in another extensive literature 416 review carried out by a dedicated Technical Committee of the 417 CIE Division 3 [23]. For instance, a large bandwidth of savings (20%–70%) has been pointed out for daylight harvesting 419 strategies, while savings ranging from 28% to 60% have been 420 reported for occupancy-sensing strategies. 421

In this project, the savings expected from the implementation 422 of the proposed lighting-control strategies were first estimated 423 through energy simulations and then evaluated by analyzing the data that were measured through the ICT-based management 425 system. 426

In this section, the main results concerning the energy consumption of lighting systems are summarized. The results of the 429 energy simulation and of the monitoring have been separated, as 430 have those of the two pairs of offices, DITER and ADMIN. The 431 analysis period for the monitoring results was October 2013– April 2014, so as to take into account a period in which the use 433 of electric lighting is more prevalent. In fact, it was observed 434 that lights are almost always switched off during the operating 435 hours in summer, due to the high daylight availability. 436

### A. Results of the Energy Simulations Carried Out in the Early 437 Stages of the Project 438

Lighting simulations were carried out in the early stages of 439 the project in order to estimate and compare the electric lighting 440 energy demand of the R and T rooms. The simulation results 441 were then used to optimize the control strategy on the basis of 442 the characteristics of the specific rooms. 443

444 Parametric 3-D models were imported into the Radiance and 445 Daysim lighting simulation tools using the Ecotect software. Radiance and Daysim were used because of the interoperability 446 between the software packages. Radiance was used to vali-447 448 date the models, while Daysim was adopted to estimate the energy demand for electric lighting and the savings that could 449 be obtained with the proposed control strategies. Daysim allows 450 an annual simulation to be run for a given site. Factors such 451 452 as the specific dynamic climate conditions, the lighting power 453 installed in the room, the type of lighting-control system, the 454 occupancy profile, the lighting requirements (the target illuminance value), and the user behavior are taken into account in 455 the simulation. An initial validation of the model has been con-456 ducted by comparing the output of the Radiance simulations 457 (illuminance distribution) with the illuminance values mea-458 sured in the corresponding rooms. After the validation phase, 459 a set of simulations was run for each room using Daysim, in 460 which the defined control strategies were introduced as input 461 and the corresponding energy demand for lighting was calcu-462 lated [in (kWh/m<sup>2</sup>year)]. The simulations were initially carried 463 out considering "mixed user behavior" (some users are active 464 and some passive with respect to the use of electric lighting and 465 blinds) and were then repeated considering only "active user 466 467 behavior." The potential savings were estimated comparing the energy demand for the new control systems and the currently 468 469 installed ones [24], [25].

470 The following savings were obtained from the simulations:

471 1) *the DITER offices:* 29% with mixed user behavior and
472 64% with active user behavior;

473 2) *the ADMIN offices:* 27% with mixed user behavior and
474 70% with active user behavior.

### 475 B. Results of the Monitoring Activity

476 1) *DITER Offices:* Fig. 4 and Table I show the main results 477 (which were found) with regard to the lighting energy use in the 478 T and R offices. Considering the whole analysis period, the T 479 room showed higher absolute energy consumption for lighting 480 than the R room [+47.5%, Fig. 4(a), continuous lines]. This 481 unexpected performance appears to be due to the following 482 combination of factors.

- 483 1) A high parasitic consumption, due to the stand-by power 484 and sensor noise [Fig. 4(b) and (c)]. If this parasitic consumption was to be subtracted from the energy con-485 486 sumption of both the T and R rooms [a constant power of 4 W was subtracted for each time-step during which 487 488 the lights are off, as this was found to be the value 489 which occurred the most; see Fig. 6(a)], the absolute consumption for the two rooms would become comparable 490 491 [+2.6% for the T room; see Fig. 4(a), dashed lines]. The power was calculated from the measured energies, for a 492 493 resolution of the sensor of 4 Wh and an acquisition interval of 15 min (thus resulting in a power of 4 W per each 494 495 15 min).
- 496 2) The occupancy time in the T and R rooms is comparable
  497 (+6.4% for the T room for the whole analysis period),
  498 but the lights remain on for more hours in the T room
  499 (+58.5%).



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

T1:1 TABLE I T1:2 SUMMARY OF THE ENERGY RESULTS FOR THE DITER OFFICES

Analysis factor	$\Delta(T;R)^a$
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%

<sup>a</sup>Calculated through the formula:  $(T - R)/R^*$  100.

500 3) During the periods when the lights are on in the T room, they are dimmed by the control system for 88.2% of 501 the time, with a mean percent of dimming of 63.7%. 502 Furthermore, the control system sets the luminaires at a 503 maximum power, which is lower than the maximum value 504 [Fig. 4(d)]. The control system seems to work effectively 505 506 by dimming the light output in response to the natural environmental brightness. 507

It is worth stressing that this latter factor (dimming of the 508 light output in the T room) is a positive aspect for the T room 509 and should lead to a decrease in energy consumption, com-510 511 pared to the R room. Nevertheless, this positive performance is 512 counterbalanced by the other previously described factors (sensor noise, stand-by power, occupancy profile, and hours during 513 514 which the lights remain on). Among all these factors, the standby power and sensor noise play the most important roles on the 515 final consumption. The energy consumed during the analysis 516 517 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 518 energy consumed for each hour of occupancy was similar for 519 the two rooms (-4.8%). These data are more in line with the 520 expected and simulated results. 521

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.

529 1) The different characteristics of the lighting systems in the530 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).
- 540 2) *The different behavior of the occupants:* The T room is
  541 occupied less than the R room (-22.2% for the whole
  542 heating period); consistently, lights are kept on for fewer
  543 hours (-26.6%).



Fig. 5. Summary of the energy and power consumption for the ADMIN offices. F5:1

T2:1 TABLE II T2:2 Summary of the Energy Results for the ADMIN Offices

Analysis factor	$\Delta(T;R)^a$
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%

<sup>a</sup>Calculated through the formula:  $(T - R)/R^*$  100.



F6:1 Fig. 6. Occurrence frequencies of the recorded power values in the DITER F6:2 (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 556 rooms was of the same magnitude [-71.4%, Fig. 5(a), dashed 557 line].

On the whole, these results show that the control system 559 in the T room (i.e., electric light management based on day-560 light levels and considering the absence of the occupants) led 561 to rather remarkable energy savings. The global energy con-562 sumed (excluding the sensor noise) for each occupancy hour 563 was found to be significantly lower in the T room than in the 564 R room (-64.3%); the same applies if the energy consumption 565 is expressed per number of hours with lights on (-62.2%). It 566 should also be noted that the stand-by power of the sensors and 567 actuators in the T room was not recorded by the ST smart plug 568 as they were managed directly by the centralized Desigo system 569 and could not be extrapolated from the overall data. 570

### V. DISCUSSION AND CONCLUSION 571

The huge amount of data measured and managed in the 572 SEEMPubS project has been used to analyze the impact 573 of lighting-control strategies (photodimming and occupancy 574 based), compared to simple manual on-off switches. The mea-575 sured data were highly heterogeneous with regard to both the 576 sensor type employed in the different rooms and to the different 577 acquisition intervals recorded by each type of sensor (temper-578 ature, occupancy, brightness, and energy). All the data were 579 "synchronized" to the same time interval (5 min) to allow a 580 comparison to be made between the different datasets. One of 581 the merits of the methodology presented in this paper is the 582 "synchronization" algorithm, which allowed all the measured 583 data to be aligned to the same time-steps. 584

On the other hand, some criticalities emerged from the 585 data analysis and they need to be pointed out. Analyzing the 586 results, a "performance gap" was found between the expected 587 performance (based on the simulation results) and the actual 588 performance observed in the real rooms. This was particularly 589 evident for the DITER offices. The energy consumption of the 590 test room was influenced to a great extent by the stand-by power 591 of the actuators and lamp ballasts and by the sensor noise, as 592 shown in Fig. 6, where the parasitic consumption is represented 593 by the recurrent 4 W. This parasitic consumption represents 594 more than 30% of the global energy consumed in the test 595 room. This result is in line with what has been found in other 596 researches [26], [27], but it also seems to have been influenced 597 by the characteristics of the sensor, which was in fact designed 598 to measure greater loads (not for a single office). Therefore, 599 the minimum reading step is greater than the minimum power 600 absorbed by the devices, which remain in stand-by throughout 601 the whole 24 h. Furthermore, the sensor was a prototype and 602 several false measurements (sensor noise) were recorded. The 603 data recorded when the lights were off, particularly during the 604 nighttime, in the rooms without stand-by loads, were consid-605 ered as sensor noise (this is the case of both the R and T room 606 in the ADMIN offices and of the R room in the DITER offices). 607

Furthermore, the data have shown that the control system in 608 the T room actually dims the light output when the room is 609 occupied [Fig. 4(d)], but the lights remain on for more hours 610 (Table I). This could be ascribed to two aspects: a limited 611 612 capacity of the photo-sensor in the T room to switch the lights 613 off when there is sufficient daylight or a "low attitude" of the 614 occupants of the R room to switch the lights on when there is 615 insufficient daylight (with respect to the target illuminance used 616 to set the dimming system in the T room). It has emerged, from 617 an analysis of the monitored data, that both conditions could 618 have occurred.

A "performance gap" was also found for the ADMIN offices, 619 but to a lesser extent; in this case, energy savings were actu-620 621 ally obtained, due to the photodimming and the implementation 622 of occupancy sensors, but they appear to be higher than could 623 be expected. This result is probably also due to the fact that the stand-by power of the sensors and actuators could not be 624 625 recorded by the system that was implemented for the present project. 626

In general, it appears evident that the high number of vari-627 ables that influence the final energy performance is hard to 628 manage in the design stages, and large differences may be found 629 between the expected and actual performance. One of the hard-630 est variables to describe seems to be the occupants' behavior, in 631 terms of actual occupancy profiles and attitude toward switch-632 ing lights on and off. It is also worth noting that analyzing the 633 energy performance, in terms of total energy consumption, may 634 635 lead to results that are very different from those that are found when the absolute total energy consumption is "normalized," 636 637 considering the number of actual monitored occupancy hours (which was adopted to overcome the problem of the quite dif-638 639 ferent occupancy patterns in the T and R rooms) or considering the number of hours when lights were detected to be on (to 640 account for the actual electric light use during the occupancy 641 642 time). This was found to be particularly evident for the DITER 643 offices: comparing the total energy consumption, in absolute terms, showed a higher consumption in the T room than in the 644 R room (+47.5%), while using the ratio of the consumption to 645 the number of occupancy hours or the ratio of the consumption 646 to the number of hours with lights on in the T room (after sub-647 648 tracting the parasitic power) shows a better performance than that of the R room (-4.8% and -36.1%, respectively). 649

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



Fig. 7. Power, occupancy, and brightness profiles for a single day in the DITER F7:1 offices. F7:2



Fig. 8. ADMIN: example of the relationship between environment brightness F8:1  $E_{\rm WD}$  and consumed power for the T room (back of the room). F8:2

two rooms comparable. Under these conditions, the energy con-661 sumption was found to be lower in the T room (-38.1%) than 662 in the R room. As a more general consideration, it is possible to 663 state that although on one hand, the global consumption during 664 the course of a year or throughout a season (heating or cooling) 665 is an important metric for the energy manager of a facility; on 666 the other hand, if the aim is to compare two different lighting-667 control technologies implemented in different rooms, different 668 metrics could be more advantageous: for instance, the energy 669 consumed per actual occupancy hour or the energy consumed 670 per hour with lights on could be used for this purpose. 671

Another criticality that was observed concerns the monitor-672 ing of the lighting amount on the working plane  $E_{wp}$  through 673 the photosensor used to dim the lights. Owing to the features 674 and position of the sensors (ceiling-mounted and suspended), 675 the brightness data monitored in the four rooms were not always 676 useful to verify the actual lighting condition over the work 677 plane [28]. These sensors measured the environment brightness 678 in the room, which was then converted into the correspond-679 ing  $E_{\rm wp}$  value through a calibration process for each room. 680 Fig. 8 shows the  $E_{wp}$  levels recorded by Gigahertz data loggers 681 (which were used to calibrate the brightness sensor) compared 682 to the ambient brightness measured by the SEEMPubS sensors. 683 In the ADMIN offices, which are unilateral daylit spaces, the 684 685 brightness responds to the variation in the daylighting levels (which hit the sensor more directly), but fails to correctly record 686 the increase in horizontal illuminance when electric lights are 687

switched on (which is measured indirectly). 688

- 689 In conclusion, the main results which have been obtained by comparing the energy consumption in the T and R rooms are as 690 691 follows.
- 1) The measured energy is influenced by a parasitic power 692 693 consumption, due to the stand-by power of the luminaires and to sensor noise. A somewhat similar behavior 694 695 (increase in sensor noise during the night hours as the sensors falsely detected the presence of an individual when 696 697 the room was actually empty) was also reported in a study by Gonzalez et al. [29]. In this case, and particularly for 698 the DITER Test office, the parasitic consumption is also 699 700 influenced to a great extent by the features of the sen-701 sor (larger minimum reading step than the actual stand-by 702 power).
- 2) The energy performance of both the ADMIN and DITER 703 offices observed in real rooms was influenced to a great 704 extent by the occupants' behavior (especially concern-705 ing the attitude of individuals to switch lights on and to 706 keep them on during the working hours). As a conse-707 quence, the consumption significantly differed from what 708 was expected during the design stage (when all decisions 709 were based on simulation results). This result is in line 710 with what was observed in [30] and [31]. 711
- 3) The choice of measuring the  $E_{wp}$  indirectly, by measur-712 ing the environment brightness through ceiling-mounted 713 714 or suspended sensors, implied a complex calibration process. Installing illuminance sensors directly on the work 715 716 plane seems to be a more reliable solution for future
- 717 applications.

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### ACKNOWLEDGMENT

The authors would like to thank G. Carioni (Livinglab, 719 Politecnico di Torino) for building the algorithm used to syn-720

chronize the recorded data. 721

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