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On the application of wireless sensors and actuators network in existing buildings for occupancy detection and occupancy-driven lighting control

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ABSTRACT

Buildings have in recent years been the target of a number of energy efficiency improvement strategies given that they are a major energy end-use sector in most countries. Whilst new buildings due to legislations, increasingly address sustainability and improved energy efficiency considerations, the refurbishment process of older buildings still presents a number of challenges. Advancement in Information and Communication Technology, particularly the application of low-cost Wireless Sensors and Actuators Network does however provide the opportunity to harness yet unrealized energy reduction in existing buildings. This paper presents results from an experimental study evaluating the performance and energy saving potentials of such off-the-shelve, low-cost wireless sensors and actuators network in an existing office building for occupancy detection and occupancy-driven lighting control. The study demonstrates that in addition to improved occupancy information obtainable from Wireless Sensors and Actuators Network, worthwhile savings in the energy consumption of the lighting systems can as well be achieved.

1. Introduction

1.1. Building energy consumption

Buildings, due to the key role they play in the society, represent the largest energy consuming sector in the economy, consuming over one-third of all final energy and half of global electricity [1,2]. In addition, buildings contribute as much as one third of greenhouse gas emissions during their operational phase in both developed and developing countries [3,4]. By 2050, the International Energy Agency(IEA) [2] projects an increase of up to 50% in the energy demand of buildings if steps are not taken to improve energy efficiency. This increase is attributable to rapid growth in the number of households, residential and service floor area, higher ownership rates for existing electricity-consuming devices and increasing demand for new products.

The existing building stock accounts for a significant part of the energy demand in the built environment. In developed economies, at least half of the buildings that will be in use in 2050 have already been built. According to a survey by the U.S. Energy Information Agency, 72 percent of floor stock in the U.S., belongs to buildings over twe nty years old [5]. And in the EU, about 35% of the buildings are over 50 years old [6]. These older buildings most of which are constrained by old equipment, aging infrastructure, and inadequate operational resources, use a great deal of energy. Retrofitting of these older buildings does however represent a great opportunity to achieve worthwhile improvement in energy efficiency and conservation in the built environment [7,8].

Even though renovation represents an opportunity to upgrade the energy efficiency of buildings, the refurbishment rate of existing buildings is still largely low. As noted by the authors in [9,10], the replacement rate of existing buildings with new builds is typically between 1.0–3.0% per annum. This low refurbishment rate is in part largely due to the fact that buildings and its various systems have a rather long-lifespan and retrofitting (i.e., retrofits that include replacing mechanical systems, windows, insulation, lighting systems and other features) requires significant investment [11,12]. This often leads to a situation whereby refurbishments are timed with major renovations or capital-intensive building system replacement.

In recent years, innovation and improvement in information and communication, technology (ICT) as well as in solid-state technology has advanced the application of a number of technologies [13,14], such as wireless sensors and actuators network

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Fig. 1. Test-bed office building.

(WSAN). Wireless sensors and actuators network, which hitherto was considered expensive and underdeveloped for practical large-scale commercial applications is now gaining widespread use in a wide range of applications [15,16]. They have in particular gained widespread use in sectors such as agriculture [16], healthcare [17], smart-grid operation [18] and building operation [19,20]. In building operation in particular, WSAN introduces significant improvement in building operation and management by reducing the complexity of harnessing wired transmission in difficult to reach places [14,21]. In addition, as most building systems are usually in place before occupants' move in, WSAN introduces additional flexibility as it relates to sensor placement [22,23]. This enables obtainability of fine-grained occupancy and indoor environmental parameter information that facilitates improved comfort and energy efficiency.

1.2. Wireless sensors and actuators application in building automation

Buildings today rely on a combination of end-point connections using wired and wireless communication platforms for interconnection of various building systems and processes. Though wired solutions are preferred in majority of cases, wireless devices are becoming more prevalent due to improvement in communication link speed, security, and battery technology [24,25]. Wireless sensors can now boast of batteries having average life spans of up to six years. Wireless sensors as a result nowadays replace, or in some cases augment, traditional hard-wired solutions, resulting in flexible, cost-effective sensing and control solutions in buildings [26,21].

Diverse wireless devices using a variety of communication protocols such as [13,27] Wi-Fi, ZigBee, Z-wave, and Bluetooth as depicted in Table 1, are now commercially available and easily accessible for use in building automation. In addition to modularity and flexibility offered by wireless devices, today's wireless devices are self-organizing, easier to install and maintain [15,28]. Self-organization and modularity of these devices in particular, makes them advantageous in achieving fast, cost effective, less-disruptive and unobtrusive retrofit in existing buildings.

2. Similar studies

2.1. Wireless sensor and actuator application in residential buildings

The residential building sector has in recent years witnessed increased use of WSAN for various applications ranging from occupancy-based control of home appliances and systems [29–31] to more advanced smart home applications [21,32,33]. In [30], the authors demonstrated through experimental data obtained from a seven room, 2100 square foot single-storey ranch-style house built in 1971, that multi-wireless sensor based control strategies for air-conditioning can reduce energy consumption and room-to-room disparities in temperature and humidity compared to a single-sensor temperature threshold thermostat. The authors concluded [30] that the application of comfort based multi-WSN sensors can provide up to 79% normalized energy savings, 32% reduction in room-to-room temperature range, 13% reduction in mean discomfort, and 22% reduction in mean maximum room-to-room difference in discomfort. In a similar study, using wireless sensors for occupancy detection in combination with a smart thermostat, the authors in [29] demonstrated that at very low initial cost per home, energy savings of up to 28% of residential HVAC energy consumption on average can be achieved without sacrificing comfort. In both of these studies however, very little detail relating to the cost effectiveness in relation to the recorded saved energy was provided.

2.2. Wireless sensor and actuator application in commercial office buildings

Whilst the application of WSAN has in recent years being more pronounced in residential buildings [27,34], its application in commercial buildings is beginning to gain momentum. In [35,36], the authors evaluated the competitiveness of wireless sensors in a range of typical building applications and demonstrated that for two different retrofitting applications with WSAN. Though the wireless based systems were reported to be moderately more cost-effective than their wired alternative, the wired sensors did however provide higher data transmission rates.

Modularity and flexibility of wireless devices make it much easier to place sensors at locations in buildings were hitherto sensors could not be placed due to cabling cost or power limitations [37]. This facilitates increased sensing density, as well as increased variety of sensor types that can be applied in a space to make imminent improvements in energy efficiency and building occupants well-being [38]. By using a network of wireless sensors, the authors in [39] showed that the air supply to a large office space can be optimized to improve temperature homogeneity and the operation of the air conditioning system in the space. The authors in [40] on the other hand demonstrated through the use of 27 sensor devices that an accurate analysis of indoor conditions, recognition of inhabitant comfort level, and recommendations on optimal balance between environmental quality and power demands could be achieved in the test-bed building. Wireless sensors also facilitate access to detailed information relating to energy consumption within buildings, as well as the prevailing context under which such consumption occurs. This way, a sophisticated approach to energy control and feedback can be enabled as demonstrated by the authors in [28,40].

The application of WSAN systems has also been shown to enhance the performance of occupancy-driven control applications through the provision of fine-grained occupancy information [41,42]. Building occupancy is a challenging parameter to determine particularly in large commercial buildings where occupants enter and exit buildings, move through spaces and floors in a

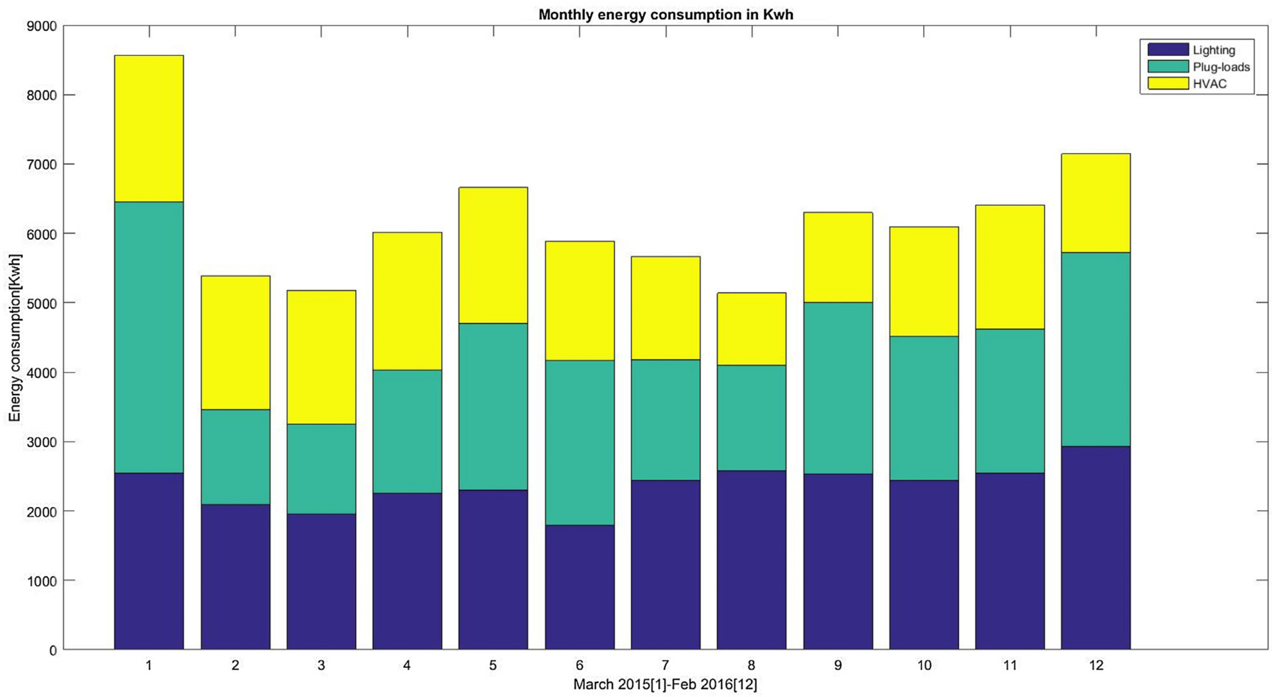

Fig. 2. Monthly energy consumption in kWh for period March 2015[1]-Feb-2016[12].

Table 1
Key Characteristics of common wireless communication protocols used in building automation.

Protocol	Number of nodes	Power consumption	Range(m)	Network topology	MaxDate rate
Zig-bee	65,000	Low	10–100	Star/Mesh	256 kb/s
Z-wave	232	Low	30–300	Star/Mesh	200 kb/s
Bluetooth	8	High	10	P2P	1 Mb/s
6LoWPAN	2^{64}	Low	10–100	Star/Mesh	256 kb/s
EnOcean	2^{32}	Low	30–300	Mesh	125 kb/s
WI-FI	255	Very High	100	star	54 Mb/s
BLE	8	Low	50	P2P/Star	1 Mb/s

stochastic manner [43]. By deploying a wireless sensor network for monitoring occupancy on a floor in an office building, the authors in [44] demonstrated that energy savings of up to 15% in HVAC electricity use and 12% reduction in HVAC thermal energy use can be achieved. In another study, the authors in [45] by utilizing a network of wireless sensors were able to obtain comprehensive fine-grained occupancy information in an office building for occupancy–driven control of key energy consuming building systems. Similarly, the authors in [46] demonstrated that the application of wireless sensors in a large university building could unlock additional energy savings with a payback of less than a year.

In addition, given that the lighting systems in the open-plan spaces of majority of commercial office buildings are often centrally controlled, the application of WSAN as proposed by the authors in [47] and [48] facilitates the use of dynamic personalized optimal lighting. This dynamic system is capable of tuning the light in the open-plan spaces to occupant's preference and needs in the most energy-efficient manner. As demonstrated by the authors in [49,50], by leveraging the individual addressability of the networked lighting systems, individual luminaires can be coordinated to deliver workstation-specific task-lighting to occupants while ensuring unoccupied spaces remain unlit or at a prescribed background level.

2.3. Contribution of this paper

Existing office buildings as mentioned earlier are usually constrained by old equipment and sub-optimal processes leading to

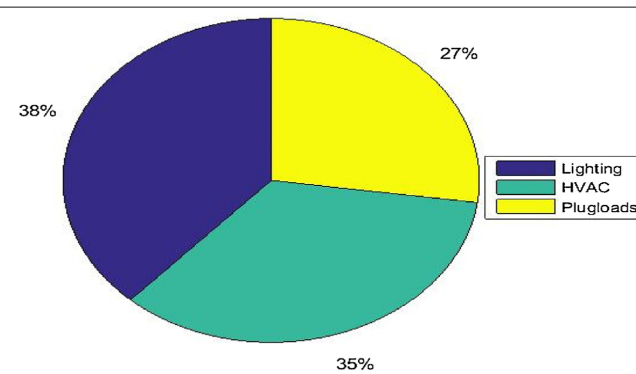

Fig. 3. Fraction of annual electricity consumption for the three main end uses lighting, HVAC and plug-loads.

relatively higher-energy consumption. Improvement in the energy efficiency of existing buildings thus represents a high-volume, low-cost approach for achieving reduction in building energy use and greenhouse gas emissions. Given that low-cost WSAN as deduced from the fore going have the potential to unlock this potential, the subsequent sections of this paper provide details of an experimental study evaluating the performance, energy saving potentials and practical implications of the application of WSAN in a medium-sized office building. The contribution of this article is noteworthy because though a number of articles highlight the key advantages of WSAN application as it relates to improvement in energy and comfort performance of buildings [18,36,47], very few studies provide

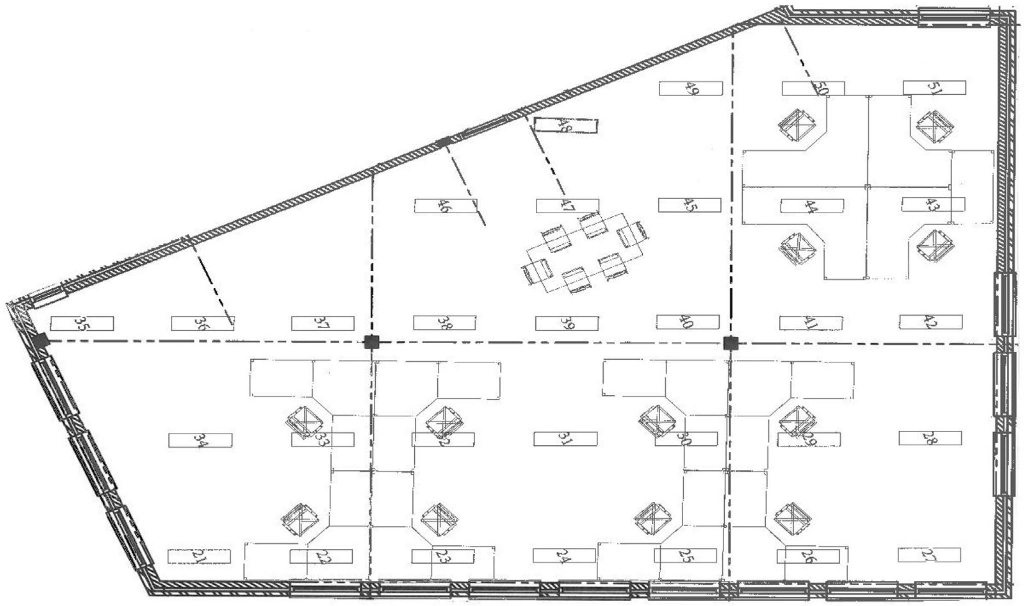

Fig. 4. Test-bed seat arrangement and luminaires position (luminaires numbered 21–51).

details of the practical implications of its implementation in practice. The remaining sections of this paper are organised as follows: Section 3 provides details of the test-bed office building and the wireless devices installed for the experiment. In section 4, results from the experiment as well as limitations of the study are discussed while in section 5, the study's conclusions, limitations and further study are discussed.

3. Methodology

3.1. Testbed description

A 2-storey office building depicted in Fig. 1, of approximately 1500 m^2 total floor area located in the Netherlands was selected as test-bed for this experiment. The building was commissioned in 1992 and refurbished in 2009. The building is composed of 4 large open-plan spaces, a large conference room, a lunch room and several singular and double cell office spaces. The building has a maximum occupancy of 59, but average daily occupancy is approximately 30. The building operation is managed via a building management system, which operates the Heating Ventilation and Air-conditioning (HVAC) system on a schedule.

The building uses a Constant Air Volume (CAV) [51] system for ventilation. Artificial lighting is achieved through a combination of luminaires. These different luminaire types contain tubular fluorescent lamps of 3*15W, 20W, 58 W and 2*36 W rated power. The lighting system is being utilized for space lighting, walkways and emergency exits. The lighting in all spaces, with the exception of essential luminaires is switched off manually at the end of the day when the last occupant exits the building. The luminaires in most of the spaces are connected in a two-grid manner: an inner and an outer grid. Each grid is controlled via a wall switch located at the entrance to the space. There are no occupancy sensors in the space.

The main electricity consuming building systems as depicted in Figs. 2 and 3 are the lighting and HVAC systems representing about 38 and 35% respectively for the period between March 2015 – February 2016 (represented with 1 through 12 in Fig. 2). The average consumption for this period was 6204 kWh; with march 2015 [1] having the highest consumption of 8567 kWh for the period under investigation. The increased consumption recorded during this period was as deduced from Fig. 2 is from the plug-loads and due to the use of heavy electrical tools.

In addition, as can be deduced from Fig. 3, the lighting energy use is slightly more than the energy utilized for space thermal conditioning HVAC. This might not be unrelated to the climatic conditions in the geographical location of the test bed building (the Netherlands) which influences the building mass design and type of building installations in the test-bed. Moreover, in well insulated buildings energy demand is usually not dominated by heating or cooling. Lighting becomes a significant factor even when high efficient lighting armatures are used. Up to 30–35% of the yearly energy is used for lighting in highly insulated buildings [52]. Therefore, it is of great importance to look for new methods to reduce the energy demand of lighting in existing buildings.

In view of fact that the electricity consumption of the lighting systems in the test-bed is quite substantial, we focus on reducing its consumption through the application of occupancy based lighting control using of wireless sensors and actuators network. Moreover, considering that the test-bed office building, and other similar buildings constructed in the same period often make use of a constant air volume ventilation system due to the climatic conditions in the location, the application of demand-controlled ventilation is hampered.

3.2. Experimental set-up

The open-plan space having the highest number of occupants was selected for the experiment. The space as depicted in Fig. 4 has 12 workspaces. Occupants in the space engaged mostly in desktop related tasks such as computer work, writing and reading. The space has 31 luminaries each equipped with 2 TL fluorescent lamps with combined nominal output power of 72 W. Each luminaire is connected to the mains electricity supply via a 2-pin plug.

3.2.1. Instrumentation

To achieve controllability of each luminaire, off-the-shelve plug-in switching nodes depicted in Fig. 5 using the Z-wave communication protocol was installed. The Z-Wave protocol is an interoperable, wireless, RF-based communications technology designed specifically for control, monitoring and status reading applications in residential and light commercial environments

Fig. 5. Z-wave sensors and gateway.

[27,53]. Sensors with the Z-wave protocol were chosen mainly because of interoperability. In addition to the power switching nodes, wireless sensor nodes also depicted in Fig. 6 for occupancy detection were installed.

The wireless nodes installed for occupancy detection were made up of Passive Infrared (PIR) motion sensors and chair sensors. The chair sensor was designed using a mechanical contact switch embedded in the chair's fabric and connected to a wireless transmitter using the Z-wave wireless communication protocol [54]. 55 Z-wave devices comprising switching nodes, motion sensors and the chair sensors were all connected to a gateway installed in the test-bed. The wireless nodes have an average range of 30 m, a maximum range of 100 m when within line of sight of the gateway and between 150 and 300 m when connected as a mesh-network.

The motion sensors were installed as depicted in Fig. 6 directly above occupant's workspaces. Placement of the sensor directly above the workspace ensures the sensed occupant remains in direct-line of sight of the sensors. This is because motion sensors are highly susceptible to false negative effect [55];- a term used in describing a situation where the sensor records occupant absence due to occupants remaining still for an extended period or due to motion occurring outside the line of sight of the sensor. The fact that the utilized sensors are wireless does however provide some respite considering that the sensors can be very easily positioned in direct line of sight of the sensed occupant. This attribute thus further reiterates the benefit of the application of wireless sensors in occupancy detection. In addition, as both sensors have individual drawbacks [54,55], the fusion of information obtained from both occupancy sensors facilitates the availability of fine-grained occupancy information, which is instrumental in improving the performance of demand driven control applications.

3.3. Control strategy and evaluation

The motion and chair sensors on the network were configured to transmit data to the gateway only when a change in state was recorded. This meant the sensors only transmitted occupancy information to the gateway only when presence or absence was detected. This way, the life span of the batteries is preserved. Data from the sensors was stored in a database from where it was accessed, processed and control instructions sent via the gateway

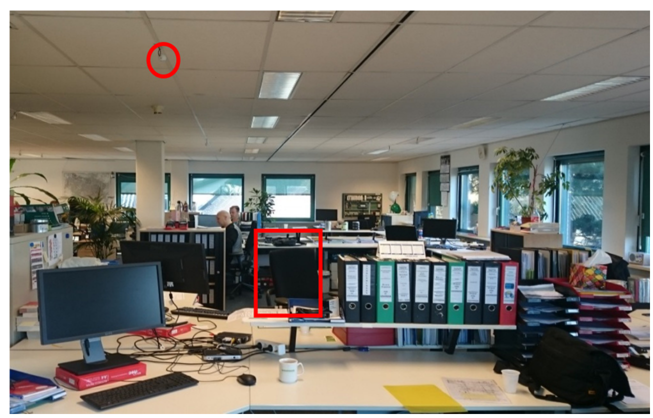

Fig. 6. sensor placement.

to the switch node connected to each luminaires. For occupancy detection, the algorithm depicted in Fig. 7 was designed using the EVE multi-agent platform [56]. Each user was assigned an agent, which processed data from the occupancy sensors positioned at the occupant's workstation. With this algorithm, the agent is able to minimize false-negatives and false-positives often caused by occupants walking-by, across and occupants seating still for extended period.

The experiment was conducted for a period of three weeks. Occupancy in the space and the corresponding lighting energy use were recorded for the 3-week duration of the study. During the first week of the experiment with the occupancy controlled lighting system, the interval between an occupant's absence and luminaire switching was set at 2 min and later increased to 5 min the following week. Considering that luminaires in the test-bed office space were not aligned directly above each occupant's workplace, which is often the case in most office buildings, horizontal illuminance values were measured at every workstation for different artificial lighting situations in the absence of daylight, i.e. luminaires in the proximity were set to different levels. These measurements were used to determine the luminaires to be switched on to provide a minimum of 500 lx on each of the desks. The chosen illuminance

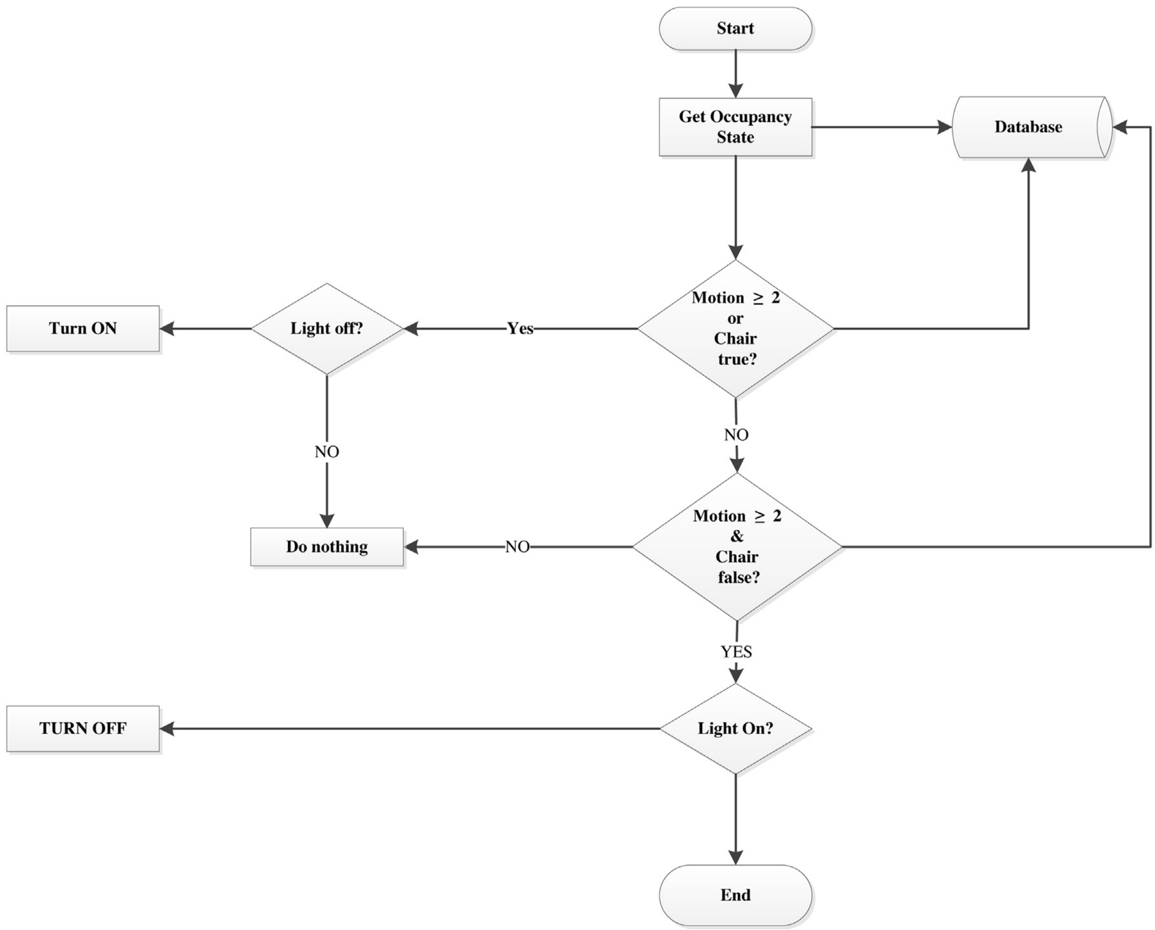

Fig. 7. Control Algorithm.

level corresponds to the recommended maintained illuminance for office workspaces according to the standard EN 12464-1 [57].

4. Discussion

4.1. Energy savings

The total daily energy-use of the lighting system in the test-bed open-plan office space for the three-weeks duration of the experiment lasted is depicted in Fig. 8. During the first week, which was without occupancy based lighting control, the weekly electrical energy consumption for lighting was 113.15 kWh. During the second and third weeks with occupancy-based control, the weekly electrical energy consumption for lighting in the space was 80.93 kWh and 90.54 kWh respectively. This represents a reduction of approximately 28% and 20% in electrical power consumption and an average reduction of 24% over the two-week duration of the study. The reduced savings recorded in the second week of the experiment can be attributed in part to changes made to the interval between luminaire switching and occupant departure from the workspace as well as varying occupancy pattern of the room.

4.2. Wireless system reliability

Wireless systems are highly susceptible to interference from other wireless sources present within a building thus seriously affecting the systems reliability. In order to improve the communication link reliability, a two-way acknowledgment algorithm depicted in Fig. 9 below was implemented in the control suite. The algorithm checks to ensure there is an active communication link between the gateway and the luminaire controller before a control instruction is sent. In addition, it also confirms that the sent command is implemented before the line is terminated. Although this approach uses additional network resource and could induce latency in the system, it does however significantly improve the reliability of the communication link. In addition, network reliability decreases with increasing number of nodes on the gateway even though theoretically the gateway can connect up to 232 devices. For this experiment, only 55 devices were connected to the gateway. For much larger applications that require more devices, the use of multiple gateways, though incurring additional cost reduces diminishing network reliability.

4.3. User comfort

Given that the primary role of buildings and building systems is the provision of a comfortable working environment. In order to evaluate user comfort questionnaires and diaries were made available to each participant. Occupants were asked to note down each time they sensed distraction from any Indoor Environmental Quality (IEQ) parameters in their diary using a 7-point Likert scale. In addition, participants were asked to rate their level of satisfaction with the lighting conditions in the space. As depicted in Fig. 10, artificial lighting was a key source of distraction during the first week the occupancy based control mechanism was implemented. Occupants were less satisfied with the level of light uniformity in the space as depicted in Fig. 11. The level of distraction experienced and satisfaction with light uniformity in the space did however improve

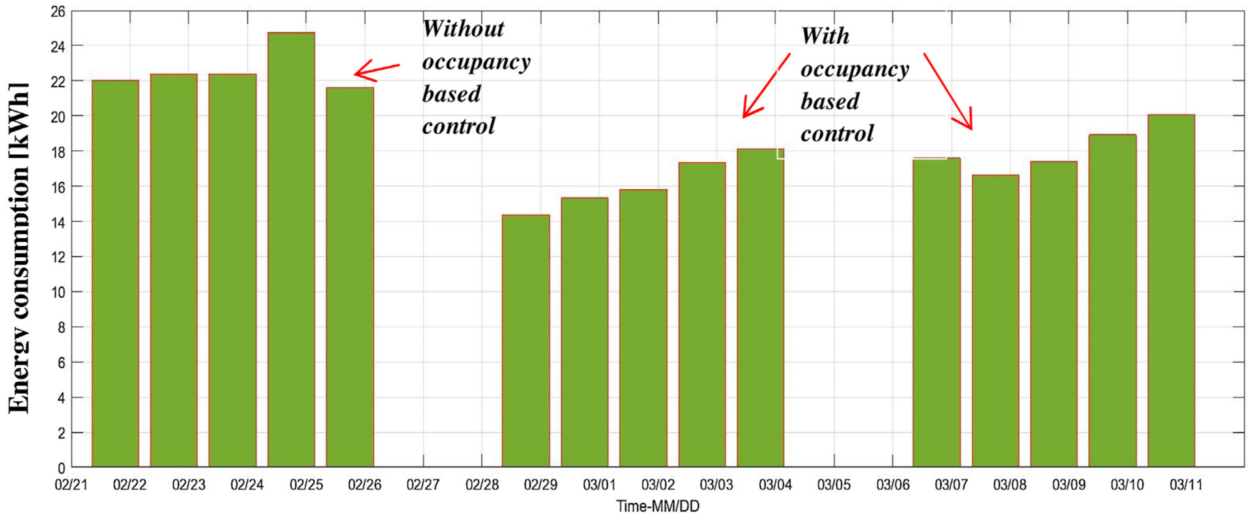

Fig. 8. Daily lighting energy consumption [kWh] for three weeks' experiment duration.

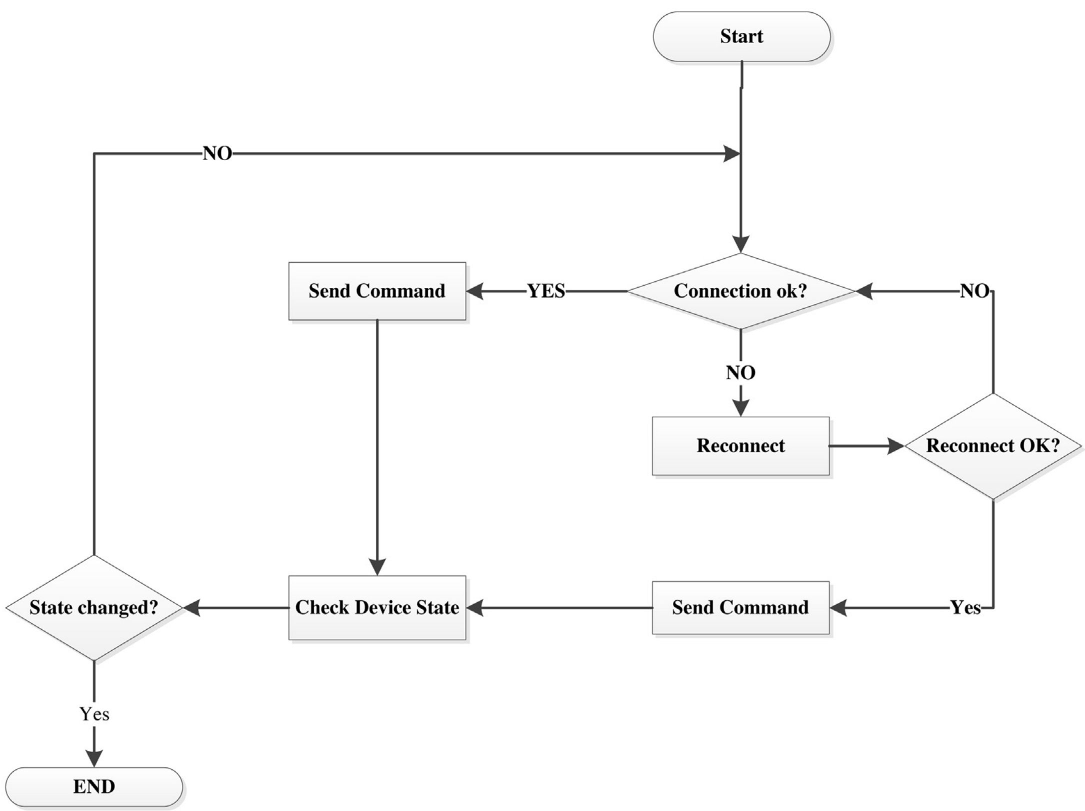

Fig. 9. Communication link check algorithm.

the following week. This improvement can be attributed to user adaptation and changes made to the interval between luminaire switching and occupant's departure from the workplace.

4.4. Limitation and implementation challenges

The installation of the system in the test-bed did not require any expert knowledge or specialized personnel and was concluded in half a day. Other than a few network glitches due to the local network firewall, the systems performed as intended. However, there were a few times connection with the remote server could not be established thus requiring the system to be manually restarted to reestablish connection. This did not however diminish the system's performance as the gateway was configured to transmit and utilize data from the local database rather than from the cloud-based database.

In terms of cost, the total cost of the system was approximately € 2575, which in essence translates to approximately € 215 per workspace. An average of 24% reduction in lighting energy use obtained during the 2-week period with occupancy-based control was within comparable range of other studies [58,59]; this provided the basis for estimation of the return on investment using the cost of electricity per kWh in the Netherlands [60]. The cost of electricity per kWh in 2014 for commercial office buildings of

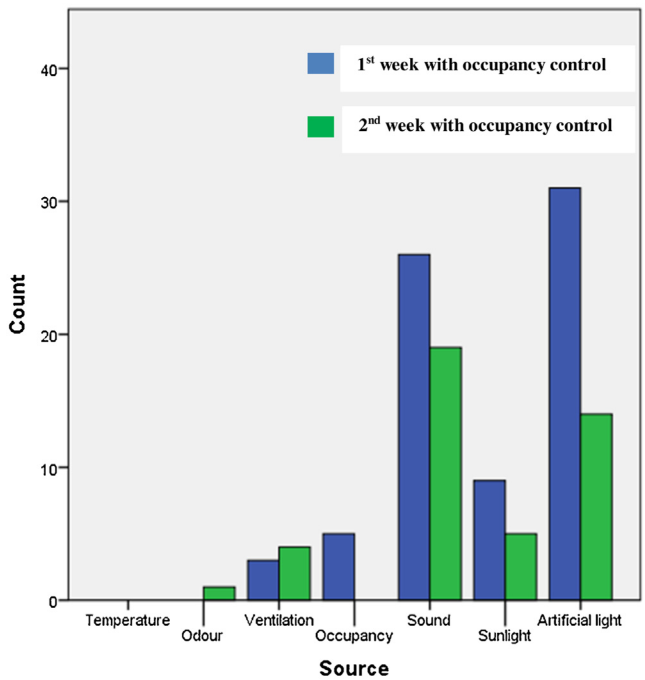

Fig. 10. Average number of times occupants observed distractions from different sources.

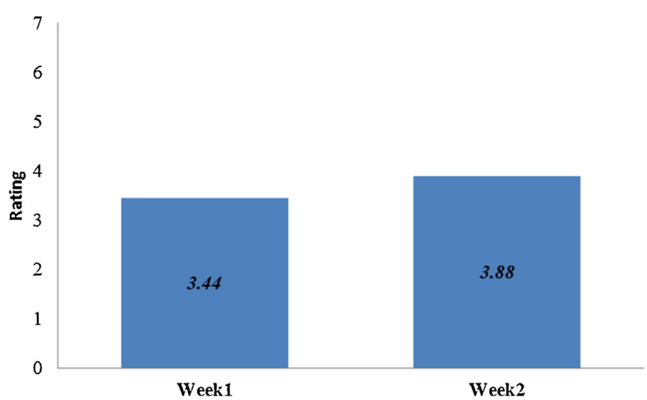

Fig. 11. Average satisfaction rating with space lighting uniformity.

this size was €0.033 [60]. Assuming that for the test-bed space, the weekly lighting electricity demand all year round remains constant as the recorded energy demand for the first week of the experiment (113.15 kWh), the total lighting electricity consumption for the space would be approximately 5884 kWh. Based on these assumptions, savings in terms of cost would be approximately €47. From this estimation, the meager return on investment in terms of energy cost is clearly not enough motivation for installing this particular WSAN. The use of cheaper WSAN or the use of just one occupancy sensor could however be a viable alternative. In addition, considering that the occupancy data used in this estimation was from data collected over a period of two weeks and given consideration to the fact that building occupancy varies over time [61], estimated savings might be considerably understated.

Another noteworthy practical implementation challenge of this system is the fact that cycling fluorescent lamps off and on will reduce lamp life; however, turning a lamp off when it is not needed will reduce its operating hours and increase its useful life. Considering that occupants' presence and movement within and around the workspace is stochastic in nature, the use of an appropriate time delay between occupants' exit and switching-off can provide an optimal balance between useful life of the fluorescent lamps and the achieved energy and associated cost savings [62]. Though investigation of the appropriate time delay is outside the scope of this study, its implication is currently being investigated in another study.

5. Conclusion

The refurbishment of existing buildings is a low-cost high volume approach to reducing building energy consumption and achievement of worthwhile reduction in emissions from the built environment. Higher initial cost, coupled with the long-life span of buildings as well as lack of awareness of technologies and their potential, can thus be considered as key contributory factors responsible for the rather slow pace of building refurbishment. Currently, there are a number of low-cost technologies available commercially which can be applied in both existing and new buildings to unlock additional energy efficiency improvements of which wireless sensors and actuators network is one.

In this paper, the potentials of wireless sensors and actuators network was evaluated in a medium- sized commercial office building. Wireless sensors and actuators were installed in an open-plan space of the test-bed office building for occupancy detection and occupancy based lighting control. During the first-week of the experiment with occupancy-based control, energy saving of 28% in lighting electrical energy use was achieved and 20% reduction the following week when the time interval between switching and occupant departure from the workstation was slightly increased from 2 min to 5 min. Although, the obtained energy savings and corresponding energy cost savings are clearly not compelling enough motivation for the application of wireless sensors in building operation, the ease of installation, improved environmental sensing and improved reliability of WSAN does however demonstrate it as a viable retrofit solution for the achievement of improvement building performance.

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References

[1] A. Allouhi, Y. El Fouih, T. Kousksou, A. Jamil, Y. Zeraouli, Y. Mourad, Energy consumption and efficiency in buildings: current status and future trends, J. Clean. Prod. 109 (2015) 118–130.
[2] IEA, Transition to Sustainable Buildings, IEA, 2013.
[3] A. Mardiana, S. Riffat, Building energy consumption and carbon dioxide emissions: threat to climate change, J. Earth Sci. Clim. Change s3 (2015).
[4] UNEP SBCI, Buildings and Climate Change, France.
[5] COMMERCIAL BUILDINGS ENERGY CONSUMPTION SURVEY, 2012.
[6] EU, Buildings. [Online]. Available: https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings.
[7] B. Tan, Y. Yavuz, E.N. Otay, E. Çamlıbel, Optimal selection of energy efficiency measures for energy sustainability of existing buildings, Comput. Oper. Res. 66 (2015) 258–271.
[8] E. Miller, L. Buys, Retrofitting Commercial office Buildingd For Sustianabillity: Tenants' Perspectives, J. Prop. Invest. Financ. 26 (6) (2008) 552–561.
[9] Z. Ma, P. Cooper, D. Daly, L. Ledo, Existing building retrofits: methodology and state-of-the-art, Energy Build. 55 (2012) 889–902, Elsevier B.V.
[10] S. Barlow, D. Fiala, Occupant comfort in UK offices-How adaptive comfort theories might influence future low energy office refurbishment strategies, Energy Build. 39 (7) (2007) 837–846.
[11] Smart market report— business case for energy efficient building retrofit and renovation, available from: http://apps1.eere.energy.gov/buildings/

publications/pdfs/alliances/business_case_for_energy_efficiency_retrofit_renovation_smr_2011.pdf. (2011).
[12] Karsten Neuhoff, H., Amecke, K., Stelmakh, Anja Rosenberg, A. Novikova, Meeting Energy Concept Targets for Residential Retrofits in Germany San Francisco, (2011).
[13] M. Kuzlu, M. Pipattanasomporn, S. Rahman, Review of Communication Technologies for Smart Homes/building Applications, 2015, IEEE Innovative Smart Grid Technologies – Asia (ISGT ASIA), 2015, pp. 1–6.
[14] H. Ghayvat, S. Mukhopadhyay, X. Gui, N. Suryadevara, WSN- and IOT-based smart homes and their extension to smart buildings, Sensors (Switzerland) 15 (5) (2015) 10350–10379.
[15] H.M.A. Fahmy, WSNs applications Wireless Sensor Networks, Signals and Communication, 67, John Wiley & Sons, Inc, Hoboken, NJ, USA, 2016, pp. 69–213.
[16] M. Dener, C. Bostancıoğlu, Smart technologies with wireless sensor networks, Procedia – Soc. Behav. Sci. 195 (2015) 1915–1921.
[17] H. Alemdar, C. Ersoy, Wireless sensor networks for healthcare: a survey, Comput. Networks 54 (15) (Oct. 2010) 2688–2710.
[18] E. Fadel, V.C. Gungor, L. Nassef, N. Akkari, M.G.A. Maik, S. Almasri, I.F. Akyildiz, A survey on wireless sensor networks for smart grid, Comput. Commun. 71 (2015) 22–33.
[19] P. Zhou, G. Huang, Z. Li, Demand-based temperature control of large-scale rooms aided by wireless sensor network: energy saving potential analysis, Energy Build. 68 (Part A) (2014) 532–540.
[20] T. Magno, L. Polonelli, E. Benini, S. Popovici, A low cost, highly scalable wireless sensor network solution to achieve smart LED light control for green buildings, IEEE Sens. J. 15 (5) (2015) 2963–2973.
[21] A.H. Kazmi, M.J. O'grady, D.T. Delaney, A.G. Ruzzelli, G.M.P. O'hare, A review of wireless-Sensor-Network-Enabled building energy management systems, ACM Trans. Sens. Networks 10 (4) (2014) 1–43.
[22] C. Peng, K. Qian, Development and application of a zigBee-Based building energy monitoring and control system, Sci. World J. 2014 (2014) 1–13.
[23] E. Arens, C.C. Federspiel, D. Wang, C. Huizenga, How ambient intelligence will improve habitability and energy efficiency in buildings, in: Ambient Intelligence, Springer-Verlag, Berlin/Heidelberg, 2005, pp. 63–80.
[24] T. Grimard, L. Kieran, Wireless options becoming more prevalent with BAS, Build. Autom. (2016).
[25] C. de Farias, H. Soares, L. Pirmez, F. Delicato, I. Santos, L.F. Carmo, J. de Souza, A. Zomaya, M. Dohler, A control and decision system for smart buildings using wireless sensor and actuator networks, Trans. Emerg. Telecommun. Technol. 25 (1) (2014) 120–135.
[26] S.A. Celtek, H. Soy, An application of building automation system based on wireless sensor/actuator networks, 2015 9th International Conference on Application of Information and Communication Technologies (AICT) (2015) 450–453.
[27] A.J.D. Rathnayaka, V.M. Potdar, S.J. Kuruppu, Evaluation of wireless home automation technologies, in 5th IEEE International Conference on Digital Ecosystems and Technologies (IEEE DEST 2011), vol. 5, no. June, 76–81, (2011).
[28] S. Wu, D. Clements-Croome, Understanding the indoor environment through mining sensory data—A case study, Energy Build. 39 (11) (2007) 1183–1191.
[29] J. Lu, et al., The smart thermostat: using occupancy sensors to save energy in homes, Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems (2010).
[30] N. Ota, E. Arens, P. Wright, Energy Efficient Residential Thermal Control With Wireless Sensor Networks: A Case Study for Air Conditioning in California, in Volume 8: Energy Systems: Analysis, Thermodynamics and Sustainability; Sustainable Products and Processes, pp. 43–52, (2008).
[31] S. Rohini, K. Venkatasubramanian, Z-Wave based zoning sensor for smart thermostats, Indian J. Sci. Technol. 8 (20) (2015).
[32] S. Rodríguez, J.F. De Paz, G. Villarrubia, C. Zato, J. Bajo, J.M. Corchado, Multi-Agent Information Fusion System to manage data from a WSN in a residential home, Inf. Fusion 23 (2015) 43–57.
[33] D. Han, J. Lim, Design and Implementation of Smart Home Energy Management Systems based on ZigBee, pp. 1417–1425, (2010).
[34] C. Gomez, J. Paradells, Wireless Home Automation Networks- A Survey of Architectures and Technologies.pdf, no. June, 92–101 (2010).
[35] M. Kintner-Meyer, M. Brambley, T. Carlon, N. Bauman, Wireless sensors: technology and cost-Savings for commercial buildings, Inf. Electron. Technol. Promises Pitfalls 7 (2002) 121–134.
[36] M. Kintner-Meyer, Opportunities of wireless sensors and control for building operation, Energy Eng. 102 (5) (2009) 37–41.
[37] N. F. Thornhill, W. Ikram, Wireless communication in process automation: a survey of opportunities, requirements, concerns and challenges, in UKACC International Conference on CONTROL 2010, no. September, pp. 471–476, (2010).
[38] S. Abraham, X. Li, A cost-effective wireless sensor network system for indoor air quality monitoring applications, Procedia Comput. Sci. 34 (2014) 165–171.
[39] P. Zhou, G. Huang, L. Zhang, K.F. Tsang, Wireless sensor network based monitoring system for a large-scale indoor space: data process and supply air allocation optimization, Energy Build. 103 (2015) 365–374.
[40] D. Brunelli, I. Minakov, R. Passerone, M. Rossi, Smart monitoring for sustainable and energy-efficient buildings: a case study, 2015 IEEE Workshop on Environmental, Energy and Structural Monitoring Systems (EESMS) Proceedings (2015) 186–191.
[41] N. Li, G. Calis, B. Becerik-Gerber, Measuring and monitoring occupancy with an RFID based system for demand-driven HVAC operations, Autom. Constr. 24 (2012) 89–99.
[42] T. Labeodan, W. Zeiler, G. Boxem, Y. Zhao, L. Timilehin, W. Zeiler, G. Boxem, Z. Yang, Occupancy measurement in commercial office buildings for demand-driven control applications—A survey and detection system evaluation, Energy Build. 93 (2015) 303–314.
[43] S.S.K. Kwok, R.K.K. Yuen, E.W.M. Lee, An intelligent approach to assessing the effect of building occupancy on building cooling load prediction, Build. Environ. 46 (8) (2011) 1681–1690.
[44] Y. Agarwal, B. Balaji, S. Dutta, R.K. Gupta, T. Weng, Duty-cycling buildings aggressively: the next frontier in HVAC control, Proceedings of the 10th ACM/IEEE International Conference on Information Processing in Sensor Networks (2011) 246–257.
[45] V. Erickson, S. Achleitner, A. Cerpa, POEM: power-efficient occupancy-based energy management system, Proceeding (2013) 203–216, 12th.
[46] J. Brooks, S. Goyal, R. Subramany, Y. Lin, C. Liao, T. Middelkoop, H. Ingley, L. Arpan, P. Barooah, Experimental evaluation of occupancy-based energy-efficient climate control of VAV terminal units, Sci. Technol. Built Environ. 21 (4) (2015) 469–480.
[47] A. Peruffo, A. Pandharipande, D. Caicedo, L. Schenato, Lighting control with distributed wireless sensing and actuation for daylight and occupancy adaptation, Energy Build. 97 (2015) 13–20.
[48] Y.J. Wen, A.M. Agogino, Personalized dynamic design of networked lighting for energy-efficiency in open-plan offices, Energy Build. 43 (8) (2011) 1919–1924.
[49] J.S. Sandhu, A.M. Agogino, A.K. Agogino, Wireless sensor networks for commercial lighting control: decision making with multi-agent systems, AAAI Work. Sens. Netw. 10 (May(2016)) (2004) 131–140.
[50] Y.-J. Wen, A. Agogino, Control of wireless-networked lighting in open-plan offices, Light. Res. Technol. 43 (2) (2011) 235–248.
[51] M.A. Aktacir, O. Büyükalaca, T. Yılmaz, Life-cycle cost analysis for constant-air-volume and variable-air-volume air-conditioning systems, Appl. Energy 83 (6) (2006) 606–627.
[52] X. Zhou, D. Yan, T. Hong, X. Ren, Data analysis and stochastic modeling of lighting energy use in large office buildings in China, Energy Build. 86 (2015) 275–287.
[53] Zwave [Online]. Available: http://z-wavealliance.org/about_z-wave_technology/ (accessed: 04.07.16.).
[54] T. Labeodan, K. Aduda, W. Zeiler, F. Hoving, Experimental evaluation of the performance of chair sensors in an office space for occupancy detection and occupancy-driven control, Energy Build. 111 (2016) 195–206.
[55] T. Teixeira, G. Dublon, A. Savvides, A survey of human-Sensing: methods for detecting presence, count, location, track, and identity, ACM Comput Surv. 5 (2010) 1–35.
[56] J. De Jong, L. Stellingwerff, and G. E. Pazienza, Eve: A novel open-source web-based agent platform, Proc. – 2013 IEEE Int. Conf. Syst. Man, Cybern. SMC 2013, pp. 1537–1541, (2013).
[57] BS EN 12464-1: Light and lighting— Lighting of work places— Indoor work places, (2011).
[58] M.A.U. Haq, M.Y. Hassan, H. Abdullah, H.A. Rahman, M.P. Abdullah, F. Hussin, D.M. Said, A review on lighting control technologies in commercial buildings, their performance and affecting factors, Renew. Sustain. Energy Rev. 33 (2014) 268–279.
[59] A. Williams, B.A. Pe, K. Garbesi, E.P. Pe, F.R. Fies, Lighting controls in commercial, Buildings (2012) 161–180.
[60] Energy price statistics. [Online] Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics (accessed: 04.05.16.).
[61] A. Mahdavi, C. Pröglhöf, User behaviour and energy performance in buildings, Wien, Austria Int. Energiewirtschaftstagung an der TU Wien, pp. 1–13, (2009).
[62] B.C.J. Spezia, J. Buchanan, Compact fluorescent lamps maximizing the economic benefits of compact, J. Ind. Technol. 27 (2) (2011).