An intervention study on automated lighting control to save energy in open space offices

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***Abstract*—We present intervention study on energy saving investigating the benefit of controlling ceiling lighting based on occupant presence information obtained at each desk. We show that fine-grained sensing and control is particularly beneficial for lighting control in open plan office spaces. Our intervention was conducted in a $63.8m^2$ modern open office space over a time of 1.5 months. Ultrasound sensors were installed to obtain presence at each desk. Self-dimming ceiling lights were made individually controllable and a novel building management system (BMS) was implemented. Every two desks and a nearby light were grouped in a cell, implicitly defined by rules of the BMS. Based on the intervention, energy savings of up to $19.01\frac{kWh}{m^2 \cdot year}$ were obtained. Recorded presence and power consumption values were used to simulate alternative lighting control strategies with reduced sensor numbers to further explore energy saving benefits.**

I. Introduction

Lighting represent up to 40% of the total energy cost of a building [8]. Triggered by the substantial energy needs of the lighting installation, many buildings have been upgraded with automatic lighting systems, including dimmable ceiling lights, presence detectors, and light irradiance sensors. Studies have shown that automatic lighting systems can attain energy savings of 16% for open space offices, to 60% for single occupant and small multi-occupant offices when compared against manual controlled lights [13], [10], [5]. The energy savings were generally attributed to moments when occupants did not require light or were not present at all.

The large variation in energy savings between the studies could be attributed to (1) differences in occupant room usage according to their office working needs, (2) differences in technology used, i.e. using dimmable or switchable lights, and (3) differences in lighting use between single occupant and large open office spaces. While occupant availability will depend on working needs, e.g. in call centres or secretary offices, use rates are higher than in a sales department, it was found that working style in general got more nomadic and actual utilisation continues to drop [1]. Hence, appropriate automatic lighting systems could leverage savings even from short moments when occupants are not present. Together with the presence detection, dimmable lights will help to gain energy savings as lights can be soft-controlled between fully on and completely off. Office room type critically influences lighting control. While for a single occupant office control depends on the room presence information alone, open space offices are more challenging to control. Presence is not a binary variable any more and due to the room size, light distribution in the room is not homogeneous. However, many "modern" automatic lighting installations rely on one or two presence detectors per room to operate ceiling lighting.

Practical evidence is lacking that could demonstrate the benefit of advanced fine-grained presence based lighting control. However, when making energy saving studies, comparing two time periods of the same space in a living-labs is challenging. The conditions for comparison rarely stay the same. Problems such as changing weather conditions, occupancy patterns, and even change of occupants have sufficient variance to obscure the benefits or drawbacks of fine-grained presence based control. A solution to the problem is usually to record sufficiently long baselines and interventions on the hope that conditions are on average comparable. Unfortunately, the availability of spaces and participants is a scarce resource. Therefore, our proposed approach records highly detailed information during the intervention period, allowing us to simulate more accurately the response of different control strategies for comparison.

In this work, we present an intervention study investigating the benefit of controlling ceiling lights based on occupant presence information obtained at each desk. While real-life studies are complex and risky, we argue that more empirical evidence is needed that supports the estimations of energy saving simulations. Our analysis is based on data from an open office space with twelve office desks, where we conducted a light control study for 3.5 weeks. In particular, the paper provides the following contributions:

1) We present results from our open office study, deploying an advanced automated lighting control system. By deploying a purpose-built measurement and control system and using the GreenerBuildings building management system (BMS), we obtained energy savings matching those anticipated by simulations in literature.
2) We show a comparative analysis between our fine-grained presence based lighting control approach and current automatic lighting systems. Our results quantify the benefit of a fine-grained automatic lighting systems.

II. Related Work

Several recent surveys summarise efforts towards energy efficient office buildings, considering user activity and lighting controls [16], [18].

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Computer vision has been frequently used to detect occupant behaviour in the built environment. Different activities were recognised including working with the keyboard or mouse, making a phone call, and doing paper work [15], [2], [19]. While occupant behaviour recognition using cameras may yield high performance, video processing remains computationally expensive and often raise privacy concerns and reduce user acceptance.

Networks of multiple ambient sensors were evaluated to identify occupant behaviour. Begole et al. [3] modelled rhythm patterns from data obtained through computer-mediated communication technologies to share availability in remote working scenarios. Similarly, commodity computer hardware, including computer microphones and speakers were used to recognise user activities from ultrasonic signals, achieving accuracies of up to 96% [17]. In earlier work, our group investigated several sensing modalities that are commonly available in office buildings for desk activity recognition such as computer work and desk work [14]. Based on this work, we concluded that the recognition performances using ambient sensors are suitable to control building installation, such as lighting. For the study described in this paper, we consider that presence data is suitable for lighting control.

Many investigations used simulation to investigate possible energy savings using advanced control information, such as recognised activity or presences. In contrast, only very few attempts were made to validate the estimations in actual office studies. Marchiori et al. [12] conduct a two day experiment in two rooms of an academic building. A network composed of Passive Infra-red (PIR) motion detectors, magnetic switches, ambient light sensors, and energy controllers (relays) was deployed to evaluate potential energy savings of various office devices using a on/off control strategy based on occupancy. A total energy savings up to 15% was achieved. In another study, location information was considered to dynamically optimise energy consuming installation in an office [7].

A study conducted by Lelkens [10] showed that self-dimmable ceiling lights controlled by PIR detectors achieved savings of 60%. In their installation the amount of light provided by the ceiling light was adjusted in response to outside light and motion detection. The study was conducted in single occupant offices. In comparison, Delany et al. [5] report savings of 16% in an open space with several workstations per presence sensor. Savings resulted from low occupancy in the monitored spaces. Finally a literature review conducted by Dubois et al. [6] summarises that changing the control strategy, the type of light used, and the inclusion of dimming capabilities to react to exterior lights provides a energy saving potential of up to 60%. Based on the European energy standard EN-15193:2007, Dubois et al. [6] report that, for an office space with an area greater than $12m^2$, the recommended energy utilisation is between $7 - 22\,\frac{kWh}{m^2 \cdot year}$

While in many simulation analysis, the lighting-related energy saving potential of office buildings has been confirmed, e.g. [1], we consider that additional real-life studies are needed to confirm findings from simulations and contribute novel strategies. While many open office spaces are installed with only a few (one or two) presence detectors, in our study installation, we deployed one presence sensor per desk and dimming lights. With the high sensor density, we investigate desk grouping strategies and actual energy savings.

III. Methodology

In this section, we describe the occupants, open office environment, and building management system deployed for sensing and controlling. Furthermore, we detail the analysis methodology used to evaluate the fine-grained presence sensing approach.

A. Study participants

Study participants were selected based on the chosen open office space, such that participants did not need to relocate their desks for the study and a most natural occupant behaviour could be achieved. The selected open office space comprised twelve desks, where in total 9 participants occupied desks during the study time frame and thus took part in the study (8 males, 1 female). All participants were office workers doing mostly computer-based work. The participants were informed about the study and asked to follow their regular everyday routine during the study.

B. Open office space

The study was conducted in a living-lab 12-desk open office installation within the "Metaforum" building on the campus of the Eindhoven University of Technology. The office building was fully renewed in 2012 and uses a state of the art BMS system. Appliances differed between desks: some desks had one monitor, other dual monitor set-ups, some participants used laptops, others work with desktop computers. Fig 1, illustrates desks, location of self-dimming lights, and the general set-up. The room was $5.5x11.6\,\mathrm{m}$ ($63.8\,\mathrm{m}^2$) in size. In the standard configuration before our study set-up, ceiling lights were organised in two rows: A north row with lights #1 to #4 and a south row with lights #5 to #8. As by the original configuration, one presence detector was available in the room. The ceiling light fixtures have integrated light sensors to automatically and independently control the intensity of the light. User could manually switch lights per rows if they were not satisfied with the BMS control.

For our study, the space was equipped with Plugwise switches to individually control all 8 ceiling lights and measure their power consumption in any dimming state. A double rocker switch was installed to control all ceiling lights or the entrance lights, depending on the study phase. Each desk was equipped with a desk light connected via a Plugwise switch to measure power consumption. A double rocker wireless switch was added to each desk to control the desk light and the closest ceiling light. To detect presence at the desk area, two ultrasound ranging (USR) sensors where placed at the desk screens such that the desk's working space was in the field of view.

Sensor data acquisition and light control was distributed onto three net-book computers. The net-books also were in charge of communicating with the BMS system. In total, the living-lab installation included the following hardware components: 3 Asus Eee PC, 13 wireless double rocker switches, 12 desk lights, 20 Plugwise plugs, 1 Plugwise USB key, 1 EnOcean USB key, 2 wireless light sensors.

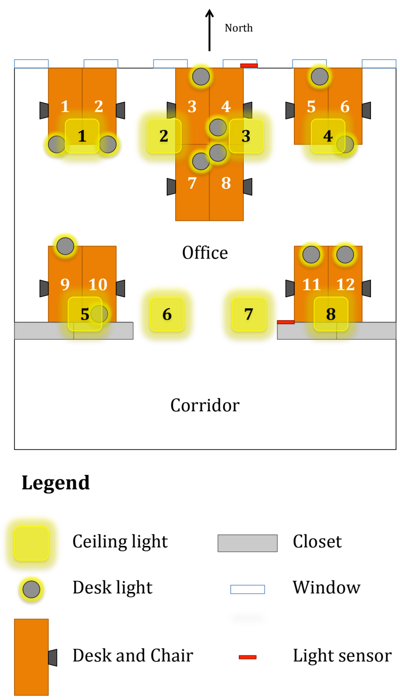

Fig. 1: Configuration of the living-lab open office space. We used a cell partitioning that comprises of one ceiling lights and two desks per cell. For example, desks #3 and #7 were grouped with light #2, desks #4 and #8 with light #3. Lights #1 to #4 constitute the north row and lights #5 to #8 the south row.

C. BMS configuration

For our living-lab installation, the building BMS was reconfigured to only log measurement variables, but not to perform actions on the office space. Instead, we deployed our GREENERBUILDINGS BMS (GB-BMS) [4]. The GB-BMS architecture has a service oriented design based on five key components. (1) The service and actuator gateway (SAGW) component was in charge of collecting data and controlling the space. (2) The context component was used in our study to convert USR measurements into presence detection and collected additional data from light sensors. (3) The composition component derived actuator settings based on a set of predefined rules and the current state information provided by the context component. New actuator states were specified as an execution plan to minimise energy consumption and conserve comfort. (4) The orchestration component implemented execution plans by communicating with SAGWs and ensuring that no race conditions occur. Finally, a copy of all sensor values, actuator states, and control actions was stored in the repository component. A detailed description of the GREENERBUILDINGS architecture can be found in [4].

For our study, GB-BMS composition rules were considering outdoor light level and desk presence information. A general form of the rules is shown in Equation 1, where i represents the desk id and j the ceiling light id associated to desk i.

TABLE I: Association of desks to ceiling lights. For GB-BMS each light and pair of desks constitutes a *cell* that is implicitly encoded by rules of the form shown in Eq. 1.

Cell	1	2	3	4	5	6
Ceiling light	1	2	3	4	5	8
Desks	1,2	3,7	4,8	5,6	9,10	11,12

$$\begin{aligned} &\textbf{if } outdoorluxlevel < 5000Lux \\ &\textbf{and } presence_i == True \\ &\rightarrow ceilinglight_j = ON. \end{aligned} \tag{1}$$

Presence detection was computed from USR sensor readings using a stochastic procedure detailed in [11]. Essentially, distribution of USR feature values in a sliding window were compared to known presence and away distributions. The comparison is done using a Gaussian kernel density estimator for each presence and away class. A binary decision was determined by selecting the highest posterior probability between the two models.

A rule of the form shown in Eq. 1 was applied to each desk. The rule does not specify the dimming level for the ceiling lights. Setting the appropriate dimming level is done automatically by the light fixtures. The rule implicitly defines a *cell* in the GB-BMS system. In the study office space, we consider a cell to comprise pairs of desks and the closest ceiling light. Lights #6 and #7 were commissioned as ambient light, not linked to desks. Hence, when presence was detected during dim outside light conditions, lights #6 and #7 were turned on. Table I shows how the desks were associated to the ceiling lights and the implicitly defined cells.

D. Study implementation

The study was divided in 3 phases: Phase 1 allowed users to get accustomed to the system. Phase 2, was used to record data about energy consumption while the GB-BMS was in operation. In Phase 3 baseline measurements of power consumption were gathered. Our study covered a period of 1.5 months, starting on September 16, 2013 and ending on November 01, 2013. The installation of the required hardware took place in the preceding weekend before Phase 1. In detail, the phases targeted the following objectives:

Phase 1: Acquaint participants to the system. Phase 1 aimed at getting participants used to the system in order to reduce novelty effects, i.e., changed behaviour patterns and comfort assessment due to a different environment. There were no recordings and measurements conducted during phase 1. Phase 1 lasted for 2 weeks and 2 days.

Phase 2: Automatic mode. Phase 2 was used to record power consumption of lighting systems under automatic control of the GB-BMS. In phase 2 we recorded contextual information, power consumption measurements, actuators states. This phase lasted 2 weeks and 3 days.

Phase 3: Baseline. Phase 3 was intended as validation period, recording power consumption of the lighting system while in classic control mode of the original building BMS. We used Phase 3 to validate the simulation method introduced below. Phase 3 lasted for one week.

E. Data analysis and simulations

Due to variations in occupation patterns and exterior weather conditions we could not perform a fair comparison between Phase 2 and 3 of the study. Therefore we chose to compare the intervention (Phase 2) to simulated BMS behaviour based on real data recordings made during Phase 2.

For simulations we used occupation and instantaneous power consumption measurements to reproduce occupant behaviour for the different BMS control approaches. In this work, we consider two scenarios: BMS-01 with one presence sensor and control rule:

$$\textbf{if } \text{any}(presence) \rightarrow \text{all}(ceilinglight) = ON.$$

BMS-02 with two motion sensors and control rule:

$$\textbf{if } \text{any}(presence_r) \rightarrow \text{all}(ceilinglight_r) = ON.$$

where r determines the presence at desks associated to the respective ceiling light row and is set to north or south ceiling rows. Both scenarios also enforce the dependency on $outdoorluxlevel < 5000Lux$ as shown in Eq 1. Table III shows the distribution of ceiling lights to cells for all simulated scenarios.

BMS-01 and BMS-02 consider respectively the entire space or each light row as individually controllable cell. In contrast, GB-BMS controls ceiling lights independently based on cells formed by desk pairs and the nearest ceiling light. Table I shows the resulting cells. As a result, not all lights are turned on during presence conditions.

To accurately simulate BMS-01 and BMS-02 a cell configuration different from the GB-BMS running in Phase 2 needed to be simulated. To refine the simulation, we took into account the following property: when the light's self-dimming function is activated, all lights in one row have similar power consumption and the south row will consume more power than the north row. In order to derive a fair power consumption estimate for ceiling lights in BMS-01 and BMS-02, we estimated power consumed by row as:

$$4 \times \text{mean}(power_r(k) > 0) \tag{2}$$

where r is either the north or south ceiling row, and k is the sampling time. Using the mean of active light at sample time k ensured that we considered a suitable current dimming value for all lights in a cell. Table II shows an example of how BMS-01 and BMS-02 were simulated based on the values recorded by GB-BMS. The example shows presence at desks #1, #2 and #6. As expected, GB-BMS activates ceiling lights #1 and #4 in the north row and ceiling lights #6 and #7 in the south row. The simulated power consumption of the ceiling lights BMS-01 and BMS-02 is shown in Tab. II. The example also illustrates how the difference in power consumption due to self-dimming between the north and south row is preserved.

To validate our simulation approach, we used study Phase 3 recordings and configured GB-BMS to operate as BMS-01. Hence, we could perform a direct comparison of our BMS-01 simulation to the original BMS installed in the office building. We calculated the root mean square error (RMSE) of energy consumption estimations to measure the performance of our simulation approach.

TABLE II: Example of how BMS-01 and BMS-02 were simulated based on the values recorded by GB-BMS. The example illustrates an instance with presence at desks: #1, #2 and #6, and the simulated ceiling lights power consumption values assigned to BMS-01 and BMS-02.

	Power [W]		Desk Presence
	North row	South row	
Ceiling lights	1 2 3 4	5 6 7 8	
GB-BMS	34.20, 0.0 , 0.0 , 34.70	0.0, 62.6, 66.2, 0.0	1,2,6
BMS-01	34.45, 34.45, 34.45, 34.45	64.4, 64.4, 64.4, 64.4	1,2,6
BMS-02	34.45, 34.45, 34.45, 34.45	0.0, 0.0, 0.0, 0.0	1,2,6

TABLE III: Assignment of ceiling lights to control cells for each BMS configuration used in our comparative evaluation.

	Cells					
	1	2	3	4	5	6
BMS-01	1,2,3,4,5,6,7,8					
BMS-02	1,2,3,4	5,6,7,8				
BMS-03	1,5,6,7	2,3,6,7	4,6,7,8			
BMS-04	1,2,6,7	3,4,6,7	5,6,7	6,7,8		
BMS-05	1,6,7	2,3,6,7	4,6,7	5,6,7	6,7,8	
BMS-06	1,6,7	2,6,7	3,6,7	4,6,7	5,6,7	6,7,8

As a final evaluation, we investigated how different cell partitions and the number of occupied cells have an impact on potential energy savings. For this purpose, we introduce additional cell partitions configurations (BMS-03, ..., BMS-06). Each cell uses a virtual presence sensor computed from the presence sensors of the desks associated to the corresponding ceiling lights. i.e cell #2 of BMS-05 uses ceiling lights #1,#2,#6 and #7, and presence sensors from desks #2, #3, #7, #8. For all new cell partitions, ceiling lights #6 and #7 were used for general illumination purposes taking into account comfort considerations. Thus ceiling lights #6 and #7 will be turned-on when any cell becomes occupied. BMS-02 does not use the general illumination lights as we estimated that a row partition is a common ceiling light division of installations in open plan offices and the light provided by an entire row is enough to implement comfort considerations.

Table III shows the distribution of ceiling lights to cells for all configurations. We simulated a worst case occupation scenario: cells were sequentially occupied by incoming occupants. Actual light power consumption values were used. The results of all permutations of cell filling order were averaged. GB-BMS used twelve presence sensors to control six ceiling lights for a total of six cells. Similarly, BMS-06 has six virtual presence sensors to control six ceiling lights for a total of six cells.

IV. RESULTS

Our automated lighting control system using GB-BMS achieved 49.96% of energy saving during Phase 2 in comparison to the original room set-up, simulated as BMS-01. The savings are equivalent to $3.32\ kWh$ per day. The average occupation for cells according to the GB-BMS cell configuration was 2.61 during Phase 2 and 1.96 for Phase 3. The validation

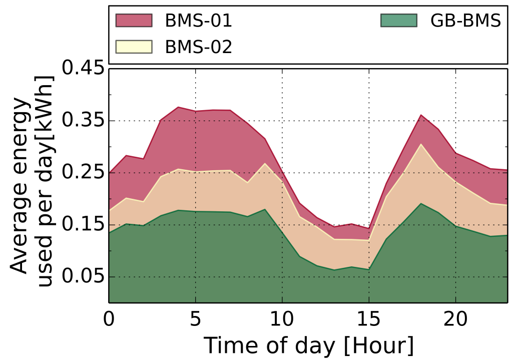

Fig. 2: Average energy consumption per hour. The GB-BMS uses the least energy followed by a 2 presence sensor system (BMS-02) and a 1 presence sensor system (BMS-01).

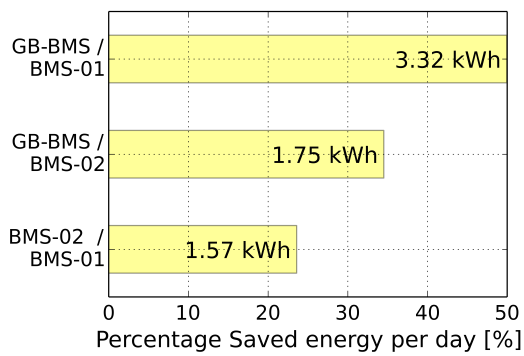

Fig. 3: Energy saving in percentage and daily average absolute values when comparing different BMS modes.

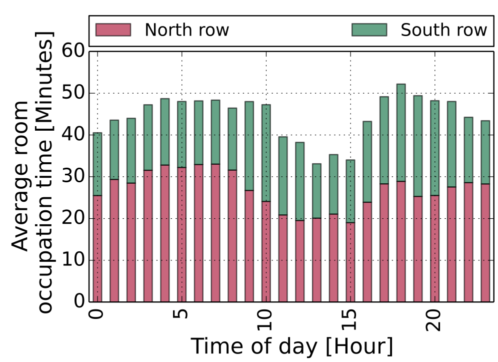

Fig. 4: Average occupation of the office space in minutes per hour of the day. The north row receives some more occupation than the south row.

on Phase 3 data showed that our approach incurred an RMS estimation error of $0.33\,W$. The open office with its occupation pattern during Phase 2 would yield an annual energy budget of $38.05\frac{kWh}{m^2 \cdot year}$. Our automated lighting control system achieved projected savings of $19.01\frac{kWh}{m^2 \cdot year}$.

The average energy consumption per hour is shown in Figure 2. GB-BMS shows lowest energy consumption followed by BMS-02. Clearly, BMS-01 obtained highest consumption. An effect of self-dimming lights can be observed in Fig. 2: the gap between BMS-01 and BMS-02 disappears as the north row lights are dimmed down leaving the energy consumption of the south row lights during daytime periods, i.e., between 10 am and 4 pm.

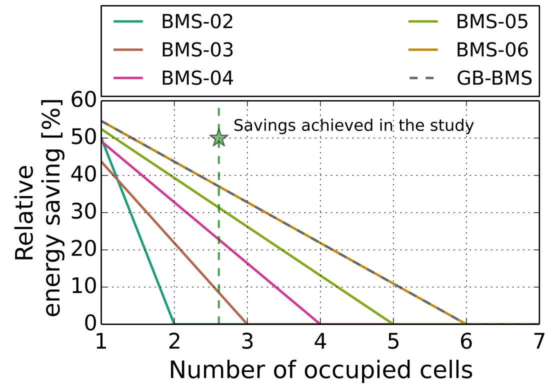

Fig. 5: Energy savings relative to BMS-01 when varying the number of occupied room cells. For BMS-02, lights #6 and #7 were not considered as general illumination lights, thus BMS-02 obtains larger relative savings than the remaining configurations. The average cell occupation during our intervention study and obtained energy saving is annotated.

The BMS operation modes BMS-01, BMS-02, and GB-BMS were compared and the energy saving with respect to the equivalent absolute value is presented in Figure 3. While the benefit of GB-BMS over both other BMS modes was expected, BMS-02 provides savings compared to BMS-01 too. Figure 4 shows the average occupation time in per hour of the day. The contribution of the north and south row indicates that north row at the windows were used somewhat more often than the south row. Fig. 4 also confirms Agarwal et al. [1] observation for shared spaces: multi user rooms tend to be always occupied as there is usually at least one person there.

Finally, we compared possible savings by sequentially increasing the occupied cell count. Figure 5 shows the potential savings obtained per sensor configuration as a function of the number of occupied cells. Fig. 5 also shows that there is no observable difference between BMS-06 and GB-BMS. In this analysis, we dedicated the two entrance ceiling lights to general illumination, creating an extra energy demand of 10% when compared to only using 1 ceiling light.

V. Discussion and Conclusions

Our study results confirm that fine-grained presence measurements to control ceiling lights individually yields the best energy savings. The optimal ratio of $1:1$ between presence sensors and light actuators was further supported by the findings in Figure 5 where BMS-06 and GB-BMS provide the same potential savings. We showed that having less sensors than actuators increases energy consumption. In addition, adding sensors can provides more detailed activity information that would leverage further energy savings potential in office appliances [9], [13].

The use of desk light was not considered in the intervention study. Participants claimed that the desk light was unnecessary as the GB-BMS usually provided sufficient lighting. When discomforted, users preferred to switch on ceiling lights.

Our intervention study revealed that the office space had a higher projected yearly energy consumption than targeted by the EU standard 15193. When implementing our proposed automated lighting control system, fine-grained presence sensing and lighting control would reduce energy consumption to $19.04\frac{kWh}{m^2 \cdot year}$, thus well into the range $7-22\frac{kWh}{m^2 \cdot year}$.

We interpret the occupancy pattern observed during Phase 2 as follows: (1) Participants were mostly young researchers who stayed after hours, e.g. until 10pm. (2) During night hours, sensor noise increased as the USRs falsely detected presence when the room was actually empty. We attribute the detection noise to cross-talk between the USRs, where pulses of one sensor were detected as object reflection by an opposite sensor. During daytime, occupants and additional objects present in the room block unwanted pulses from other sensors, thus reducing false detection. Consequently, the actual energy consumption could still be lower when cross-talk is corrected. The proportional energy saving when using GB-BMS would be maintained.

Considering the additional energy consumption originating from the installed equipment during the study, optimisation of the GB-BMS is still necessary. The powered Plugwise devices used for switching lights could be replaced by switchable/dimmable light ballasts, e.g. HF-R 418 TL-D EII. While we could demonstrate the energy saving potential using USR sensors for presence detection, their cross-talk behaviour and power consumption make USRs unsuitable for regular building deployments. Novel low-power presence sensors are needed to leverage the energy saving potential related to occupant behaviour.

Our study showed that the considered open office space has a low concurrent occupation. Open offices with different purposes may gain higher occupation. As shown in Fig. 5, our approach alone can not save energy during typical working hours where occupation average is high. Instead, our approach would save energy, e.g. when occupants stay extra hours as only the occupied areas need to be lit. As described by Agarwal et al. [1], vacant periods are the main contributors to energy savings. When using our fine-grained sensing and control approach, a shared room that would be occupied most of the time by at least a few users, becomes a collection of individual cells that will be empty most of the time. Thus, the overall energy consumption of the space can be improved. General illumination and orientation lights can play an important role regarding the actual amount of energy saved. A balance between saving and comfort needs to be considered when designing new lighting systems.

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