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This is the published version of a paper presented at *eceee 2019 Summer Study, Belambra Presqu'île de Giens, France, 03–08 June, 2019*.

Citation for the original published paper:

Azizi, S., Nair, G., Olofsson, T. (2019)
Demand-controlled energy systems in commercial and institutional buildings: a review of methods and potentials
In: *eceee 2019 Summer Study on energy efficiency:: Is efficient sufficient?* (pp. 1444-1450). European Council for an Energy Efficient Economy (ECEEE)
eceee Summer Study proceedings

N.B. When citing this work, cite the original published paper.

Permanent link to this version:
http://urn.kb.se/resolve?urn=urn:nbn:se:umu:diva-160341

Demand-controlled energy systems in commercial and institutional buildings: a review of methods and potentials

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Keywords

occupancy detection, demand-side management

Abstract

Heating, ventilation and air-conditioning (HVAC) are by far the most energy intensive systems in commercial and institutional buildings with office spaces. This makes HVAC systems attractive targets for energy efficiency improvement. New technological advancements can play significant role on improving energy efficiency. Such advancements have been also emerged in form of novel management and control strategies, which might lead to considerable energy savings with relatively minor investments. This paper evaluates demand control HVAC and lighting to assess the energy saving potential of upgrading the conventional building energy systems.

This paper provides a summary of different methods and occupancy detection technologies. A range of technologies and methods are covered that vary in complexity, limitations and energy saving potential. Additional benefits such as demand response are evaluated and other emerging applications are discussed. Based on the review of methods and potentials, the paper assesses the state of the art in demand controlled energy systems and suggests areas for further research.

Introduction

Today, buildings are responsible for up to 40 % of total final energy use in developed countries above industry or transport sectors (U.N. 2009). Energy use in the building sector is growing due to population increase, rise in the time spent inside buildings and improvement in building services and comfort levels (Pérez-Lombard, Ortiz, and Pout 2008). HVAC systems used for space conditioning to maintain thermal comfort and ventilation requirements have become predominantly the most important end user in the built environment in both residential and non-residential buildings (EIA 2019). The increase in energy use related to HVAC systems are predicted to continue in non-residential buildings in the coming years (EIA 2019). Non-residential buildings accounted for the highest growing rate in building sector in terms of energy use before the economic crisis (Pérez-Lombard, Ortiz, and Pout 2008). During the crisis, from 2007–12 the final energy consumption in Europe decreased by 8 % while on the contrary the final energy consumption of non-residential buildings remained quite stable (Saheb et al. 2015). Non-residential buildings account for a quarter of total energy consumption in European building stock and comprised of different typologies such as offices, hotels and restaurant, educational, hospitals, wholesale and retail (BPIE 2011). Different types of buildings have different distribution of energy use although HVAC, followed by lighting are the most energy intensive systems in European non-residential buildings (Balaras et al. 2017). In Canada, they are responsible for 66 % of energy use in commercial and institutional buildings (NRCan 2015). Office buildings are important typology within non-residential building category and consume between 2 % and 3.2 % of final energy use (Pérez-Lombard, Ortiz, and Pout 2008). Since 2008 the electricity consumption has increased by 74 % mainly due to increase in required IT devices, new telecommunication types, new appliances and air-conditioning (D'Agostino, Zangheri, and Castellazzi 2017). Office buildings comprise of the second biggest category of non-residential floor spaces. They have similar cooling and heating conditions as residential buildings while they are used in shorter periods (BPIE 2011).

Building energy systems are meant to provide a comfortable environment for the occupants in the building. The level of occupancy has a great impact on building's indoor environmental qualities (IEQ) thus on energy use in the building (Elie and C. 2012). This is because occupants generate CO_2, sensible and latent heat and their behaviour such as opening windows and using equipment affect IEQ in the building. Demand-controlled energy systems are meant to deliver the services only when and where they are needed, in the amount that they are needed (Shen, Newsham, and Gunay 2017). This strategy requires accurate occupancy detection in real time. It is even obligatory in some building codes and standards for certain building spaces to have occupancy sensors for lighting control (IRC 2011).

Occupancy detection has long been practiced especially in the field of automated lighting systems (Guo et al. 2010) The application of occupancy detection technologies in the HVAC area is relatively recent and emerging field (B. Dong and Lam 2011; Gunay, O&Amp, et al. 2016). Occupancy detection technologies provide information that can be used by building control systems to operate the energy systems proportional to the number of occupants in the building. Accordingly, the energy use would be optimized by integrated control of active and passive heating, cooling, lighting and ventilation systems (Sun et al. 2013). Webber et al. (2006) investigated the energy use by office equipment after working hours and found the turn-off rate of most types of equipment are under 50 % signifying considerable energy saving potential. A study in South Africa showed higher energy use during non-working hours than working hours in commercial buildings (Masoso and Grobler 2010). The occupant's behaviour and poor building control are presented as the reasons for such energy waste while occupancy-based building automation systems can be a solution to improve the energy efficiency.

The objective of this paper is to review the conventional and new innovative methods of detecting building occupancy. Resolution and accuracy are defined as two important qualities of occupancy detection. Conventional methods of occupancy detection are identified and implicit sensors linked together in network is introduced as important emerging approach. Subsequently, energy efficiency potential of demand control energy systems are investigated and other possible applications are presented. The final section provides some concluding remarks and presents areas for future research.

Qualities of occupancy detection

Different applications of occupancy detection require different qualities of detection. Resolution and accuracy are distinguished the main qualities of occupancy detection in the literature (Melfi et al. 2011).

RESOLUTION

Most common methods of occupancy detection are limited to a binary output showing whether or not a space is occupied. However, many applications require more detailed information such as the number of people in the space. Melfi et al. define resolution of a sensor as measure of the quality of information that consists of 3 dimensions (Figure 1). As resolution of a sensor increases the occupant becomes more defined, the space becomes smaller and the information is available more quickly. Four levels of occupant resolution include:

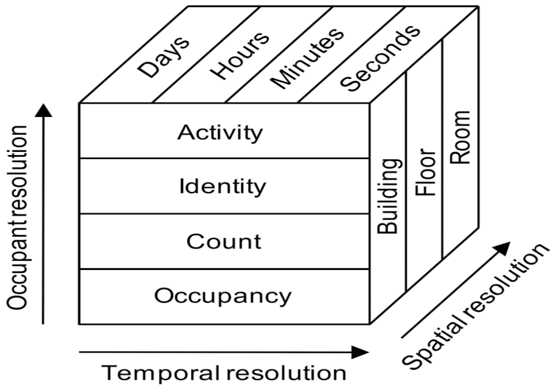

Figure 1. Resolution of occupancy detection (Melfi et al. 2011).

- Level 1: Occupancy; whether there is at least one person present in the zone
- Level 2: Count; how many people are present in the zone
- Level 3: Identity; who are the people present in the zone
- Level 4: Activity; what are the present people occupied with

ACCURACY

In order for the building management systems to operate efficiently, the occupancy information has to be accurate and reliable. The accuracy of occupancy detection can be defined in two different ways based on whether considering the presence or absence of occupants (Gunay, Fuller, et al. 2016). The accuracy of presence detection is the ratio of correct presence detections and the accuracy of absence detection is the ratio of correct absence detection. In order to calculate these ratios, the acquired occupancy information is contrasted to the ground-truth. The ground truth is obtained with a reliable method of occupancy detection, e.g. in a study by Ghai et al. (2012) the occupants manually tagged their location by using a desktop application. Similarly, there are two types of occupancy detection errors (Shen, Newsham, and Gunay 2017). False negative detection is when the zone is occupied but wrongly concluded to be empty. On the other hand, false positive detection is when a zone is empty but wrongly considered to be occupied.

False negative errors are more problematic type in the field of building energy management. For example, a false negative error causes the automatic lighting systems to be switched off when space is occupied leading to occupant's dissatisfaction and reduction in productivity. Occupants' annoyance might lead them to find ways to resolve the problems by dismantling the sensors or control systems leading to adverse energy performance (O'Brien and Gunay 2014). Nagy et al. (2015) found, even 90 % accuracy of presence detection can cause considerable dissatisfaction for the occupants in the case of lighting control. Nevertheless, the required accuracy might differ in different applications. For example, occupancy detection for heating control might require less accuracy because of the buildings' thermal inertia. The concerns about false negatives usually lead the designers to adjust long timeout period for occupancy sensors (Nagy et al. 2015). The system must detect no occupancy during the entire timeout period before it undertakes a control action. This increases the confidence that there is no occupancy despite increase in false positive errors leading to lower energy efficiency potential. Increasing accuracy of occupancy detection usually associates with higher investment in deployment. Thus, the decision on level of accuracy should be based on acceptable return on investment calculations that depends on the application of occupancy detection system.

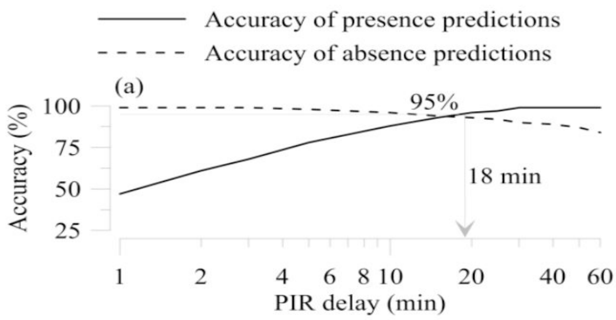

Figure 2. Selection of PIR delay period based on the accuracy of presence detection – adopted from Gunay et al. (2016).

Technologies and Methods of sensing occupancy

PIR SENSORS

PIR sensors are one the most common types of sensors that are often used in building automation applications specifically for automatic lighting systems (Guo et al. 2010). These devices detect movements by sensing the changes in infrared radiation thus, inferring human presence in the space (Dodier et al. 2006). Since movement is the key determinant for functionality of these sensors, presence detection is not possible during the periods of immobility. Moreover, these sensors require direct line of sight, thus, they cannot detect movements happening behind the objects in a room (e.g. a partition). In order to decrease false negative errors, usually an arbitrary delay period is introduced. The more being conservative on occupant annoyance and discomfort, the longer delay period is selected. Long delay period reduces energy efficiency potential, which is the primary intention of these systems; thus, the optimum delay period is required to be determined. Nagy et al. (2015) examined the accuracy of presence detection with different set delay periods. They inferred that the optimum delay period for lighting control is when the accuracy level for presence detection reaches 95 %. The delay period associated with this accuracy level lies between 4 and 20 min depends on the space and location of installed sensors. Figure 2 by Gunay et al. (2016) shows similar approach that can be used to develop algorithms to determine the optimum delay periods for sensors in their specific location of installation.

Considering the PIR sensor's line of sight, their accuracy is sensitive to where they are installed. Furniture and room geometry can sometimes disrupt motion detection therefore; it might be more efficient to use multiple sensors to cover a room (Tiller et al. 2009). There are also other limitations to some PIR sensors on where they can be installed. Some PIR sensors are incorporated with other devices such as switches and thermostats in order to reduce the costs (Shen, Newsham, and Gunay 2017). Switches are designed to be installed 1 m above the floor while thermostats are supposed to be installed 1.5 m above the floor. The PIR sensors that are built-in parts of these devices are likely to have suboptimal performance due to positioning limitations (Shen, Newsham, and Gunay 2017).

ULTRASONIC SENSORS

Ultrasonic sensors are a type of occupancy sensors that similar to PIR sensors detect motions. Unlike PIR sensors, ultrasonic sensors are active which means they emit sound waves to their surrounding environment. When they receive sound waves reflected from moving objects, they can perform detection due to the change in the wavelength (Guo et al. 2010). Unlike PIR sensors, ultrasonic sensors do not need a direct line of sight since ultrasonic waves can travel through the obstacles in a room. These sensors are more prone to false positive errors compared to PIR sensors due to their sensitiveness to movement of inanimate objects such as blowing curtains (Maniccia and Luan 1994).

CO_2 SENSORS

Both ultrasonic and PIR sensors can only have a binary output to indicate the presence of occupant(s). The number of occupants in the space is more often desired in different applications such as demand-controlled ventilation. An inactive person would generate CO_2 in the rate of 0.3 L/min causing the CO_2 concentration of a closed space to increase (ASHRAE 2005). As a result, CO_2 sensors' output have the potential to estimate the number of occupants in a space by sensing CO_2 concentration (Wang, Burnett, and Chong 1999). The challenge with CO_2 sensors is that detection has some delay (Arora et al. 2015). For example Arora et al. (2015) reported 30 min delay in their experimental setup. The delay in observation might be due to factors such as airtightness of the room, furniture layout and distance between the occupants and sensors. Such disruptions diminish the reliability of CO_2 sensors for occupancy detection. Without considering the complex of different variables, it will be misleading to apply models with assumption of perfectly mixed indoor air. CO_2 sensors can also be used to complement PIR sensors especially when it is hard to provide a direct line of sight for them (Lam et al. 2009).

ACOUSTIC SENSORS

Acoustic sensors are passive devices that do not emit energy but await to detect changes in the energy they receive (Guo et al. 2010). Unlike ultrasonic sensors that operate with ultrasonic waves, acoustic sensors receive energy in form of audible sounds. These sensors cannot distinguish between noises generated by human and other sources therefore have high rate of false positive errors.

VISION-BASED OCCUPANCY DETECTORS

With the recent advancements in image processing techniques, the video cameras can extract high-resolution occupancy information including presence, location, number and types of activities in very high rates of accuracy (Benezeth et al. 2011). Despite the usefulness of these systems in buiding service management, their application is restricted mainly due to privacy concerns. The concerns are aggravated when the videos and information are sent to be processed and stored in a central server. One solution to resolve the concerns could be to process the images locally and send only limited occupancy information to the building control system.

CHAIR SENSORS

Labeodan et al. (2016) experimentally evaluated three types of chair sensors for occupancy detection. The results showed that mechanical-switch sensors have better performance than both strain and vibration sensors. Moreover, chair sensors outperformed PIR sensors in terms of reliability and accuracy although their durability and long-term reliability is uncertain (Labeodan et al. 2016).

IMPLICIT OCCUPANCY SENSING

Melfi et al. (2011) introduced *implicit occupancy sensing* as using existing building infrastructure to detect occupancy despite they are not originally intended for this purpose. The data from these systems is usually available for building control purposes. Some examples of such systems include computer network traffic, connection of mobile devices to Wi-Fi, security access cards and usage of elevators. Some other building systems can be used to measure occupancy but require some modifications. Some examples of such systems are computer keyboard, mouse, webcam and microphone while the level of required modification differs between them. Since such systems are already available in the buildings, they usually can provide occupancy data with no cost or little extra cost. The inferences made from each of these data sources might be unreliable but the aggregation of data from different sources can increase the accuracy and reliability of occupancy detection (B. Dong and Lam 2011; Tiller et al. 2009). Melfi et al. (2011) categorized the implicit occupancy sensing methods in three different *tiers*:

- Tier 1 does not require any modification to existing systems and data is available to process and use.
- Tier 2 requires additional software to make data accessible.
- Tier 3 requires additional software and hardware produce and provide data to detect occupancy.

There are various innovative technologies mentioned in the literature used for implicit occupancy sensing. RFID (radio frequency identification) is a technology based on electromagnetic signal detection that is often used in security access tags and cards and is capable to determine the occupants' location in a cost effective manner (Zhen et al. 2008). Li and Becerik-Gerber (2011) implies despite the potential of RFID-based indoor location sensing solutions, widespread implementation is not possible, as the adaptability to each indoor environment needs to be further justified. Han et al. (2007) used only humidity sensors to examine occupancy and calibrated the data with size of windows. The results showed that humidity measurements could potentially disclose occupancy information.

Newsham et al. (2017) examined occupancy in single-occupant offices by using the data that can be easily collected from occupant's PC in low-cost such as mouse, keyboard and webcam. These data sources are usually fit into tier 2 as their data is ready to use with small modifications. The analysis showed such data sources could be much more accurate than usual ceiling-based PIR sensors with over 90 % accuracy of occupancy detection. In this case, high accuracy associate with very low rate of false negative errors enabled to reduce timeout period. Reduced timeout period can significantly increase energy savings in lighting and HVAC systems. Ghai et al. (2012) used only context sources that are commonly available in commercial buildings to infer occupancy. They used *soft sensor data* (implicit sensor data) such as Wi-Fi access points, area access badges, calendar and instant messaging clients. The use of these readily available data lead to 90 % accuracy of presence detection.

NETWORK OF SENSORS

Shen, Newsham, and Gunay (2017) count a number of drawbacks for the conventional single-sensor occupancy detection approaches:

- The conventional sensors are expensive and require high investment costs. They mentioned recent advances in wireless systems have decreased the installation cost although such systems are not as reliable as wired sensors in terms of data communication and their need to change batteries is cumbersome.
- The conventional sensors often have low occupant resolution and do not provide any information on count, identity and activity of occupants.
- The conventional sensors are prone to false detection by a shadow or flash such as headlight from a passing car.
- Building systems that operate by a single sensor can easily malfunction if the sensor fails indicating the low reliability of the system.

The outcome from occupancy sensors usually associate with uncertainty. Instead of using expensive high-end sensors, a network of different sensors can be an answer to many of the drawbacks assigned to conventional occupancy detection systems and enable to achieve more reliable and robust determination of occupancy. Moreover, with propagation of "Internet of Things" (IoT), the implicit sensors data are more widely available that more often have even more uncertainty than conventional sensors. The challenge would be to develop an analysis method to infer occupancy information from combination of data from different sensors (Dodier et al. 2006).

There are several methods in the literature for data fusion and control strategies in real time. Dodier et al. (2006) applied analysis models based on Bayesian probability theory to determine occupancy from a network of PIR sensors. They conclude this approach offers significant benefit as compared to single-point sensing. Hailemariam et al. (2011) in their experimental setup in an office tested a heterogeneous sensor array. They used decision trees to classify the sensors and explored the relationships between them. The results showed improvements in accuracy when they used data from multiple PIR sensors. On the contrary, combining different types of sensors worsened the accuracy of detection when they analysed the data with decision trees. Another study in an office-type environment in university premises used ambient sensing data such as lighting, acoustics, motion and CO_2 incorporated into an event-based pattern detection algorithm (Gaussian Mixture Model). The results showed the experimented occupancy detection system could count the number of occupants with 83 % accuracy although the maximum number of occupants was 4 and accuracy might drop with higher occupant traffic. Ghai et al. (2012) used data from context sources such as area access badges and Wi-Fi access points to measure occupancy. This study applied machine-learning techniques including regression and classification to analyse *opportunistic* data (implicit sensors data) to infer occupancy and could achieve 90 % accuracy. Ekwevugbe, Brown, and Fan (2012) used indoor climatic variables, indoor events and energy data to infer occupancy patterns by using a novel method from artificial intelligence (AI) named Adaptive Neuro-Fuzzy Inference System. They conclude more reliability is possible with this approach as compared to single-sensor approach. Markov Chain model which is an approach based on machine-learning was used in several studies (V L Erickson, Carreira-Perpiñán, and Cerpa 2011; B. Dong et al. 2010; Varick L. Erickson and Cerpa 2010). Dong et al. (2010) tested three different machine-learning approaches in an open-plan office building to estimate the number of occupants and could achieve, in average, 73 % accuracy by Hidden Markov models.

Energy efficiency potential

Energy saving is found to be the primary reason for applying occupancy sensing systems in most related literature. The energy efficiency potential of occupancy based energy systems are also dependent on intensity of occupation in the building.

Table 1. Comparison of research papers investigated energy saving potential of demand-controlled energy systems.

Author(s)	Sensing technology	Detection accuracy	Occupancy modelling	HVAC energy savings	Lighting energy savings	Climate	Type of building	Energy saving calculation method
V L Erickson, Carreira-Perpiñán, and Cerpa (2011)	Network of low resolution cameras	80 %	Markov chain approach	42 %	_	Average of 3 climates	University building	Computer simulation-EnergyPlus
Dong and Lam (2011)	Network of environment sensors	83 %	Gaussian Mixture Model based Hidden Markov Models	18.5 %	_	Humid continental climate-Pittsburgh	University building	Computer simulation-EnergyPlus
Varick L. Erickson and Cerpa (2010)	Sensor network of cameras	80 %	Moving Window Markov Chain	20 %	_	Local steppe climate-Fresno	NS*	Computer simulation-EnergyPlus
Newsham et al. (2017)	Office IT equipment	>90 %	Machine learning-genetic programming	16.6–64 %	20–68 %	semi-continental climate-Ottawa	mock-up office environment	proof-of-concept demonstration
Floyd, Parker, and Sherwin (2002)	PIR sensors	NS*	_	_	10–19 %	humid subtropical climate-Florida	Office building	Field study
Agarwal et al. (2010)	PIR sensors	NS*	_	10–15 %	_	Tropical and Subtropical Steppe Climate-San Diego	University offices	Computer simulation-EnergyPlus
Goyal, Ingley, and Barooah (2013)	PIR and ultrasound	NS*	_	50 %	_	Humid Subtropical Climate-Gainesville	Office building	Field study
Peng et al. (2017)	Motion and indoor climate sensors	93 %	Machine learning-(KNN)	20.3 %	_	Tropical Rainforest Climate-Singapore	Offices in commercial building	Field study
Dong et al. (2018)	PIR sensors	70 %	Expectation maximization, finite state automata, uncertain basis functions	20 %	_	NS*	Office	Field study

** Not specified*

Comparing the irregularly and regularly occupied spaces shows 6–40 % difference in their lighting energy saving potential (Guo et al. 2010). Climate condition has great influence on the energy saving potential associated with applying demand control HVAC systems (V L Erickson, Carreira-Perpiñán, and Cerpa 2011). Buildings in colder climates are in general more energy intensive, thus, have more potential to reduce energy use. This was shown in a study related to university buildings in the United States based on sensor network occupancy model predictions. Their investigations in three different climates showed it is possible to achieve, in average, 42 % annual energy savings by using their model for demand controlled HVAC instead of conventional control (V L Erickson, Carreira-Perpiñán, and Cerpa 2011). It is worthy of note that baseline control strategy of energy systems has significant effect on energy saving potential. Some studies might inflate the accuracy and saving potential by considering overnight periods while vacancy in commercial buildings is self-evident and attributing energy saving is irrelevant (Shen, Newsham, and Gunay 2017).

Dong and Lam (2011) deployed a complex environmental sensor network consist of lighting, acoustics, motion and CO_2 sensors in two university buildings. The occupancy output was fed into a computer model and the comparative simulation analysis showed 18.5 % energy saving compared to conventional temperature set-point schedule. Another study with similar approach also found 20 % annual energy savings is possible by using acquired occupancy information in computer simulation of building (Varick L. Erickson and Cerpa 2010). Newsham et al. (2017) highlighted the importance of "Internet of Things" and new emerging data sources that can be used with low cost for building control and management. A combination of keyboard, mouse and pixel changes in webcam image showed promising results for occupancy detection. The enhanced accuracy of the system compared to conventional PIR sensors could reduce timeout period from 20 to 5 minutes leading to 25–45 % higher energy saving potential for lighting. Further analysis showed the possibility to reach up to 64 % reduction of HVAC energy use. Floyd, Parker, and Sherwin (2002) investigated the energy savings by application of occupancy sensors to lighting control and found 10–19 % energy savings in the commercial buildings. The summary of abovementioned studies and several other research projects focused on demand control energy systems and their entailed energy savings are presented in Table 1.

Applications of occupancy sensing

Occupancy detection enables demand-controlled energy systems that lead to direct energy savings through HVAC and lighting systems. However, occupancy information can be used for other applications that may or may not be energy related. Occupancy information can be used for converting or reusing spaces by building service designers, for example emergency evacuation plans (Suter, Petrushevski, and Šipetić 2014). Guo et al. (2010) mentioned a real- case example of required occupancy information for firefighters to evacuate the elevators in a building. They also mentioned the application of occupancy detection in building security and highlighted the use of network of sensors to enhance the reliability of occupancy detection to avoid the high cost of false positive errors leading to false alarm calls to police department.

Occupancy patterns are basic information required for building design and are important information for building simulation tools (Crawley et al. 2001). These simulation tools are often used for building energy analysis and design of energy systems. In order to achieve an optimal design, it is important to have accurate occupancy pattern for each specific type of building. Yu et al. (2010) used occupancy information to develop a building energy demand predictive model. Such a model can lead to accurate prediction of building energy consumption to improve the energy performance of a building.

Energy use in commercial buildings is strongly related to their occupancy. Demand response is referred to the effort to shift the energy peak load and has become more important in building management due to fluctuation of energy prices in different times of a day. Chaney, Hugh Owens, and Peacock (2016) investigated the influence of occupancy pattern on applying demand response and they inferred occupancy information is important to enable demand response programs. Timm and Deal (2016) investigated the role of energy information dashboards such as occupancy information in changing the energy behaviours of occupants in a behaviour change campaign. The occupants behavioural change can lead to significant energy savings in commercial buildings without any technical intervention while occupancy information can lead to exploit this potential (Meier 2006).

With multiple applications of occupancy detection systems, it will be easier to justify cost of their deployment although different systems must be integrated with each other. Currently in the existing buildings, even energy systems are not integrated so that the occupancy data that is used for lighting control cannot be easily used by HVAC systems without modifications. Implicit data sources are often described to be easily accessible and inexpensive to be used to detect occupancy although there might be hidden costs that are often not considered by the researchers. Such data sources are seldom integrated with the building management systems and required modifications that incur extra expenses. Ghai et al. (2012) mentioned access control information might be considered sensitive information and is rarely used for lighting and HVAC control despite being a promising source of occupancy information. Integration of different data sources with control systems is a major barrier to use implicit sensing approaches. In future, with increase in market penetration of wireless sensors, the data would be more easily accessible through the IoT environment.

Conclusions and areas for further research

Occupancy detection is important approach to tailor the building services and to improve their efficiency. This paper investigated different aspects of occupancy detection in building management specifically with respect to the application in demand-controlled energy systems. The subjects that are covered include conventional and emerging occupancy sensors and methods, implicit occupancy sensing, network of sensors, multi-sensor data fusion, energy efficiency potential of demand-controlled energy systems and other possible applications for occupancy sensing systems.

Using a network of different sensors is an advantageous approach to improve the reliability of occupancy detection by using inexpensive accessible data from implicit sources. There are many different multi-sensor data fusion methods to analyse such data although there is not enough research to compare these methods for different kinds of sensors and data sources. Further research is required to investigate the optimal use of each fusion method in respect to different combination of data sources and contextual factors such as probable occupant traffic.

The recent advancements in detection sensors to track the occupants and their activities would open up new applications and possibilities. Nevertheless, this level of detailed information has already caused concerns about privacy issues. Some examples of the sensors that caused concerns on privacy include cameras and webcams with image processing features and security access cards. Future research should consider such concerns and try to improve the functionality of such technologies while mitigating the privacy concerns.

The focus on sensing technologies has currently caused a discrepancy between development of new sensing technologies and the requirements of applications in practice (Li and Becerik-Gerber 2011). Some of emerging hot topics such as building-to-grid integration and using buildings for demand-response may not require highly detailed and accurate occupancy detection. It is important that future research involves more deciplines related to building industry into this area to identify the value and functionality of sensing technologies by developing their applications in the built environment.

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Acknowledgement

The authors gratefully acknowledge the financial support from the European Union under RUGGEDISED project.