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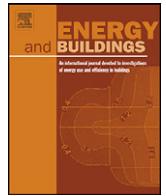
Energy intelligent buildings based on user activity: A survey

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ABSTRACT

Occupant presence and behaviour in buildings has been shown to have large impact on heating, cooling and ventilation demand, energy consumption of lighting and appliances, and building controls. Energy-unaware behaviour can add one-third to a building's designed energy performance. Consequently, user activity and behaviour is considered as a key element and has long been used for control of various devices such as artificial light, heating, ventilation, and air conditioning. However, how are user activity and behaviour taken into account? What are the most valuable activities or behaviours and what is their impact on energy saving potential? In order to answer these questions, we provide a novel survey of prominent international intelligent buildings research efforts with the theme of energy saving and user activity recognition. We devise new metrics to compare the existing studies. Through the survey, we determine the most valuable activities and behaviours and their impact on energy saving potential for each of the three main subsystems, i.e., HVAC, light, and plug loads. The most promising and appropriate activity recognition technologies and approaches are discussed thus allowing us to conclude with principles and perspectives for energy intelligent buildings based on user activity.

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Contents

1. Introduction

In the United States, buildings account for a surprisingly high 41% of energy consumption [1]. In 2004, building consumption in the EU was 37% of final energy, bigger than industry (28%) and transport (32%). In the UK, the proportion of energy use in building (39%) is slightly above the European figure [2]. Large and attractive opportunities exist to reduce buildings' energy use at lower costs and higher returns than in other sectors. These reductions are fundamental to supporting achievement of the International Energy Agency's (IEA) target of a 77% reduction in the planet's carbon footprint against the 2050 baseline to reach stabilized CO_2 levels called for by the Intergovernmental Panel on Climate Change (IPCC). Research by World Business Council for Sustainable Development (WBCSD) in 2009 demonstrates that we can cut the energy used in buildings dramatically, saving as much energy as the entire transport sector currently uses.

Using more grid electricity from non-fossil sources (such as solar and wind) will help to address climate change, too. But cutting energy consumption is also vital because it helps to preserve finite resources, lowers costs for businesses and consumers, and can be accomplished relatively quickly. In addition, the contribution of non-carbon sources is likely to be constrained for several decades. Hence, to move towards a low carbon economy, making "more intelligent" use of energy in buildings will fundamentally contribute to energy and cost savings. Energy intelligent buildings, which facilitate intelligent control of the building, are becoming a trend of the next generation's commercial buildings.

Building energy and comfort management (BECM) systems are control systems for individual buildings or groups of buildings that use computers and distributed microprocessors for monitoring, data storage and communication [3]. The general objective of a BECM system is to fulfill the occupants' requirements for comfort while reducing energy consumption during building operations. Heating, ventilation, and air conditioning (HVAC) control, lighting control, hot water control, and electricity control are commonly seen as required functions for the BECM system.

Occupant presence and behaviour in buildings have been shown to have large impacts on space heating, cooling and ventilation demand, energy consumption of lighting and space appliances, and building controls [4]. Careless behaviour can add one-third to a building's designed energy performance, while conservation behaviour can save a third [5], see Fig. 1. One particularly interesting example is an experiment regularly performed by the company 3M at their headquarters in Minnesota: office workers are asked to switch off all office devices, lights, etc. not in use during peak-price periods. The results of such that experiment were profound: the building's electricity consumption dropped from 15 MW to 13 MW in 15 min and further to 11 MW over 2 h [6]. This corresponds to a saving of 26% in electrical energy. Though the results of this experiment are remarkable, the savings depend on the conscious action of the employees, which is not likely to be constant over time. Thus, recent research is focused on developing energy intelligent buildings by integrating occupant activity and behaviour as a key element for BECM systems with which the buildings can automatically turn off unused lights, computers, etc. This key element has long been used for control of various devices like artificial light, HVAC devices, etc. As an example, past research has shown that the use of real-time occupancy information for control of lighting can save a significant amount of the electrical energy used for lighting [7].

How are user activity and behaviour taken into account in a BECM system? How does this key element play its so-called important role in energy intelligent buildings? What are the most valuable activities or behaviours and their impact on energy saving potential? In order to answer these questions, we here study prominent international projects on energy savings in buildings that are based on user activity as the key element of the system.

We start by introducing the criteria for BECM systems that are evaluated in this survey (Section 2); the section also contains the basic descriptions of the features that are used to evaluate and compare the studies. The features are the types of energy intelligent buildings, energy saving potential, activities taken into account, approaches, and technologies. The actual comparisons of the studies using these features are presented in Section 3, Section 4, Section 5, and Section 6. Future perspectives on user activity as an important part of energy intelligent buildings are discussed in Section 7, which also provides conclusions.

2. Criteria and methods

The field of intelligent buildings, intelligent homes, building automation systems (BMS) encompasses an enormous variety of technologies, across commercial, industrial, institutional and domestic buildings, including energy management systems and building controls. The function of building management systems is to control, monitor and optimize building services such as lighting, heating, security, closed-circuit television (CCTV) and alarm systems, access control, audio-visual and entertainment systems, ventilation, filtration and climate control, etc., even time and attendance control and reporting (notably, staff movement and availability). This often leads system developers to describe their systems variedly, for example, part of 'e-health' or 'home-care' subsystems. Therefore, for this literature review, a set of selection criteria needs to be introduced to identify studies in which BECM systems based on user activity are covered.

2.1. Terminology

According to the research conducted by Wigginton and Harris [8], there exist over 30 separate definitions of intelligence in relation to buildings while [9] discusses the best known academic and technical definitions of the term *intelligent building*. Two most of the most often accepted definitions are proposed by the Intelligent Building Institute (IBI) of the United States and the UK-based European Intelligent Building Group (EIBG). The IBI defines an intelligent building as *'one which provides a productive and cost-effective environment through optimization of its four basic elements including structures, systems, services and management and the interrelationships between them'* [8]. While EIBG defines an intelligent building as *'one that creates an environment which maximizes the effectiveness*
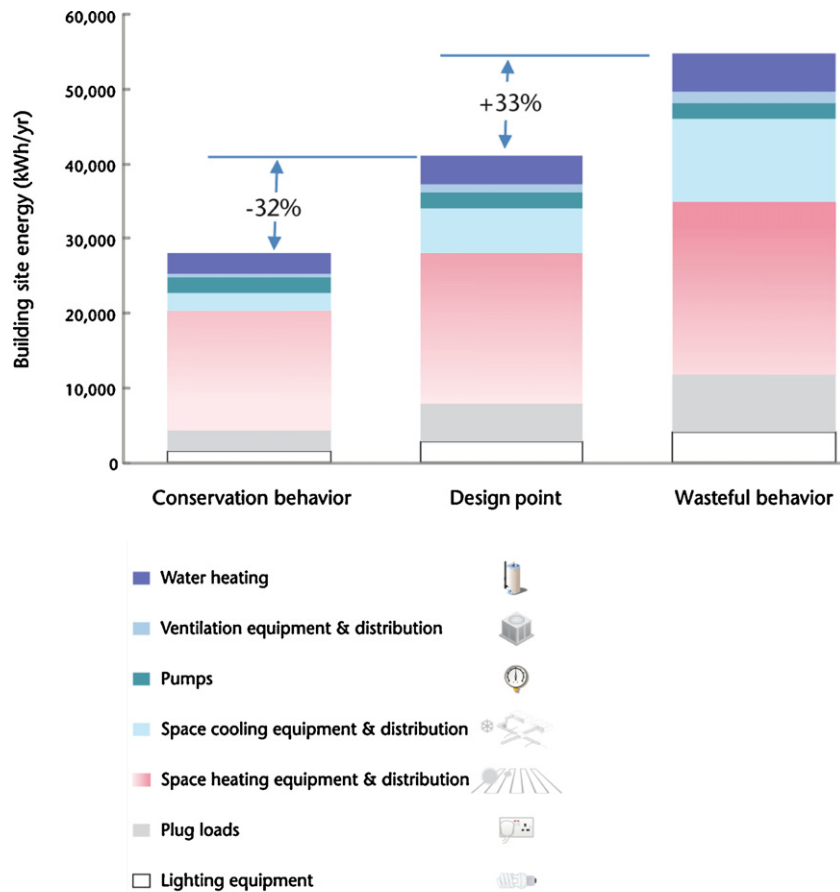
Fig. 1. Energy-unaware behaviour uses twice as much energy as the minimum that can be achieved (figure from [5]).

of the building's occupants, while at the same time enabling efficient management of resources with minimum life-time costs of hardware and facilities' [8]. The IBI definition focuses more on the benefit of the owners and their desired indoor environment, while the EIBG one concentrates on the benefit of the users and creating desired indoor environment for occupants. Nevertheless, both definitions also call attention to the benefit of the managers and the environmental and economic impact of creating desired indoor environment. Therefore, an intelligent building can be comprised of 10 'Quality Environment Modules (QEM)' (M1M10) [10]. The 'QEM' (M1–M10) includes:

1. M1: environmental friendliness – health and energy conservation;
2. M2: space utilization and flexibility;
3. M3: cost effectiveness – operation and maintenance with emphasis on effectiveness;
4. M4: human comfort;
5. M5: working efficiency;
6. M6: safety and security measures – fire, earthquake, disaster and structural damages, etc.
7. M7: culture;
8. M8: image of high technology;
9. M9: construction process and structure; and
10. M10: health and sanitation.

With 10 key modules mentioned above, intelligent building can be considered as one which is 'designed and constructed based on an appropriate selection of 'Quality Environmental Modules' to meet the user's requirements by mapping with appropriate

building facilities to achieve long term building values' [9]. Each appropriate selection of QEM forms one type of 'intelligent building', such as 'smart house' or 'green building'.

Domotics, meaning automation of the house [11], is also often used to indicate a home with mechanical and electronic automation facilities. More recently, the term *smart house* has emerged, intending an intelligent building used for any living space designed to assist people in carrying out daily activities [12].

Another type of intelligent building is the so called *green building* (also known as *green construction* or *sustainable building*). Green building is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout the building's life-cycle: from siting to design, construction, operation, maintenance, renovation, and demolition [13]. This requires close cooperation of the design team, the architects, the engineers, and the client at all project stages. The green building practice expands and complements the classical building design concerns of economy, utility, durability, and comfort. Although new technologies are constantly being developed to complement current practices in creating greener structures, the common objective is that green buildings are designed to reduce the overall impact of the built environment on human health and the natural environment by efficiently using energy, water, and other resources, by protecting occupant health and improving employee productivity, or by reducing waste, pollution and environmental degradation.

Green buildings often include measures to reduce energy consumption both the embodied energy required to extract, process, transport and install building materials and operating energy to provide services such as heating and power for equipment. In this context, *energy efficient building* (also known as *low-energy house*

or *zero-energy building*) that from design, technologies and building products uses less energy, from any source, than a traditional or average contemporary house.

2.2. Inclusion criteria for studies

In this paper, the term *'energy intelligent buildings'* refers to buildings equipped with technology that allows monitoring of their occupants and/or facilities designed to automate and optimize control of appliances, in particular, lights, HVAC system, and home appliances, with the goal of saving energy. The term does not include reference to the technologies used to help people to overcome dependence and health problems. For an intensive review of smart houses whose major targets are improving comfort, dealing with medical rehabilitation, monitoring mobility and physiological parameters, and delivering therapy, one should refer to [14].

Many energy efficient buildings are designed to take advantage of (1) cutting energy demand including the use of designs, materials and equipment that are more energy efficient, (2) producing energy locally from renewable and otherwise wasted resources, and (3) using smart grids generating a surplus in some buildings and feeding it into the grid. Nevertheless, these studies show limited evidence of innovation in the area of activity based computing, thus, they are not discussed in this survey.

2.3. Inclusion criteria for systems

The inclusion criteria for systems to be part of the survey are:

1. Systems which feature:
   - wearable, portable, or implantable devices;
   - mobile or stationary devices, such as sensors, actuators or other information and communication technologies (ICT) components embedded in the structural fabric of the intelligent buildings or everyday objects such as furniture, etc.
2. Systems which have components with 'activity recognition' or 'user behaviour' in the sense of context awareness or decision support properties.
3. Systems that perform actions to save energy and satisfy user comfort without human intervention or interaction.

2.4. Search methods

This literature review includes published work that has undergone peer review. Our search is restricted to articles in journals, chapters of periodicals and proceedings of conferences written in English and published between 1996 and 2012. Some web sites describing prototypes, projects and systems or devices are also included. Searches are conducted through IEEE Xplore, ACM Digital Library, or using the Google search engine.

2.5. Sectors and subsystems

We use "sector" to describe a global building type, such as an office or a single family, while "subsystem" to describe a group of appliances which have the same or similar functionality, such as lighting or HVAC system. Many surveys on energy consumption, namely, [2,15,5,16], and [1] share the same figures about energy consumption distributions on sectors and subsystems. According to the survey of WBCSD [5], three key sectors that collectively represent over 50% of building energy consumption world wide are residential houses, offices, and retails. The following proportions of energy consumption of subsystems in each sector are summarized from the above surveys.

Residential sector: The residential sector use significantly more energy than commercial buildings and are responsible for over 40%

of total buildings' CO_2 emissions [5]. Heating, ventilation and cooling (HVAC) is the single largest contributor to a home's energy bills and carbon emissions, accounting for 43% of residential energy consumption in the U.S. and 61% in Canada and the U.K., which have colder climates [1,17,18]. In France, space heating and cooling have the highest energy consumption at 60%, at the second place comes water heating at 20%, followed and lighting and auxiliaries at 10% each [5].

Offices : The office sector is the largest in the commercial sector in floor space and energy use in most countries. Heating, cooling and lighting are the largest energy consumers in offices. The balance varies depending on climate and the type or size of office building, but space heating is typically the largest one in the The European Environmental Bureau markets. In the US, HVAC consumes 33% of all office energy, 9% of which goes to cooling system, followed by interior lighting at 25% [1]. In Japan, heating accounts for 29% of the total, the largest proportion, while cooling and ventilation consumes 19% in total. Lighting and plug load share the same figure at 21% [16].

Retail: Retailing is growing and becoming more energy-intensive as it develops from small shops to sophisticated malls. The mercantile retail segment accounts for 16% of commercial energy use in the US. In Europe, the total retail is responsible for 23% of energy use in the commercial sector [5]. Retail's main energy consumers are HVAC and lighting. This is true in street shops as well as malls, but cooling takes a larger share in malls than in smaller shops.

2.6. Features for comparison

This review examines the studies based on several points of view. Firstly, we examine the literature to determine the building types which their BECM systems most benefit from taking user activity into account. Next, the energy saving potential of energy intelligent buildings based on user activity is investigated followed by the summary of the most important user activities and behaviours for BECM systems. Last but not least, methodologies and technologies used for activity recognition or pattern prediction are analysed in order to show the most appropriate methods and technologies that are used for the sake of energy saving and user comfort in energy intelligent buildings.

3. Energy intelligent buildings

We select projects which have been deemed among the most significant from an international perspective and represent well the whole field, but the list does not have the ambition to be exhaustive. We particularly focus in this survey the perspectives of user activity as it is and will be an essential element of a BECM system. Table 1 summarizes the energy intelligent buildings discussed, along with their focus on subsystems, i.e., HVAC, light, and plug loads. The table also illustrates how energy intelligent buildings are classified by mean of sectors, i.e., residential, office, retail, and other. It can be seen from the table that much attention has been given to residential and office sectors.

3.1. The residential sector

Many systems pay attention to residential sector, that takes up to 40% of energy consumption. In the Vienna University of Technology, Austria, the ThinkHome project [19] has been designed to ensure energy efficiency and comfort optimization. Primary targets are functions that require comparably high amounts of energy, such as HVAC, and lighting/shading in the home (domestic) environment. The users can be tracked using radio-frequency identification

Table 1
Energy-intelligent buildings and their subsystems.

Sector/Subsystem	HVAC	Lights	Plug loads
Residential	[34,60,24,35,30,47,36,19]	[34,24,30,25,19]	[34,28,23,31,27,30,25,32]
Office	[55,51,61,60,52,39,47,56,46,42]	[51,61,48,63,39,37,46,59]	[45,39,49,37,58]
Retail			
Others	[47,65,41]	[65,62,41]	

(RFID) tags that allow determining the inhabitant's position relative to the building structure stored as static data [20,21], and [22].

The BeyWatch [23] project, led by the Spanish telecommunication company Telefonica, aims to reduce energy consumption at the household level by developing and evaluating innovative user-centric solutions to raise energy awareness and usage flexibility.

eDIANA (embedded systems for energy efficient buildings) [24] is a research project co-founded by the ARTEMIS Joint Undertaking Organisation and by National Authorities of each partner. The goal of the project is to develop a technology (eDIANA platform) to improve energy efficiency and optimize household energy consumption, providing real-time measurement, integration and control. In eDIANA, users express their preferences and drive the platform toward energy consumption optimization.

iSpace [25] is a student study bedroom that was built by refitting a room on the campus of the University of Essex, United Kingdom. iDorm is an installation of gadgets, sensors and effectors in a student bedroom. iDorm is a two-bedroom apartment with an installation of sensors and actuators heavily influenced by iDorm [26]. iSpace furnishings are fitted with intelligent gadgets that can detect and learn the occupants behavior. The intelligent gadgets communicate with each other, allowing groups of agents to coordinate their actions. The agent can intelligently remember the user habits under particular environmental conditions and then make changes to the environment according to those habits.

The overall objective of the E3SoHo project [27] is to bring about a significant reduction of energy consumption in European social housing by providing tenants with feedback on consumption and offering personalized advice for improving their energy efficiency.

The project AIM [28] is a consortium of eleven partner organisations from five different European countries. The main goal of the project is to provide a generalised method for managing the energy consumption of household appliances that are either powered on or in a stand-by state. The project AIM aims at developing a technology for profiling and optimizing the energy consumption patterns of home appliances and providing concrete examples related to three application areas: white goods, audio/video equipments and communication equipments. In terms of user activity, the project develops an event-based pattern detection algorithm for sensor-based modelling and prediction of user behaviour [29]. Behavioural patterns (Markov model) are connected to building energy and comfort management.

In France, the G-SCOP Laboratory of Grenoble for Sciences of Conception, Optimisation and Production proposes a general method to predict the possible inhabitant service requests for each hour in energy consumption of a 24 h anticipative time period. The idea is based on the use of the Bayesian Network (BN) to predict the user's behaviour [30]. The authors use a database obtained from Residential Monitoring to Decrease Energy Use and Carbon Emissions in Europe (REMODECE)[1] which is a European database on residential consumption, including Central and Eastern European Countries, as well as Bulgaria and Romania.

The CASAS Smart Home project [31] is a multi-disciplinary research project at the Washington State University focused on the creation of an intelligent home environment. The approach is to view the smart home as an intelligent agent that perceives its environment through the use of sensors, and can act upon the environment through the use of actuators.

At the University of California, Kim et al.[32] present SPOTLIGHT, a prototype system that can monitor energy consumption by individuals using a proximity sensor. The basic idea is that an occupant carries an active RFID tag, which is used for detecting proximity between a user and each appliance. This proximity information is then used for energy apportionment, reporting the energy consumption profile in terms of useful/wasted power of each user with each appliance (e.g. TV, living room lamp, etc.)

In Colorado, Michael Mozer uses a soft-computing approach using neural networks to focus solely on the intelligent control of lighting within a building [33]. Mozer's system [34], implemented in a building with a real occupant, achieves a significant energy reduction, although this is sometimes at the expense of the occupant's comfort.

Gao et al.[35] at the University of Virginia sought to use coarse occupancy data (leave home, return home) to drive a self-programming home thermostat. The occupancy information is collected manually within one month then occupancy pattern is built upon the observed data.

The authors in [36] utilize door and a passive infrared (PIR) sensors for binary detection of occupancy for residential buildings and examine reactive and predictive control strategies for thermostat. The predictive strategy is achieved using a Hidden Markov Model. The model estimates the probability of home being in one of three states: unoccupied, occupied with an occupant awake, and occupied with all occupants asleep.

3.2. The office sector

In the context of the intelligent buildings project [37], a collaboration between a number of Swedish universities, Paul Davidsson and Magnus Boman produce a multi-agent system (MAS) that monitors and controls the lighting system in an office building. In the MAS, badge system agent (BSA) keeps track of where in the building each person is situated and maintains a database of the users' preferences and their associations to persons (badges) [38].

In the context of the GreenerBuildings project [39], we propose a recognition system that performs indoor activity recognition with the goal of providing input to a control strategy for energy savings in office buildings [40]. Our solution uses a wireless network of simple sensors (infrared, pressure and acoustic).

The SEEMPubS research [41] is funded by the European Commission, within the Seventh Framework Programme (FP7). SEEMPubS aims at raising users' awareness of energy consumption in public spaces and at involving the users themselves in the global process finalized to achieve the main objective, i.e. energy efficiency.

The EcoSense project [42] is a joint initiative of the i3A, the Albacete Research Institute of Informatics and AGECAM, the regional Energy Agency of Castilla La Mancha. The main objective of the EcoSense project is to develop a methodology for the design and deployment of monitoring [43] and control environmental indoor systems built around wireless sensor and actuator networks. User presence is detected by passive infrared detectors, door and

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[1] http://www.isr.uc.pt/remodece/

window opening sensors [44]. Then occupancy information is used to control heating system.

The FP7 EnPROVE project [45], which started in 2010, looks into how to predict the energy consumption of a specific building with different scenarios implementing energy-efficient technologies and control solutions based on actual measured performance and usage data of the building itself. The outcomes of the project will consist of software tools that can plug into existing building design and management solutions as well as a prediction engine and a decision support engine that can interface with building usage data (from available sensors). The EnPROVE approach is based on the monitoring of the building usage by a wireless sensor network to build adequate energy consumption models. Monitoring building usage can be seen as looking at users (in particular, user behavior).

The 'Positive Energy Buildings thru Better Control Decisions' (in short, PEBBLE) Project [46] is another FP7 project supported by the European Commission. The project is about utilizing harmoniously and most effectively all installed systems in a building, taking into account human factors and adapting the decisions in (almost) real-time as and when uncertainties occur. The architecture considers a building (renewable sources, passive systems, HVAC systems, and users) that interacts with control-decision and optimization tools through an adequate networking/communication infrastructure.

The goal of the HOMES program [47], in association with the French Electrical Contractors' Association (FFIE), is higher energy efficiency for all buildings while maintaining or improving comfort. A variety of buildings are involved (offices, hotels, schools and residential buildings), new or existing, possibly refurbished, covering a surface area between 500 and 3000 m^2. HOMES's approach takes into account the real occupancy of each zone in the building. HOMES systems to detect occupancy and number of people and anticipates unoccupied periods to just heating, cooling and ventilation strategies accordingly.

The University College Dublin, Ireland introduces LightWiSe (LIGHTting evaluation through WIreless SEnsors), a wireless tool which aims to evaluate lighting control systems in existing office buildings. LightWiSe uses two common sensing devices (1) a light detector used for detecting ambient light and luminaries state and (2) PIR sensor to detect people presence [48].

The authors at Trinity College Dublin, Ireland examine the power management of users' stationary desktop PCs in an office environment. The solution uses two simple location-aware policies that use the location context derived from detecting users' bluetooth-enabled mobile phones and tries to dynamically and probabilistically assign each user a state from the set using, about to use, not using in order to set the power state of the associated PC appropriately [49].

The University of Cambridge, the UK installs a personnel tracking system at the AT&T Research building in Cambridge, UK, which features an ultrasonic location system that provides three-dimensional tracking. The authors analyse the collected location data to form a picture of how people work and what energy savings might reasonably be expected if we are able to prevent device 'idling' [50].

The BODE project [51] at the University of California deals with occupancy measurement, modelling and prediction for building energy savings. Bode project develops a system that tracks user movement in building spaces using a camera network solution called SCOPES (a distributed smart cameras object position estimation system) [52,53]. Bode aims to develop a framework that estimates and predicts user occupation of building spaces. This information is used to save energy in various areas, most notably HVAC [54] and lighting.

Another research group at the University of California also utilizes a deployment of PIR and door sensors to obtain a binary indication of occupancy. In order to demonstrate the benefits of the presence system, they simulate an example building along with its HVAC energy consumption [55].

The Institute for Research in Construction, National Research Council Canada develops an ARIMA model to forecast the power demand of the building in which a measure of building occupancy is a significant independent variable and increases the model accuracy. To gather data related to total building occupancy, they install wireless sensors in a three-storey building in eastern Ontario, Canada comprising laboratories and 81 individual work spaces [56].

The University of California deploys a wireless camera sensor network [57] for collecting data regarding occupancy in a large multi-function building. Using data collected from this system, they construct multivariate Gaussian and agent-based models for predicting user mobility patterns in buildings. Using these models, they predict room usage thereby enabling to control the HVAC systems in an adaptive manner [52].

The authors at the Colorado School of Mines propose a general framework where building systems can share information in order to optimize performance. Their prototype is currently deployed in two graduate student offices on their campus, monitoring the occupancy information for each room and several switched devices (e.g. LCD displays, printer, speakers, desk lamp, microwave, coffee pot) [58].

The Carnegie Mellon University proposes and demonstrates a lighting control system with wireless sensors and a combination of incandescent desk lamps and wall lamps actuated by the X10 system [59]. The system satisfies occupants' lighting preference and energy savings by maximizing the modelled personal lighting utility function and building operator's utility function. In their scenario, where the occupants are equipped with sensor badges, it is possible to achieve relatively accurate localization using, for example, RFID tags.

Also coming from the Carnegie Mellon University, Bing Dong develops an event-based pattern detection algorithm for sensor-based modelling and prediction of user behaviour. They connect behavioural patterns (Markov model) toward HVAC system control [60].

The authors at the IBM Thomas J. Watson Research Centre propose a high-level architecture for smart building control system [61].The policy of building's management takes users' preference into account when adjusting the system's operation. However, due to physical limits and constraints, they have not tested the prototype system on real buildings.

In India, the authors at the SETLabs, Infosys Technologies Ltd study the iSense system to recognize two states of a conference room, namely, meeting state and no meeting state, by using a network of wireless microphone, PIR, light, and temperature sensors [62].

Another group in India, at the Centre for Energy Studies, Indian Institute of Technology design a smart occupancy sensors which can learn the variation in activity level of the occupants with respect to time of the day. With this information, the system can change the time delay (TD) with the time of the day. Thus, more energy can be saved as compared to non-adapting fixed TD sensors [63].

Zhen et al. [64] at the Tsinghua University, China implement a system with multiple active RFID readers, and develop a localization algorithm based on support vector machine (SVM), shedding insight on lighting control for energy saving.

3.3. Other sectors

HosPilot [65] is a project started in 2009 that addresses the environmental aspects of hospitals. The HosPilot aims to install and to tune an ICT-based system that will significantly reduce the energy
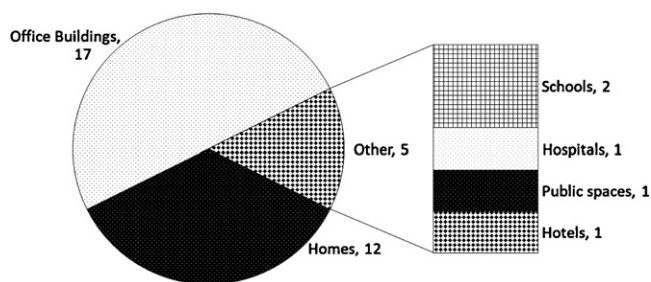
Fig. 2. Number of studies on each sector of buildings.

consumption regarding lighting and HVAC in a hospital environment. Three pilots is executed in hospitals (in the Netherlands, Spain and Finland) during normal operation. HOMES program [47] chooses hotels and schools as representatives for the goal of higher energy efficiency while maintaining comfort.

3.4. Discussion

In summary, much attention has been given to residential and office sectors, while only few research pays attention to buildings of other types, namely, hospital, school, and public space. On the other hand, there is no research dealing with the retail sector, thus there is no suggestion how user activity and behaviour influences the way of saving energy in the buildings of this type. Fig. 2 summarizes the number of the analysed studies on each sector of buildings. Regarding the subsystems, all three subsystems which are main energy consumers in buildings, namely, HVAC, light, and plug loads, draw the attention of the studies. [34,39], and [30] inspect all three subsystems. Some other studies try to save energy for two of the subsystems rather than focusing on one subsystem only. HVAC and light subsystems capture the attention of [51,61,65,46,41], and [19], meanwhile [37] and [25] pay their attention to light and plug loads subsystems. At the same time, other works tackle the issue of one of the three subsystems. While [52,35], [55,47,36,56,42], and [60] choose to deal with HVAC subsystem, [24,63,62,48], and [59] focus on light subsystem. Last, [58,27,31,23,45,32,28], and [49] save energy for plug loads subsystem. This information is summarized in Table 2, which is refined from Table 1 in order to provide a better view at how literature pays attention to the subsystems.

From a geographical perspective, the projects are mainly from the United States and Europe with some studies that consider Chinese or Indian cases, to the best of our knowledge there are no studies in Japan that consider energy intelligent building based on user activity. The countries whose studies are analysed together with the number of analysed studies for a given country is shown in Fig. 3. The impression is that while in Europe and the U.S. there is a growing concern about the preservation of the environment and more energy intelligent buildings are designed and researched. However, this trend is perceived to a lesser extent in Asia, where most countries are developing ones where few very expensive to run high-rise buildings coexist with poor constructions. In these cases, energy saving is often a minor requirement. As an interesting exception, which we believe to be a sign of a new trend, we mention Taipei's 101 building[2] which in the last year has transitioned to a greener model. The solutions are basic and cannot really be considered intelligent, though, they do provide for a substantial saving of energy over a yearly period.

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[2] http://www.taipei-101.com.tw/index_en.htm

Table 2
Works on each subsystem.

Work	HVAC	Light	Plug loads	No. of works
[34]	✓	✓	✓	
[39]	✓	✓	✓	3
[30]	✓	✓	✓	
[51]	✓	✓		
[61]	✓	✓		
[65]	✓	✓		6
[46]	✓	✓		
[41]	✓	✓		
[19]	✓	✓		
[37]		✓	✓	2
[25]		✓	✓	
[52]	✓			
[35]	✓			
[55]	✓			
[47]	✓			8
[36]	✓			
[56]	✓			
[42]	✓			
[60]	✓			
[24]		✓		
[63]		✓		
[62]		✓		5
[48]		✓		
[59]		✓		
[58]			✓	
[27]			✓	
[31]			✓	
[23]			✓	8
[45]			✓	
[32]			✓	
[28]			✓	
[49]			✓	
Total	**17**	**16**	**13**	**32**

4. Energy saving potential

With respect to HVAC systems, many of the works use EnergyPlus [66], one of the premier tools for modelling the energy of buildings, to run their simulations, evaluating the potential energy savings of HVAC control based on occupancy prediction. Even though thermal comfort is a complex measurement that depends on many aspects such as temperature, humidity, air velocity, occupants clothing and activity [67]. Each of the studies in this survey simulates its own control strategy with different parameters, such as the physical description of a building (including walls, floors, roofs, windows and doors, each with associated construction properties such as R-Value of materials used, size of walls, location and type of windows), the descriptions of mechanical equipment (heating and cooling), the mechanical ventilation schedules, the occupancy schedule, the other household equipment, air temperature, radiant temperature, humidity, air velocity, occupants clothing and activity, and so on.

For the above, this survey does not intend to compare the energy saving potential between the studies. Nevertheless, the simulation results show that occupancy-based control can result in 10–40% in energy saving for HVAC system, see Fig. 4. In addition, other investigations also indicate that occupant satisfaction can be improved using dynamic HVAC adaptation concept, [68] and [69]. The latter, in turn, is attributed to productivity gains [6].

Regarding lighting systems, a previous survey [70] evidences that up to 40% of the lighting electricity could be saved by adopting a combination of modern control strategies, such as daylight harvesting, occupancy sensing, scheduling and load shedding. Simulations of the studies shown in Fig. 4 also confirm such that high energy saving potential from lighting control. [48] can potentially save
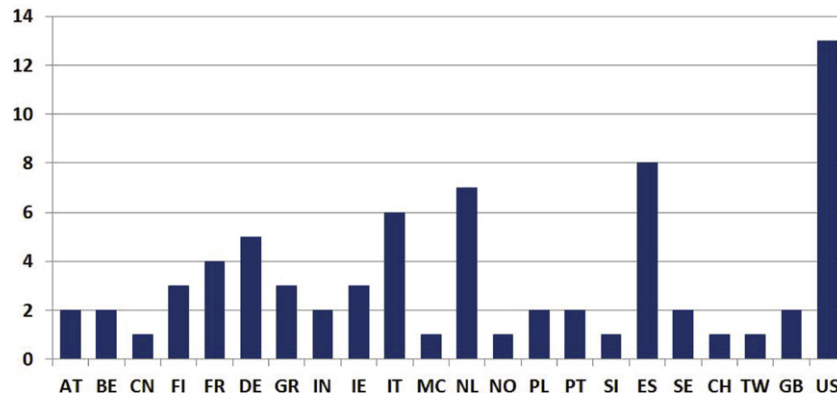
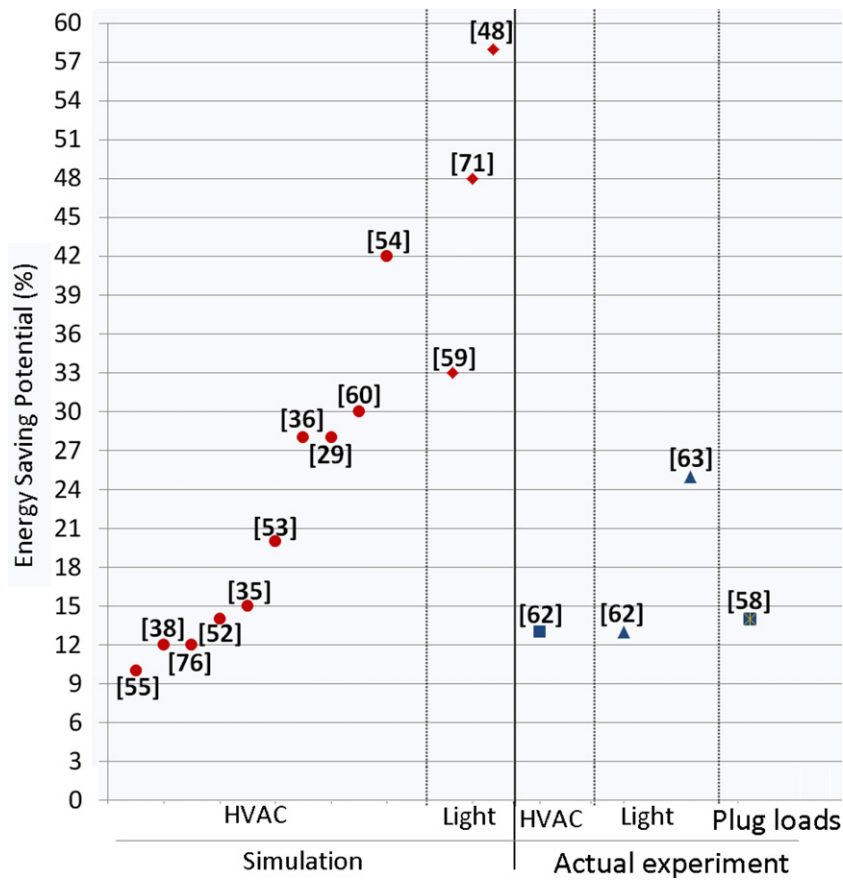**Fig. 3.** Number of reviewed studies per country.

Fig. 4. Energy saving potential.

58% of energy for lighting. At the second place comes [71] whose energy saving potential is 48% followed by [59] at 33% energy saving potential. Moreover, individual visual comfort has been gradually receiving more attention than energy conservation in the energy-efficient lighting technologies. Studies conducted in typical office environments have shown the positive correlation between lighting satisfaction and productivity of the occupants [72]. This trend is also reflected on the focus of the surveyed studies [59,48], and [71]. Nevertheless, among 16 works that evaluate their energy saving potential only three evaluate their solution in a real test-bed

Table 3
Activities taken into account.

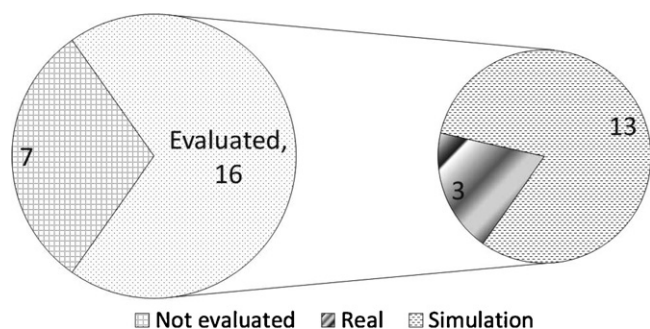| Application	Occupancy		Occupants' preferences	No. of more detailed activities	
	Real-time	Pattern prediction		Single-user	Multi-user
Lighting	[29,48,50,59,61–64,73,71]	[30,33]	[29,48,33,59,61,74,71]	[40]: 5 [74]: 3	
HVAC	[55,61,62,76]	[29,30,33,35,36,52–54,60,77]	[61,74,76]	[74]: 3	
Plug Loads	[58,50,75]	[30]	[56] [75]	[40]: 5 [49]: 3	[32]: 4

Fig. 5. Number of studies that evaluate their energy saving potential.

or actual experiments (see Fig. 5), while some others deal with energy consumption apportionment or prediction instead of controlling appliances. iSense [62] is able to save 13% of air conditioning and lighting electricity by alerting mechanism in place. The experiment was carried out in three conference rooms of different sizes and shapes as a test bed. In [58], a real test-bed that includes two LCD displays, a laser printer, two powered speakers, a desk lamp, a microwave, and a coffee pot is used to evaluate the energy saving potential of an occupancy-based control strategy for plug loads. While in calculating the savings, Garg et al. [63] have taken lighting load of four fluorescent lamps (240 W). Their smart occupancy sensor saved 25% of energy consumption while ordinary occupancy sensor saved 20% energy. Given this figure, 5% more energy can be saved by using their occupancy sensor as compared to non-adapting fixed time-delay sensors. On the other hand, seven of the works, as illustrated in Fig. 5, namely, [40,73,56,74,61,64], and [49] deal with activity or behaviour patterns recognition for energy savings. Though, they have not shown any evaluation of potential energy savings. In addition, [32,75], and [30] choose to deal with the apportionment and prediction of energy consumption.

Discussion

In summary, while conceptual benefits of occupant-related building control approaches have shown energy saving benefits, their feasibility must be confirmed in real-life installations. In parallel to optimizing energy consumption and performing automated adaptations, user comfort continues to be an essential success criteria for ICT-based solutions. In addition, energy saving potential expressed in terms of percentage of saved kWh is convenient for an easier comparison. In fact, 20% savings if one starts at 250 kWh/m^{2}a is much different from starting at 20 kWh/m^{2}a. Therefore, better evaluation metrics such as kWh/m^{2}a should be used in order to have a fair evaluation of energy saving potential for energy intelligent buildings.

5. Activities taken into account

Occupant presence and behaviour in buildings have been shown to have large impacts on space heating, cooling and ventilation demand, energy consumption of lighting and space appliances, and building controls [4]. Real-time occupancy information has long been used for control of various devices like artificial light, HVAC devices, etc. Past research has shown that use of real-time occupancy information for control of lighting can save significant electrical energy [7]. Recently, occupants' individual preferences have received growing interest in order to not only save energy but also to satisfy user comfort with respect to lighting system. More importantly, predicted occupancy (and sleep) patterns play a significant role in the performance of the smart thermostat since conditioning a room is not instantaneous and requires time for

adjustments. Thus, much research has been focused on predicting occupancy patterns for HVAC control. Furthermore, the total number of building occupants should be taken into account as it significantly affects the performance of HVAC system. Table 3 summarizes how reviewed studies take into account user activities and behaviours.

5.1. Real-time occupancy information

Several projects investigate and improve the way of using real-time occupant location data for lighting control. In Europe, the authors of [50] consider lighting devices as instantaneous resume energy sinks (i.e., to the human eye, these devices switch power state instantaneously). They use the room outlines as the relevant spatial zones, and take advantage of the faster update rates associated with fine-grained 3-D ultrasonic tracking to minimise the delay in turning on lights as a user enters.

In [76] and [38], a multi-agent system seeks to satisfy the preferences for an occupant's room only when the occupant is present in the building. The system attempts to conserve energy by automatically reducing the temperature for an occupant's room when the occupant is not in the building. In the U.S., the authors in [73] propose using a belief network to improve the accuracy for occupancy detection within buildings.

With iSense [62], the authors use the occupancy information, air conditioning system and lights' state to determine when the air conditioning system and lights are turned on when meetings do not actually take place. In other words, there is the wastage of electricity with the air conditioning and lighting systems being operational even when the rooms are unoccupied. Garg et al. [63] and Delaney et al. [48] improve the estimates of simple occupancy sensors by adapting to changing activity levels according to the time of day. Zhen et al. [64] propose a system that can localize the occupant to the correct region with an average accuracy of 93.0%.

5.2. Real-time together with occupant's preferences

Real-time location information alone is not enough for effective building energy and comfort management. This issue is especially true for lighting system as they affect user's visual comfort. The reason is that most of the commercially available occupancy sensors use a timeout for turning off the lights after the last motion is detected by the sensor. A 30 min timeout is common and sometimes it is adjustable in the range of 5–30 min. However, if the timeout is very small, the lights may turn off while users are still present, which can be annoying to users. By contrast, if the timeout is longer than necessary, the lights are still on when the room is not occupied, which may result in energy wastage. Thus occupants' individual lighting preferences should be taken into account. Both [59] and [71] keep track of occupants' location and try to optimize the trade-off between fulfilling different occupants' light preferences and minimizing energy consumption. In a similar approach, Chen et al. [61] propose a smart building control system that is able to keep track of workers' real-time location in an office and retrieve their personal preferences of lighting, cooling, and heating.

Instead of using occupant's preference, Newsham and Benjamin [56] use the total number of building occupants to forecast the power demand of the building in which a measure of building occupancy was a significant independent variable and increased the model accuracy. The total number of building occupants is also used in [75] to apportion the total energy consumption of a building or organisation to individual users.

5.3. Prediction of occupancy patterns

Temperature control has a long response time to power state changes and demands a predictive approach [50]. Therefore, much research focuses on predicting occupancy patterns for HVAC control: AIM [29], and [30] in Europe and the UK; IntelligentLighting [59], IBMIntelligentBuilding [61], ACHE [33], the self-programming thermostat [35], the smart thermostat [36], OBSERVE [54], and the research of Bing Dong and his colleagues [77] are conducted in the U.S.

The AIM system creates profiles of the behaviour of house inhabitants and through a prediction algorithm AIM is able to automatically control home appliances (mainly devices used for space heating/cooling, lighting) according to the users' habits. When users change their habits due to unpredictable events, the AIM system detects wrong predictions analysing in real time information from sensors and modifies system behaviour accordingly.

Hawarah et al. [30] deal with the problem of the prediction of user behavior in a home automation system. The goal of this project is to predict future users requests on energy needed in order to avoid some problems like peak consumption.

ACHE uses various *predictors*, attempting to determine the current state and forecast future states. Examples of predictions include expected occupancy patterns in the house over the next few hours, expected hot water usage, and likelihood that a zone will be entered in the next few seconds [33].

Gao et al. [35] seek to use coarse predicted occupancy data (leave home, return home) to drive a self-programming thermostat for the home environment.

In [36], the authors propose a model to estimate the probability of being home in one of three states: (1) unoccupied, (2) occupied with an occupant awake, and (3) occupied with all occupants asleep. The state information is then used for residential buildings and to examine reactive and predictive control strategies of the smart thermostat.

Erickson et al. construct several models in [52,54], and [53] for predicting user mobility patterns in buildings. Using these models, they can predict room usage, thereby enabling to control the HVAC systems in an adaptive manner.

Bing Dong and his colleagues introduce and illustrate a method for integrated building heating, cooling and ventilation control to reduce energy consumption and maintain indoor temperature set points, based on the prediction of occupant behaviour patterns and local weather conditions in [60], and [77].

5.4. Detailed activities

More detailed activities which are typical of building/home presence (e.g., working with or without PC, having a meeting, watching TV, using coffee maker) may affect comfort. In addition, energy efficiency can be achieved if one can control plug loads (e.g., LCD, TV, multimedia entertainment devices, a coffee maker).

iDorm [74] is able to recognize three activities of a person, namely, sleeping, working, and entertaining. The system is also able to learn users' preferences, to predict users' needs (e.g., light intensity, temperature), and to self-adjust system behaviour (including lighting, heating, and cooling) when users change their habits.

[40] and [49] try to automatically recognize typical activities of office presence and use the recognized activities as drivers to control the lighting system and plug loads to save energy. [40] recognizes five typical activities, namely, working with/without PC, having a meeting, presence, absence, while the typical activities recognized in [49] are working, sleeping, and entertaining. Likewise, for the sake of controlling plug loads, the activity monitoring subsystem of SPOTLIGHT in [32] identifies who and which activities happen in the area of interest in the home environment. The

identified activities are watching TV, using coffee maker, and using living lamp/bedroom lamp.

5.5. Discussion

In summary, present energy intelligent buildings mostly use occupancy information for control strategies. Real-time occupancy information is well suited to the lighting system. It is estimated that energy expended on lighting could be cut by around 50% [50]. Additionally, research pays significant attention to occupants' individual lighting preferences to maximize occupants' satisfaction. Along these lines, BECM systems should be designed to reduce energy consumption under the constraint of satisfying user comfort in order to improve user acceptance of the system. Temperature control has a long response time to state changes and demands a predictive approach. As a result, much research focuses on proposing smart thermostats based on occupancy prediction approaches.

6. Methodologies and technologies

Activity recognition has attracted increasing attention as a number of related research areas such as pervasive computing, intelligent environments and robotics converge on this critical issue. It is also driven by growing real-world application needs in such areas as ambient assisted living and security surveillance. For further information about existing approaches, current practices and future trends on activity recognition, the readers are suggested to read intensive surveys in the field, such as [78] or [12]. We review here in this survey the most common technologies and approaches for indoor activity recognition for energy saving in building.

6.1. Technologies

Wireless sensor networks are the common approach of the various projects to address user activity recognition. Furthermore, most of the projects stress the requirement of not resorting to any advanced sensors, such as cameras, which are expensive and generate privacy concerns or require changes in user behaviour, such as cameras, RFID tags, or wearable sensors. Instead, simple, wireless, binary sensors are favoured since they are cheap, easy to retrofit in existing buildings, require minimal maintenance and supervision, and do not have to be worn or carried.

Simple sensors are used in many energy intelligent buildings in the interest of activity recognition. For instance, PIR-based sensors are often used (especially with lighting system) for occupancy detection. The sensors are connected directly to local lighting fixtures. These PIR sensors are also simple movement sensors and often cannot actually determine if the room is occupied or not.

Padmanabh et al. [62] investigate the use of microphones and PIR sensors for the efficient scheduling of conference rooms. In [48], Delaney et al. use PIR-based wireless occupancy sensors to measure wasted energy in lighting even when there are no occupants. In the AIM Project, authors suggest to measure some physical parameters like temperature and light as well as user presence based on PIR sensors in each room of a house [29]. Gao et al. [35] seek to use coarse occupancy data (leave home, return home) to drive a self-programming home thermostat. With the goal of providing input to a control strategy for energy savings in office buildings, [40] performs indoor activity recognition by using simple sensors (infrared, pressure and acoustic). [36] uses occupancy sensors (PIR sensors and door sensors) to automatically turn off the HVAC system when the occupants are sleeping or away from home. Agarwal et al. chose to build their occupancy platform using a combination of sensors: a magnetic reed switch door sensor and a PIR sensor module [55].

In [56], to gather data related to total building occupancy, wireless sensors are installed in a three-storey building in eastern

Ontario, Canada comprising laboratories and 81 individual work spaces. Contact closure sensors are placed on various doors, PIR motion sensors are placed in the main corridor on each floor, and a carbon-dioxide sensor is positioned in a circulation area. In addition, the authors collect data on the number of people who log in to the network on each day. Marchiori et al. [58]. use a simple tailored occupancy solution to their office environment. Each room is outfitted with one PIR sensor and one door sensor (magnetic reed switch). In [74], pressure pads are used to measure whether the user is sitting or lying on the bed as well as sitting on the desk chair. At the same time, a custom code that publishes the activity on the IP network senses computer-related activities of the user. The activities are (1) running the computer's audio entertainment system, and (2) using video entertainment on the computer (either a TV program via WinTV or a DVD using the Winamp program).

In some other research of the field, more advanced systems that use active badge, cameras, and vision algorithms have been presented. Erickson et al. propose a wireless network of cameras to determine real-time occupancy across a larger area in a building, [54,52]. In [59,76,38,61], and [64], the occupants should be equipped with sensor badges, with which it is possible to achieve relatively accurate localization using, for example, RFID tags, however [59,76], and [61] consider user tracking as a blackbox problem. Similarly, in SPOTLIGHT [32], the authors present a prototype system that can monitor energy consumption by individuals using a proximity sensor, while the building used in [50] is featured with an ultrasonic location system that is a 3D location system based on a principle of trilateration and relies on multiple ultrasonic receivers embedded in the ceiling and measures time-of-flight to them. The location system provides three-dimensional tracking solution.

The authors in [30] use a database obtained from residential monitoring to decrease energy use and carbon emissions in Europe (REMODECE) which is a European database on residential consumption, including Central and Eastern European Countries, as well as Bulgaria and Romania. A method based on Bayesian Network is proposed to predict future users requests on energy needed.

[75] uses the entry-exit logs of the building security system. An algorithm is used maintain a stable estimate of the building population. In [71], the users' location is associated statically with their own workspace. The locations are used as input for optimizing energy savings and user satisfaction.

6.2. Methodologies

On the one hand, logical inference of sensor data approach is usually used to detect real-time occupancy. As summarized in Table 4, almost all of the projects ([29,40,48,35,36,55,56,58,62], and [74]) choose to use simple sensors and logical inference of sensor data approach. On the other hand, Bayesian inference techniques are usually used to predict the behaviour patterns of the user. In AIM system, Barbato et al. build user profiles by using a learning algorithm that extracts characteristics from the user habits in the form of probability distributions. Sensor network collects 24 h information about users presence/absence in each room of the house in a given monitoring period (i.e., week, month). At the end of the monitoring time the cross-correlation between each couple of 24 h data presence is computed for each room of the house in order to cluster similar daily profiles [29]. While Bayesian networks is used in [49] to support prediction of user behaviour patterns. The authors also propose the use of acoustic data as context for predicting finer-grained user behaviour.

Whereas, in OBSERVE [54,52], Erickson et al. construct a multivariate Gaussian model, a Markov Chain model, and an agent-based model for predicting user mobility patterns in buildings by using Gaussian and agent based models. The authors use a wireless camera sensor network for gathering traces of human mobility patterns in buildings. With this data and knowledge of the building floor plan, the authors create two prediction models for describing occupancy and movement behavior. The first model comprises of fitting a multivariate Gaussian distribution to the sensed data and using it to predict mobility patterns for the environment in which the data is collected. The second model is an agent based model (ABM) that can be used for simulating mobility patterns for developing HVAC control strategies for buildings that lack an occupancy sensing infrastructure. While the Markov Chain is used to model the temporal dynamics of the occupancy in a building.

In [30] the authors propose a general method to predict the possible inhabitant service requests for each hour in energy consumption of a 24 h anticipative time period. The idea is based on the use of the Bayesian network to predict the user's behavior. Exploiting algorithms based on fuzzy logic, in [74] a system able to learn users preferences, to predict users needs (e.g., light intensity, temperature), and to self-adjust system behavior when users change their habits is proposed. Neural networks are adopted also in [33] to create a system able to control temperature, light, ventilation and water heating.

Davidsson develops an MAS for decision making under uncertainty for intelligent buildings, though this approach requires complex agent [38]. The system allocates one agent per room and the agents make use of pronouncers (centralized decision support), where decision trees and influence diagrams are used for decision-making. Similarly, the iDorm [74] learns and predicts the user's needs ability based on learning and adaptation techniques for embedded agents. Each embedded agent is connected to sensors and effectors, comprising a ubiquitous-computing environment. The agent uses our fuzzy-logic-based incremental synchronous learning (ISL) system to learn and predict the user's needs, adjusting

Table 4
Technologies and Approaches used to recognize activities in energy intelligent buildings.

Approaches /Technologies	Wireless sensor networks				
	Active badge		Wireless network	Cameras	Other
	RFID	Ultrasonic	of simple sensors		
Logical inference from sensor data			[29,40,48,35,36,55,56,58,62,74]		
Neural network			[33]		
Fuzzy-logic-based			[74]		[74]
Bayesian: Markov chain				[54]	
Bayesian network					[30]
Bayesian: Belief network			[73]		
Multivariate Gaussian model				[52]	
SVM	[64]				
Cross-correlation			[29]		
Statistical data analysis					[75]
Other	[59] [61]	[50]			[71]

Table 5
Literature review summary.

Subsystem/Feature	HVAC	Lights	Plug loads
	Up to 40%.	Up to 40%.	Energy saving potential should be evaluated.
Energy saving potential	There is a vital need to evaluate the BECM framework in real-world situations. A good evaluation metric (such as kWh/m^{2}a or kWh/m^{3}a) should be used.		
Activities taken into account	Smart thermostat should be based on occupancy pattern prediction approaches.	Real-time occupancy information and occupants' individual lighting preferences should be used.	Real-time occupancy information should be used.
Methodologies and technologies	Wireless sensor networks are today considered the most promising and flexible technologies.		

the agent controller automatically, non-intrusively, and invisibly on the basis of a wide set of parameters (which is one requirement for ambient intelligence).

In [73], the authors propose a belief network for occupancy detection within buildings. The authors use multiple sensory input to probabilistically infer occupancy. By evaluating multiple sensory inputs, they determine the probability that a particular area is occupied. In each office, PIR and telephone on/off hook sensors are used to determine if rooms are in occupied states. The authors use Markov chains model the occupied state of individual rooms as a Markov Chain, where the transition matrix probabilities are calculated by examining the exponential distribution of the sojourn times of the observed states.

6.3. Discussion

In building energy and user comfort management area, wireless sensor networks can play an important role by continuously and seamlessly monitoring the building energy use, which lays the foundation of energy efficiency in buildings. The sensor network provides basic tools for gathering the information on user behaviour and its interaction with appliances from the home environment. The sensor network can also provide a mechanism for user identification (so that different profiles can be created for the different users living in the same apartment/house). The sensor network can be implemented using several available technologies. In addition, in contrast to other smart home applications, such as medical monitoring and security system, the domain of energy conservation can tolerate a small loss in accuracy in favour of cost and ease of use. Therefore, an energy intelligent building might not require cameras or wearable tags that may be considered intrusive to the user. Nevertheless, wireless sensor networks are today considered the most promising and flexible technologies for creating low-cost and easy-to-deploy sensor networks in scenarios like those considered by energy intelligent buildings.

7. Conclusions and future perspectives on user activity as part of energy intelligent buildings

Current situations show that building control is mainly done manually, from switching lights and appliances to control heating systems seasonally. Building automations are typically limited, such as lighting control with simple motion detection and a fix timeout or indoor climate control based on temperature and CO_2 level. However, user activities and behaviours have large impact on energy consumed in all sectors of buildings (i.e. residential, offices and retail sectors). Significant amount of energy spent for these buildings can be saved by regulating installations and appliance according to actual needs. In order to realize this approach, user activities and behaviours are required as the most important input for building automation systems.

The designers of energy intelligent buildings aim to realize a BECM solution that addresses the challenge of energy-aware adaptation from basic sensors and actuators up to embedded software for coordinating thousands of smart objects with the goals of energy saving and user support. In parallel to optimizing energy consumption and performing automated adaptations, we try to maximize user productivity, comfort and satisfaction. We claim that, in order to make buildings truly adaptable and maximize efficiency and comfort, they need to be more aware to the activities of the users and to the context of their environment.

This paper provides a novel survey of prominent international intelligent buildings papers and projects with the theme of energy saving and user activity recognition. The paper also determines the most valuable activities and behaviours and their impact on energy saving potential, discussing the most promising and appropriate activity recognition technologies and approaches for scenarios like those considered by energy intelligent buildings. Table 5 summarizes the lessons learned and conclusions from this survey that, in turn, suggest the realization of an effective BECM system, which we list next:

- For substantial savings in building energy consumption, no static assumptions should be made about a building's use. Dynamicity is an essential property to achieve energy efficiency in buildings.
- In parallel to optimizing energy consumption and performing automated adaptations, user comfort continues to be an essential success criterion for ICT-based solutions in order to improve user acceptance of the system.
- Concluding from the analysed studies, occupancy-based control can result in up to 40% in energy saving for HVAC system. Regarding lighting systems, also up to 40% of the lighting electricity could be saved by adopting a combination of modern control strategies, such as daylight harvesting, occupancy sensing, scheduling and load shedding. However, while conceptual benefits of occupant-related building control approaches have shown energy saving benefits, their feasibility must be confirmed in real-life installations. There is a vital need to evaluate the BECM framework in real-world situations. This will include a concrete evaluation as well as a good evaluation metric, such as kWh/m^{2}a or kWh/m^{3}a, of power consumed by the total system in order to evaluate the energy saving potential.
- Much research pays significant attention to occupants' individual lighting preferences for maximum occupants' comfort and satisfaction, while many studies have been focusing on proposing a smart thermostat based on occupancy prediction approaches.
- In contrast to other smart home applications, such as medical monitoring and security system, the domain of energy conservation can tolerate a small loss in accuracy in favour of cost and ease of use. Therefore, an energy intelligent building might not require cameras or wearable tags that may be considered intrusive to the user. Instead, wireless sensor networks are today considered the most promising and flexible technologies for creating

low-cost and easy-to-deploy sensor networks in scenarios like those considered by energy intelligent buildings.

- Activity-awareness is to be achieved through ubiquitous sensing and data processing. However, since this is a new way of thinking about buildings, validated insights and user requirements need to be developed.

In addition, our strong belief is that further building context information is needed for more effective BECM systems and that energy intelligent buildings should be ready to take advantage of Smart Grid.

User context enables highly-effective building energy and comfort management. However, this knowledge alone is not sufficient enough and further building context information is needed for more effective BECM systems. In this context, the Greenerbuildings project [39] specifically emphasises occupant activity and behaviour as a key element for adaptation as well as addresses other building context information.

The Smart Grid promises to not only provide for a more reliable distribution infrastructure, but also give the end-users better pricing and information. It is thus interesting for energy intelligent buildings to be ready to take advantage of features such as dynamic energy pricing and real-time choice of operators, together with user and building context information. Along this line, we propose a system that monitors and controls an office environment and couples it with the Smart Grid [79].

Energy-intelligent buildings can respond to their actual use and changes in their environment. Energy-intelligent buildings based on user activity should be able to recognize occupant activity and building context, and to adapt buildings for saving energy. This review shows that many projects are still in the prototype stage, but will soon make the transition from research to viable industrial products and broad applications.

Acknowledgements

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