Effect of occupant behaviour on the energy consumption. Smart Homes and occupants' interaction with building control. Survey of data acquisition technologies for a Smart Home.

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A B S T R A C T

In the European Union households generate one-fourth of total energy consumption. Building performance depends on many external and internal factors. Often, there is a great discrepancy between the designed and the real total energy use in buildings, what can be caused by occupant behaviour. Good knowledge of occupant behaviour allows an accurate prediction of building and effective operation of building systems. Occupants affect building energy use in both active and passive ways, which is the driver of energy consumption. There are many factors, which are influencing occupant behaviour. The paper analysed them on the heating adjustment and window opening behaviour examples in order to show the importance of a better description of occupant behaviour in energy prediction tools. Then, the definition of smart home and relation between building control and occupant is introduced.
Subsequently, in the second chapter, some recent behaviour-related data acquisition technologies opportune for domestic ambience are summarised. Data acquisition technologies are divided and discussed in four main groups: occupancy detection, occupant behaviour control, indoor and outdoor environment control and energy consumption and usage pattern.

Keywords: occupant behaviour, driving forces, data acquisition technologies, smart home, residential buildings, energy consumption

1. Introduction

Nowadays, the building sector consumes more than one-third of total primary energy in the world [1]. In the European Union only households generates about one-fourth of total energy consumption. To address the challenge of climate change and meet urgent energy reduction goals worldwide, it is essential to improve innovation in the construction and use of buildings. However, building performance does not depend only on its physical characteristics and external conditions but it is also regulated by many internal factors like operations and maintenance, occupant behaviour and indoor environmental conditions [2] (Fig. 1).

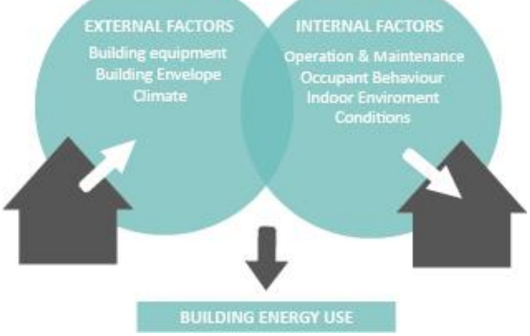

Fig.1: Influencing factors on total energy use in buildings (adapted from IEA-ECBCS Annex 53)

The design standards for energy efficiency in buildings have more and more strict requirements regarding energy efficiency performance of both buildings and appliances. During the last decade it is possible to notice important improvements in building design (like green roofs, intelligent facades etc.), building technologies (automatization of lighting and shading systems etc.) and building operational strategies (occupancy driven HVAC control, etc.) [3]. (Heydarian et al., 2016) However, comprehensive building energy use does not decrease but rather in many cases rise up. Often, there is a great discrepancy between the designed and the real total energy use in buildings. The reasons for this discrepancy are usually not well known, but often it is more due to the occupants' behaviour and life style than the building design. In fact, many researches have shown that the energy consumption can be very different even in the identical buildings. For example, Branco et al. (2004) [4] for their 3 years long study have found that real energy consumption was 50 % higher than the predicted. Much higher consumption was among others caused by highest heating temperature than predicted and not enough effective control of mechanical ventilation. This energy performance gap was also confirmed by other studies.

Herrando et al. (2016) [5] have analysed the discrepancy between estimated energy consumption simulated by a software and the real one for the Faculty Buildings of the University of Zaragoza. As in other studies, actual energy consumption of the majority of the buildings studied was higher than what it is estimated in the Certification software. The have found an average deviation of 30%. The main reasons which have caused discrepancies were that standard operating conditions are considered in the simulation tool instead of the real ones. Moreover, the energy performance gap increased significantly due to energy consumption of IT and laboratory equipment, as these equipment cannot be implemented in the software. And at the end, the occupant behaviour was found as an influencing factor as well, especially in correlation with use of IT equipment. It was observed that, in many cases, the office equipment (computers, printers, etc.) were not turned off when not in used and the users confirmed that they do not usually disconnect computers at night.

The similar correlation was found by Masoso et al. (2010) [6], who have verified the "dark side" of the influence of occupant' behaviour. They have performed energy audits for the office buildings. They have found that more than 50% of energy was used during non-working hours than during official working hours due to occupant behaviour. The reasons were, among others, leaving light and equipment (computers) on at the end of the day and not enough good building zoning and controls.

However, not many studies have investigated the interactions of the occupant in real indoor environment in detail. In most buildings, occupant can behave with windows, heating or artificial light to obtain comfortable indoor environmental conditions. Good knowledge of occupant behaviour is crucial for an accurate prediction of building and effective operation of building systems.

1.1. Occupant behaviour: from drivers to energy use

Energy consumption in residential buildings is influenced by the behaviour of occupants in many ways. Occupant behaviour is complex and can be defined as *observable actions or reactions of a person in response to external or internal stimuli, or respectively actions or reactions of a person to adapt to ambient environmental conditions (such as temperature, indoor air quality and sunlight), household and other activities.* [2]

Factors, which are influencing the occupant behaviour, both external and internal, could be named as the general term "*Drivers*". They are leading to a reaction in the building and suggesting him to operate an action. These drivers include physical environmental conditions, psychological factors, physiological factor, social factors and contextual factors [7].

Second operator, which can influence the energy consumption is the occupant itself (*"occupant stimoulus")*. The occupant can react to those drivers in certain way (consciously or unconsciously) in order to improve restore the comfort conditions (i.e. thermal, indoor air quality or lighting).

Generally the behaviour of the occupants in the building can be separated in two main categories: the first one is how they occupy the building (when the building is occupied and how many people for every zone), which can be call *occupancy*. The second category is the occupants interaction with indoor climate; how the occupants interact with the building devices like windows, doors, blinds, air conditioning terminals, lights, thermostats and equipment like TVs, computers and so on. Usually the occupants have the possibility to adjust and control those devices, thus, those interactions are closely related to occupancy. For example, some devices like lights or ventilation can be turned on by the occupants when they are in the zone and switched off when they are out. Those actions can be defined as *"action scenarios"*. More precisely, the occupant influence on the indoor environment can be grouped in three following groups [7]:

- Occupant can modify the indoor environment in direct way by adjustment of heating and the ventilation systems, opening and closing windows and shading windows.
- In other hand, occupant can have an effect on indoor environment indirectly. His actions can be related to the change of internal heat gains/ energy use.
- Third type of influence affects indirectly indoor environment. Occupant can act in order to restore comfort by the adjustment of the occupant himself to the existing environmental conditions. The actions include the change of position (for example leaving the room), active body adaptation (i.e. the amount of clothes worn), and the thermo-regulation or passive body adaptation (i.e. drinking cold or hot liquids)

Action scenarios have direct impact on indoor environmental quality and energy consumption. Both outputs have an effect on the drivers.

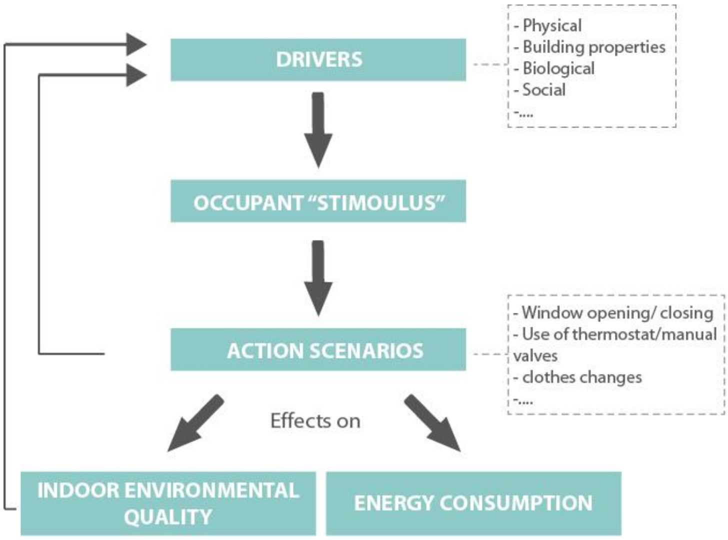

Fig.2, Flux diagram- from drivers to energy consumption and indoor environment, adapted from Fabi et al. (2010)

1.2. Identification of driving forces

As mentioned before, the comfort is a state of mind that can vary from occupant to occupant because of personal (physiological, psychological) and social drivers, which are influencing the energy use in direct way. Moreover, climatic parameters, economical parameters, regulations and policies, architecture and interior design of the space and building types can also directly influence energy behaviour of occupants. (fig. 3)

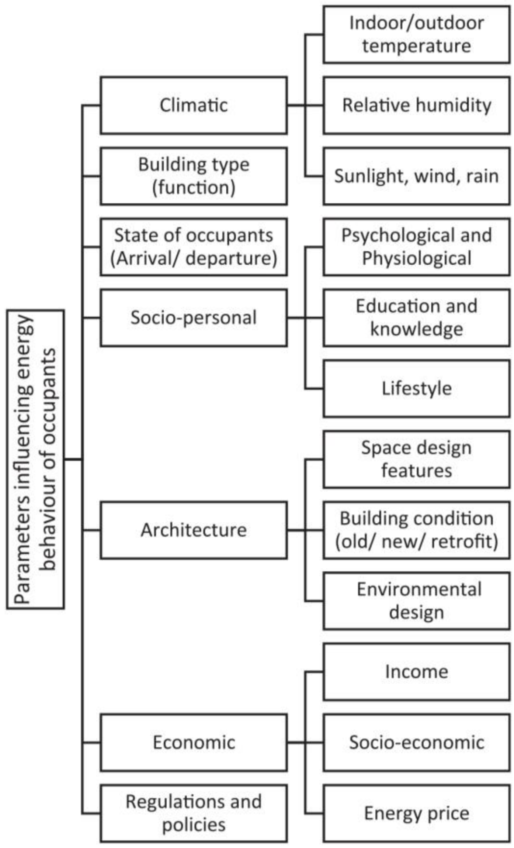

Fig. 3, Drivers influencing energy behaviour of occupants, source: Delzendeh et al., 2017

In the following sections are analysed the main drivers which are stimulating occupants to behave with window opening and closing and heating/cooling in residential buildings.

1.2.1. Identification of driving forces: Window opening and closing

Window opening behaviour has an immediate impact on indoor air quality, indoor humidity and energy performance of building.

In the domestic environment, window opening behaviour is the easiest way to for occupants to control indoor thermal environment and to restore their comfort. Occupants usually open the window to cool the indoor environment when they feel hot indoors, but they will close the window if the indoor thermal environment are to cool and the window is still open. This would mean that occupants are not satisfied with the indoor conditions and at the same time they decide to take some actions (opening or closing window). When they feel comfortable with the indoor thermal conditions, they don't interact with the windows [8].

As mentioned before, there are many factors which are influencing occupant behaviour (drivers). For window opening behaviour, one of the most important driver is the *climatic condition*.

Among all physical environmental drivers, one of the most influencing is the temperature (outdoor and outdoor). When the outdoor temperature is high, occupant is used to open window more often [9]. However, some researchers have observed that this tendency is changing when the outdoor temperature is perceived as too high. It may be due to the tendency to utilize split air-conditioners when outdoor air temperature is high [10].

Another physical environmental parameter which has influence on occupant window opening behaviour is the presence of wind and rain. Windows are usually opened either to let fresh air into the room and thus improve the room air quality, or they are opened for cooling. Both reasons are dominated by internal parameters of the room, however more or less influenced by the difference between room and outside air temperature. But there are some occasions, when influences from the outside of the building become predominant concerning ventilation control by occupants. These are the occurrence of wind and rain. Concerning wind, occupants are used to close the windows when the wish for fresh air or cooling, if the sensation of draft in the apartment is producing a predominant discomfort. This likelihood is strongly depending on wind direction, and generally increased at higher wind speeds [11].

Second influencing driver *is architecture of the building*. The orientation, type of the room and thermal mass play also an important role. Some studies have shown that windows in kitchen and living rooms are open for shorten periods than windows in bedrooms [12]. The effectiveness of natural ventilation strongly depends on properties of ventilation openings and their controllability, what is to facade design. The behaviour of occupants can be considered as a reaction to the controls provided by the specific design. For the facade design it is possible to distinguish two main factors influencing ventilation- the choice of the window opening type and the second is the size and placement of the openings on the facade. Type of the room influences how long the windows are opened. Several studies have demonstrated [13] that the most ventilated rooms are bedrooms, while the windows in the living rooms and kitchens are open usually for shorter periods.

Window opening behaviour can be also influenced by ventilation type. Nicol et al. (2004) [14] have found that the windows in the households without mechanical ventilation are kept open even four times longer than in flats with mechanical ventilation.

It is worth to highlight also the *biological drivers*. As found by some researchers, age of the occupants plays important role. Elderly people behave in different way than younger people- they tend to ventilate less than the young [15].

Several researches have investigated also the *social aspects*, as the drivers which are stimulating the windows opening behaviour. Among them, the most important is the lifestyle (like a presence in home or smoking behaviour). The longer the dwelling is occupied the more windows are kept opened. The smokers usually ventilate their houses more than two times longer than occupants without smoking habit. It is important also to consider household activities (i.e. cooking), when occupants are used to ventilate the apartment [15].

Indoor temperature is related with outdoor temperature, but also to the thermal comfort. Many studies have demonstrated that indoor climate preference (temperature) is important driving force for the behaviour of the occupants. This driver is strongly correlated to the occupants' perception of comfort [15].

Indraganti et al. (2014) [16] have found that also *sociocultural aspect* can influence the operation of window openings. They noticed that some occupants preferred to keep the windows shut to avoid vandalism (stone-pelting). Others preferred to keep windows closed for privacy reasons.

Table 1. Driving forces for occupant behaviour regarding windows opening

Climatic	**Architecture (building properties)**
Outdoor temperature Indoor temperature Wind speed Presence of rain	Orientation Type of the room Thermal mass Façade design- openings type/size Ventilation type

Biological	**Socio-personal**
Age of the occupants	Indoor climate preferences (temperature) Occupant presence Smoking behaviour Household activities

Sociocultural
Privacy Vandalism

1.2.2. Identification of driving forces: Heating adjustment

Occupants typically heat their apartment to keep warm in winter. Their preferred indoor temperature, however, can vary substantially from person to person. As demonstrated by [17] different user behaviour in identical houses may result even in a three times higher energy consumption for heating. In fact, Chen et al. (2015) [18] have found that only less than 40 % attempt to the reduce frequency of use in order to save energy.

One of the factors determining the energy consumption for heating or cooling are *climatic drivers*. One of them is outdoor temperature. Already Vine (1987) [19] have found that homes in warmer climates turned the heater off and maintained lower winter settings than homes located in other climates. Besides outdoor temperature, outdoor humidity and the wind speed are also influencing the heating set point in dwellings. In fact, Fabi et al. (2013) [20] noticed that for occupants who frequently adjusted thermostat settings, indoor relative humidity drove them to turn up thermostatic radiator valve settings significantly.

The building properties have also the important impact on the occupant behaviour. Free-standing houses consume more energy than other types of dwellings. Guerra Santin et al. (2009) [15] have demonstrated that the detached houses consumes more than double energy than flats. Tachibana (2010) [21] also found that residents of apartments and condominiums are used more to turn off their heating systems, compared to those living in houses.

Some studies have also found that the room type has great influence on heating behaviour. Usually occupants prefer to set up higher temperatures in living rooms than kitchen or bedrooms [22, 23].

The type of heating system has been investigated as a driver as well. Centrally heated houses usually have higher temperatures than non-centrally heated) [22].

Also the type of temperature control can have indirect influence on choices and the behaviour patterns. Guerra Santin et al. (2009) [15] have found that households with programmable thermostat were associated with higher indoor temperatures settings during the night and with more hours with radiators on. Also according to Lutzenhiser (2009) [24], manual control involves the deliberate cooling of people or the deliberate preparation of a cool space for people, while automatic cooling occurs regardless of occupancy or activity.

The biological aspects has been classified as a driver as well. The required indoor temperature often correlates with age of the occupant. Elderly people prefers higher indoor temperature settings that the young [25, 26]. Also the presence of children stimulate to set up higher indoor temperature [27]. Some researchers have reported that also the occupant gender can have influence on heating usage in residential buildings. Females prefer a higher set point, meanwhile males adjust the thermostat set point more often than females [28].

Several researchers have investigated also *socio-personal* drivers as decisive for heating adjustment. Indoor climate preferences is the main psychological driver related to the heating set-point adjustments. Moreover, some researchers have demonstrated thermal background has influence on heating adjustment. Schweiker et al. (2009) [29] conducted a survey in students' house in Japan and they have found that students originating from hot and dry as well as from moderate climates are normally used to a wider range of temperature and humidity and they are able to adapt easier than those from hot and humid climate. The number of occupants is also an important factor for energy use. There is linear correlation between household size and energy use [15]. Also the presence of occupants at home is crucial for energy use for heating. The continuous presence is correlated with an increase of energy use compared with a variable presence [17].
The influence of house ownership also has been evaluated in some studies. It was found that occupants who rent accommodation tend to spend more on heating [28].

Economic situation can also drive occupants to set up the heating. More heating leads to higher heating cost. Households with lower income tend to use less energy for keeping warm in the winter [22]. In the other study, it was found that a 1% increase in income results in 0.63% increase in energy use [30]. Wilhite et al. (1996) [31] have compared the heating behaviour in Norwegian and Japanese dwellings and they have found that Japanese families were much more disciplined to in their heating setback habits. They had the habit of turning the heat down (or off) when they went to bed and off when they leave the house. This behaviour was, among others, probably related to the higher cost of energy (heating price).

Table 2. Driving forces for occupant behaviour regarding heating and cooling adjustment

Climatic	**Architecture (building properties)**
Outdoor temperature Indoor temperature Indoor relative humidity Climate Wind speed	Dwelling type Room type Type of heating system Type of temperature control

Biological	**Socio-personal**
Age of the occupants Gender of the occupants Health conditions	Indoor climate preferences (temperature) Number of occupants Occupant presence Ownership

Economic
Household income Heating price

1.3. Smart home definition

Smart homes and other smart technology, like smart grids and smart meters, are existing as concepts since many years, but are gaining increasing attention only in the last decade. Nowadays, smart homes are one of priorities for the European Union, included in Strategic Energy Technology Plan: "*Create technologies and services for smart homes that provide smart solutions to energy consumers*" [32]. (EC, 2015).

Smart home can be defined as a residence supplied with a communications network, linking sensors, domestic appliances, and devices, that can be remotely monitored, accessed or controlled and which provide services that respond to the needs of its occupants. The definition "smart home" may refer to any form of residence, for example, a detached house, an apartment, or a unit in a social housing development. Sensors can be used to detect the location of occupants, or to collect data about states (e.g. temperature, energy usage, open windows). Domestic appliances refer to the equipment like refrigerators or washing machines [33].

Smart Home can be managed by many various devices, from big ones like furniture to small ones like temperature sensors. It is possible to distinguish a lot of different kinds of devices with different properties. They can vary in technical parameters, used software, feature, size and a lot more. Some of them have low computing power and memory capacity and run with battery like a sensor network node. Others have high energy consumption or need water to work, for example a washer. It's possible to group the main services into following categories [33, 34] (fig. 4):

- Energy efficiency control
- Security control surveillance
- Entertainment and communications
- Convenience and Comfort control
- Assisted living and e-health control:
  - eldercare;
  - healthcare;
  - childcare;

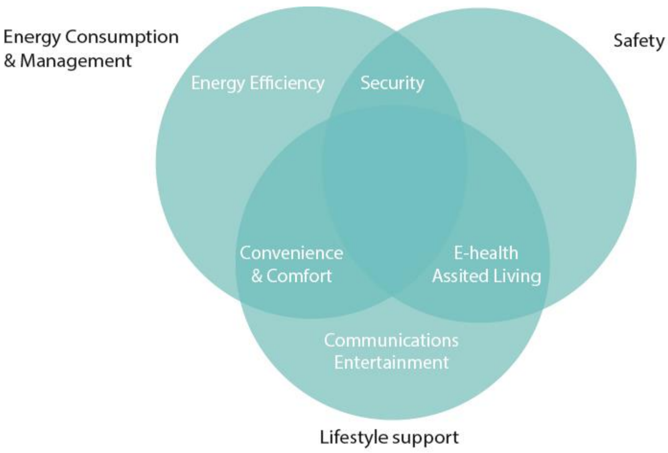

Fig. 4: Types of smart home services

1.4. Smart homes and occupants' interaction with building control

Occupant behaviour has important impact on the energy consumption. Occupants' satisfaction in terms of indoor comfort allows to save energy. Energy saving could be achieved by automatically switching on or off lights when people are not present in the room/building, or by minimalizing the quantity of the artificial lights in case there is enough quantity of daylight to perform the required visual task. However, energy saving actions should match with the occupants' satisfaction and his control feeling of their living environments. In fact, if the actions of the building automation system is based only on energy-saving requirements, the resulting indoor environmental conditions could not be perceived as "comfortable" by the occupants. That's why a balance between energy efficiency and occupants' needs and perception of comfort is required. Moreover, human behaviour at home is highly unstructured. Multiple sensory modalities are required to sense such behaviour. Advance pattern recognition techniques are required to recognize the behaviour of multiple residents. Nowadays, one of the main aims of a building automation system for energy and comfort is to match comfort requirements by reaching high comfort indexes, i.e. visual, air quality or hygro-thermal [33].

2. Data acquisition technologies

Use of data acquisition technologies is the first step to create a predictive ambient intelligence environment. Using data acquisition technologies it is possible to obtain data occupancy for different areas, environmental conditions data, the state of the intelligent devices, and interactions between occupants and devices. Collected data can be used by intelligent approaches for training and adaptation in a predictive ambient intelligence environment. A data acquisition system should perform two major tasks - sensation and transmission [35].

Unfortunately, there are not many localisation systems that are opportune for a domestic ambience. For example, for occupant comfort, video surveillance should be excluded for privacy reasons; the Global Positioning System (GPS) is not able to penetrate external walls and even other tag-based systems, such as Radio Frequency Identification (RFID), would restrict the inhabitants to wear a device. In a domestic environment should be used a methodology, which is not obtrusive, which needs low maintenance, which is visually pleasing and which is energy efficient itself [36].

For purpose of this paper, data acquisition technologies are divided and discussed as follow categories (fig. 5):

- Occupancy control

- Occupant behaviour control
- Indoor and Outdoor environment control
- Energy Consumption and usage pattern control

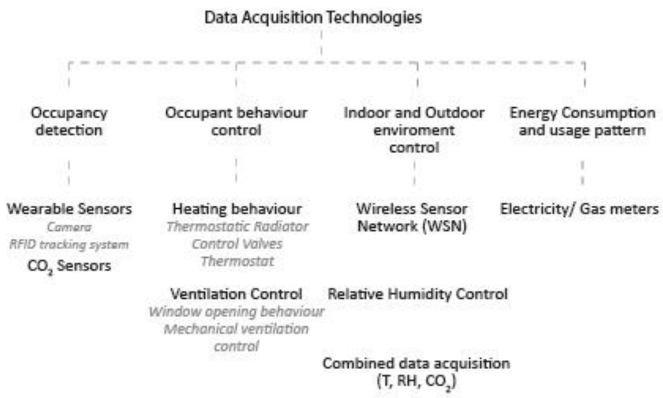

Fig. 5: State-of-art data acquisition technologies for occupant behaviour modelling

2.1. Occupancy detection

To understand the occupant behaviour and improve energy management system it may be opportune to use some kind of sensor, which allows to detect occupant in the building. Knowledge about occupant position can significantly reduce the energy consumption. Motion detection sensors may be especially opportune for lighting and heating control. For example, the light can be switched off, when the sensors don't detect the presence of person. Similarly for heating/ ventilation systems. In this section they are analysed some examples of motion detection sensors, which are opportune for domestic environment.

2.1.1. Passive Infrared Sensors (PIR)

This kind of sensors is mostly popular for the security and energy management systems. However, PIR sensors can be used also to detect the presence of someone in the building. PIR sensors exploit the fact that heated objects emit infrared light. They detect moving objects of one temperature on a background of another temperature. In the buildings the PIR sensors should be adjusted close to the average temperature of human body to identify occupancy more effectively [36].

PIR sensors usually use tree type of sensing elements: thermistors, thermopiles, and pyroelectrics. However, for the motion detection, the pyroelectric elements are used almost exclusively because they are simple, low cost, high responsivity, and a broad dynamic range [37]. (Handbook of Modern Sensors)

Fig. 6: Example of PIR sensor, source: http://www.dsc.com/index.php?n=products&o=view&id=65

Use of PIR sensor to detect presence of occupant has been investigated in many studies. For example, Gopinathan et al. (2003) [38] have developed motion tracking system which is capable of detecting human motion in one of the 15 cells in an area covering 1.6m × 1.6m using 4 pyroelectric detectors. An optical element, reference structure, was used to implement a mapping from source state to measurement space. Hao et al. (2010) [39] have presented wireless distributed pyroelectric sensor system for human motion tracking based on TI's microcontroller MSP430149 and RF transceiver TRF6901. They demonstrated that it is possible to use the system to track a single human target by detecting its angular displacement while moving.

However, many researchers have shown that this method causes some issues. For example, Spataru & Gauthier (2013) [40] demonstrated that even when room was occupied sometimes PIR doesn't show any measurements, what was caused by reduced movements of the occupant. Moreover, with the presence of more than one person in the room, PIR did not show greater peaks. This means that PIR can provide informations on the amount of the movement, but not the effective number of people. Naghiyev et al. (2014) [36] published an experiment with very similar conclusions. Moreover, they demonstrated that smaller rooms what could therefore trigger greater outputs.

To reduce the error of PIR-based localization caused by the PIR sensing area and deployment some researchers propose a new indoor human localization system. For example, Yang et al. (2015) [41] together with PIR sensor, improved accessibility map, which reflects occupant visiting preferences in the degree of accessibility in indoor environment. This makes it possible to improve the location accuracy through particle filtering. Particle filters fuse the raw position estimate and the accessibility map information to obtain more accurate position estimate. The proposed solutions require fine maps based on long-term observation and behaviour habits. Simulations have shown that accuracy error of this combined method decreased to 0,1m, when the PIR only method had an error of 0,2m. The better accuracy could be achieved if the accessibility map is more refined.

2.1.2. CO_2 Sensors

Carbon dioxide concentration is usually monitored in buildings in order to assess the indoor air quality and it may be also used to properly operate building services. However, it can be successfully used for occupancy detection, as the greatest source of Co_2 in home environment are people. They naturally excrete CO_2 on a constant basis. Therefore, the CO_2 concentration in a building can be used as an indicator of occupant presence. Human's CO_2 generation depends on the type of activity they are doing (fig. 8) [42].

	Type of activity	*G* (L/min per person)
Very light work:		
	Seated, writing	0.27
	Seated, typing	0.29
	Seated, talking	0.29
	Seated, filing	0.31
	Standing, talking	0.31
	Standing, filing	0.35
Light work:		
	Walking	0.44
	Lifting, packing	0.53

Fig. 7: Types of human activity associated with different CO_2 generation rates, source: Leephakpreeda et al.

Carbon Dioxide Gas sensors measure the carbon dioxide content of a gas. It is possible to distinguish few types of CO_2 sensors: mass airflow sensors, solid state electrochemical sensors, mixed oxide sensors, ion selective membrane sensors and optical sensors. The sensor uses a beam of infrared light, which is reflected around a highly polished cavity. Carbon dioxide is a strong absorber of infrared, the more the light is absorbed the greater the concentration of carbon dioxide present [43].

Fig. 8: Example of CO2 sensor, source: https://www.bapihvac.com/product/co2-room-co2-transmitter-in-bapi-stat-3-enclosure-periodic-occupancy/#documents

Naghiyev et al. (2014) [36] have shown that CO_2 measurements highly depend on the air circulation in the building. During the experiment, the doors and windows once were closed and opened to establish the relationship between CO_2 level generated by people and air flow. Once the doors were closed, the content in the occupied room accumulated faster whilst it slightly decreased in the unoccupied rooms. When the doors were opened again, the air with higher CO_2 content mixed with the air of the unoccupied spaces. This leaded to misinterpretation of occupation and mask the actual change of location of an occupant [36]. Similar conclusions were demonstrated in the experiment of researchers Spataru&Gauthier (2013) [40]. Moreover they observed the sharp rise which was related to an increased in metabolic rate due to physical exercise, when the occupants own a static exercise bike. In this case CO_2 concentration monitoring also provided wrong informations on the number of occupants.

Cali et al. (2015) [44] have analysed the efficiency of CO_2 concentration monitoring in the indoor air based on the algorithm. The algorithm depends on mass balance equation of the carbon dioxide in rooms and delivers occupants presence profiles. The results have shown that the simulation algorithm can lead to high levels of PM indices (from 76 % to 96 %) when information about window positions in provided. Also knowledge about the door position helped in some cases for better PM indices.

2.1.3. Wearable Sensors

Wearable devices can include sensors, which can monitor movement, position and also physiological and environmental parameters. This type of sensors provides data, which can be used to monitor changes in activity or location. It is possible to use many types of devices, like cameras, fitness trackers or even smartphones. Nowadays, the most spread wearable devices are RFID tracking systems, and it is analysed below.

Active Radio Frequency Identification (RFID) tracking system

A typical RFID system includes two components- a reader and a tag. Operates at a certain frequency, as shown in fig. 9. A tag has a microchip and an internal antenna. Attached to an object, a tag stores a specific ID and other object-related data, and sends the data to a reader upon its request. Tags can be distinguished as passive or active, depending of their power source. Passive tags need to be activated by the electromagnetic energy the reader emits and depend on that for power to operate. Therefore, they have shorter read ranges and smaller data storage capacities. Active tags rely on internal batteries for power supply, which enhances the read ranges significantly and enables additional on board memory and local sensing and processing capacities. [45]

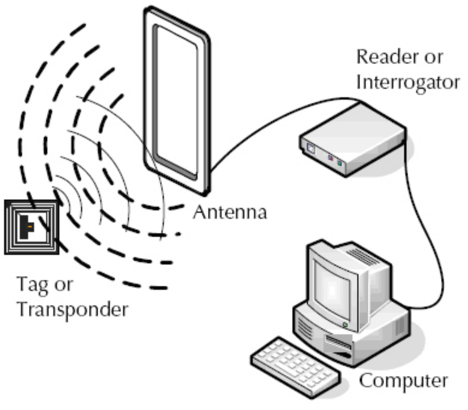

Fig. 9: The RFID system, source: http://www.epc-rfid.info/rfid

RFID is an effective technology for indoor localization and it has wide range of advantages: it can provide adequate accuracy, it is cost efficient, it does not require line of sight conditions; it has on-board data storage capacity that can be used for another purpose such as building asset management; and it is widely used by the construction industry so that hardware can be shared by multiple tasks.

Use of RFID tracking system is also investigated by many researchers. Li et al. (2012) [46] measured and monitored occupancy with an RFID based system for demand-driven HVAC operations. The proposed individualized occupancy detection system was composed by: readers, antennae, tracking and reference tags, and server. Test were done at a floor of an educational building at the University of Southern California and were conducted using off-the-shelf ultra-high frequency (UHF) active RFID equipment that runs at a frequency of 915 MHz and provides a read range of up to 100 m. The results showed that the examined system had the high ability of detecting and reporting the number of multiple users- both stationary and mobile- at the thermal zone. The rate of detection of occupancy was 100 % in both cases in all tests. The average zone level detection accuracy was 88 % for stationary occupants and 62 % for mobile occupants. However, the researchers pointed out that the reduction of energy consumption using these strategies could lead to compromises of users comfort at the same time. It is connect to insufficient ventilation, high CO_2 concentration and limited flow of conditioned air. Moreover, they noticed two factors which have effects on the occupancy detection rate. The first one is the density of the reference tags, what could potentially give low detection rate in the test. However, increasing the tag density increases the possibility of radio signal collision, what cause that the accuracy of location computation goes down. Second factor which cause the problem is the targets localisation. This issue has caused the lower detection rate for mobile occupants than stationary occupants, as mobile targets weren't enough covered when they moved to the boundaries of the sensing area.

Manzoor at al. (2012) [47] presented an approach to combine the already implemented PIR lighting control with occupancy information collected through passive RFID technology. Occupancy detection infrastructure was implemented in an open plan office of a University campus building. In order to determine the accuracy of the RFID-based occupancy monitoring demonstrator, all user were asked to fill in "timesheets" every time they enter or exit the office area. The proposed method was used to control a building's indoor artificial lighting. System validation results show that an accuracy of 91.43% was achieved from the rest being miss-reads. The researchers analysed that it is possible to save up to 13 % of electrical energy in one day. This translates to a total of 655.36 kWh of annual energy and €75 cost savings for only one office area. The *PIR+RFID* method shows improvement of building lighting control in comparison to the *PIR-Only* method which relies only on PIR sensors. However, a fully practical implementation of the proposed approach in the respective building requires changes in building physics and operation which requires prior approval and consent of various stakeholders including facilities and services managers, building owners, and the space users.

2.2. Occupant behaviour control

Another group of sensors are sensors which allow to understand the way occupants behave with building equipment. In this section there are analysed the control system for heating adjustment and window opening behaviour.

2.2.1. Heating behaviour

There are four main possible interaction points with a basic gas central heating system: thermostat, programmer (which can be operated manually or through a timer), radiator valves (either manual radiator valves or thermostatic radiator valves (T.R.V.s)) on individual radiators and temperature controls on the boiler.

Thermostatic Radiator Control Valves (TRVs)

The TRVs are the most common sensors for the central heating systems. The first TRVs were used in early 40'. (fig.10)

Fig. 10, Example of traditional and wireless TRV, sources: http://www.plumbworld.co.uk/honeywell-valencia-traditional-1358-32558 ; http://www.johnguest.com/speedfit/product/jg-aura-wireless-range/wireless-trv/

TRVs do not use electric power. They consist of a valve and an operator (fig.11). A fluid-filled capsule inside the TRV operator expands as room temperature increases. When it expands, it closes the valve. In the case of one-pipe steam, the TRV is connected to the air vent and blocks the release of air when it is in the closed position, preventing steam from entering the radiator. When the room temperature decreases, the capsule contracts; this allows air to escape the radiator and steam to take its place. In the case of two-pipe steam, the TRV is connected to the radiator inlet and, when in the closed position, prevents steam from entering the radiator body entirely [47] (Dentz & Ansanelli, 2015)

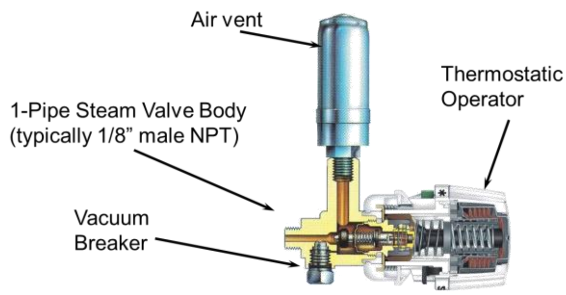

Fig. 11: TRV schematic, source: https://basc.pnnl.gov/resource-guides/thermostatic-radiator-valves-steam-heating-systems#quicktabs-guides=0

Monetti et al. (2015) [47] tried to investigate the control effectiveness of TRVs applied on an existing multifamily building located in Turin, built at the beginning of XIX century. Due to its construction age and to its belonging to the cultural heritage patrimony, TRVs resulted as the most eligible EEMs for reducing the energy consumptions. The energy assessment was carried out by means of dynamic energy simulation with the EnergyPlus code. The case study was simulated with and without TRVs. In every apartment, each room with a radiator was defined as a thermal zone in order to evaluate the effect of each single TRV. The results showed that the use of TRVs can bring up to 10 % of reduction on the total heating energy consumption during a complete heating season. Moreover the economic analysis using the Cost Optimal approach demonstrated that in less than 7 years the overall investment cost of TRVs application can be overcome. In the view of retrofitting the existing building stock, among a range of EEMs, TRV can be considered one of the lowest investment cost measures that can be applied without problems also for the historical buildings.

Dentz & Ansanelli (2015) [48] have done a deep analysis of the effectiveness of TRVs for a multifamily building in New York, U.S. At the beginning they examined the evaluation of the market perception of TRVs though discussions with leading heating system engineers and contractors. They found that understanding and opinions about the effectiveness of TRVs are very various. The dominant opinion was that, because of their relatively high installation cost, TRVs are good solution for the spaces, which are reported to be overheated. Most experts also recognized that while TRVs are generally simple to install, but there is possibility to do it incorrectly that can lead to subpar performance. Mistakes include poorly positioned valves and sensors and a failure to ensure that the overall system is working with the TRVs. Most of interviewed people considered TRVs as very reliable and durable. After interview, the researchers have monitored indoor air and radiator temperatures in two apartments before and after the TRVs were installed. They collected measurements about surface temperature of each radiator, and indoor space temperatures. Moreover they used one T-type thermocouple near the window above each radiator to determine if the window is opened. The results of the BEopt-modeled TRV savings indicated that average space temperature reduction needs to be in area of 6 $^{\circ}$F (3.3 $^{\circ}$C) in order for TRV savings to be cost effective. However, the results of examined apartments showed that the post- TRV installation space temperature averages not always were reduced (in one of the apartments the temperature increased 1 $^{\circ}$F (0.56 $^{\circ}$C)). They understood that TRVs may be more effective for overheated apartments and with south exposition (high solar loads). They also noticed that window behaviour (opened window when heating is on) may also contribute to improper TRV function. In fact, in the initial winter heating season residents continued to open window regularly. Infiltration by unconditioned air (drafts) through small gaps in window frames and radiator cabinet framing could also cause a nearby TRV sensor to read low temperatures that do not reflect the average ambient temperature. Finally, they collected all the most important factors which should be considered in the deployment of TRVs (fig. 12)

System	Impact and Tradeoff, If Any
Occupant Comfort	TRVs are intended to reduce overheating, which improves occupant comfort. They also provide an improved level of occupant control over heating. However, slow response times and a lack of understanding of how they operate have been reported to lead to tenant dissatisfaction (Colgrove, 2012).
Occupant Health and Safety	Overheating in winter can result in excessively low humidity levels, which can have negative health consequences.
Building and Equipment Durability	Reducing overheating should decrease energy use, and thus the load on the heating system, possibly increasing the equipment's lifetime.
Building Code Compliance Issues	TRVs should maintain building owners' ability to comply with local minimum heat ordinances.
Building and Equipment Maintainability	TRVs are another component and as such must be maintained; however, most interview respondents indicated that they require little or no maintenance.

Fig. 12, TRV Impacts and Tradeoffs, Dentz & Ansanelli (2015)

Thermostatic Radiator Valves (TRV) have an important role in energy savings in last years. However, in central heating systems with thermostatic valve temperature control it is a well-known fact that room temperature oscillations may occur when the heat demand becomes low due to the non-linear behaviour of the control loop. This creates not only discomfort, but it also increases the overall energy cost of heating. To overcome this problem, the thermostatic valve must be given working conditions which keep the small signal gain sufficiently low to avoid instability. There are two solutions to maintain a satisfactory low gain, one is to decrease the boiler temperature (radiator inlet temperature) and another is to reduce the pump pressure by reducing the pump speed. In modern pumps speed control is an integrated feature, making it possible to control the pressure in a central heating system [49].

Thermostat

Nowadays a good number of smart thermostat products are available on the market. Modern thermostats have a wide range of features, for control and the user interface, with different levels of sophistication. One range of features is related to *what* is under control. Thermostats are usually used for heating and cooling control, which can include forced air, radiant floor (usually using water) or radiant ceiling systems (water or electric), or radiators (usually steam). Some equipment, such as heat pumps, requires specialized control. Moreover, thermostats can control related equipment, such as humidifiers/dehumidifiers, auxiliary heating systems, economizers, whole house fans, or other ventilation systems [50].

Fig. 13, Wi-Fi 7-Day Programmable Thermostat, source: https://yourhome.honeywell.com/en/products/thermostat/wi-fi-7-day-programmable-thermostat-rth6580wf

A simple thermostat has four basic components: a temperature sensor, a switch or actuator to the physical target of heating, ventilating, and air conditioning (HVAC) equipment, a feedback loop between the two, and some means of displaying the current (and target) temperatures as well as providing a means for the user to change the target temperature. Nowadays electronic devices with digital displays have mostly replaced traditional mechanical and mercury-based thermostats. Wired connections are slowly being replaced by wireless. Advances in communication networks have allowed thermostats to become increasingly disaggregated into separate component [50]. More advanced thermostats can include also additional sensors that can monitor humidity, outside temperature or occupancy through infrared sensors. Moreover can be connected to the security system that includes window or door entry sensors.

Several studies have analysed the effect of the type of thermostat control on energy use, considering that homes with programmable thermostats set the temperature at a lower level when nobody is home or during the night. Therefore, a reduction on energy use is assumed in households with a programmable thermostat in comparison with households with manual thermostats or no thermostat control.

Nevius&Pigg (2000) [51] have done a study in 299 houses to determine the thermostat setting during determined times of the day and the average number of hours per week that occupants were present at home. They have found that the presence of a thermostat has a minimal effect on energy use, and temperature settings do not significantly differ between households with programmable thermostats and those with a manual thermostat. In the other study [52], it was found that in homes with thermostats, the mean temperature setting is lightly lower than in homes without a thermostat. Moreover, homes with a programmable thermostat keep the heating system on for longer than homes with manual thermostats, but the difference was not significant. In another study, survey of 279 houses in California, Lutzenhiser (1992) [53] found that households with manual thermostats used less energy in comparison with households with programmable thermostats. According to Lutzenhiser, manual control involves the deliberate cooling of people or the deliberate preparation of a cool space for people, while automatic cooling occurs regardless of occupancy or activity.

Conner and Lucas (1990) [54] measured indoor temperature and gathered data on self-reported heating behaviour on 400 households. They found that the temperature setting in dwellings with programmable thermostats decreased only by 0.58 F in comparison with dwellings with manual thermostats. They concluded that programmable thermostats do not significantly decrease the incidence of setback behaviour.

2.2.2. Ventilation Behaviour

Occupant controlled ventilation consists of window opening, background ventilation from trickle vents, and, in some dwellings, mechanical systems such as extract fans or whole-house mechanical ventilation and heat recovery (MVHR). This is to be differentiated from infiltration, which is involuntary air exchange through unsealed parts of the building fabric.

Window opening behaviour (Natural Ventilation Control

One of the most common tools to control the window opening behaviour is the magnetic induction device installed directly on the window.

In the home environment, the window and door opening sensors are used especially for home security system. However, the magnetic induction devices are commonly used to monitor occupancy behaviour in the research field.

Door and window sensors come in two pieces. One fits onto the door or window itself, while its counterpart attaches to the frame. Adhesive usually keeps the sensors in place, though sensors can be screwed directly into the frame. Position the two pieces of the sensor right next to each other, because they interact (Fig. 14) [55].

Fig. 14, Example of door and window opening sensor, source: https://www.sabrered.com/pepper-spray/door-and-window-sensor

When the window is slid open and the distance between the magnetic induction device and magnet is larger than few centimetres, the output signal of the magnetic induction device is "negative". In those conditions, the window is considered to be open. The output of the magnetic induction device is "positive" when the windows are closed [10] (fig. 15).

Fig. 15, Features of monitored windows and the magnetic induction device: horizontal sliding window. Source: Shi and Zhao, 2016

Occupants' interaction with windows has important impact on building energy consumption and on exposure to air pollutants in indoor environments. Many studies have shown that the energy consumption in two the same buildings can be completely different because of different occupants' interactions with windows (e.g. [4]). Moreover, how the occupants behave with window openings influences indoor air quality by affecting air exchange between indoor and outdoor ambiences.

In the domestic environment, window opening behaviour is one of the easiest ways for occupants to control indoor thermal environment and to restore their comfort. Occupants usually open the window to cool the indoor environment when they feel hot indoors, but they will close the window if the indoor thermal environment are to cool and the window is still open. This would mean that occupants are not satisfied with the indoor conditions and at the same time they decide to take some actions (opening or closing window). When they accept the indoor thermal conditions, they don't interact with the windows [8].

This relationship was observed in the research of Jian et al. (2011) [8]. They carried out measurements of environmental conditions for five representative apartments in Beijing (China). They controlled indoor air temperature, relative humidity, concentration of CO_2, and concentration of CO using an IAQ-CALC Indoor Air Quality Meter. Results showed that indoor air quality varies with time. The variation of the concentration of room CO_2 is completely accord with window opening behaviour. They noticed that window opening behaviour and environmental conditions have an effect on each other and work together. As a response to environmental conditions, window opening behaviour is strongly influenced by both indoor and outdoor thermal environment, indeed. On the other hand, the effect of occupants' need for indoor air quality and their presence at room on window opening behaviour cannot be treated as a small detail to overlook. Moreover, the researchers observed that while defining window opening behaviour for one room in residential building, it is necessary to consider also the window adjustment of its connecting room and the adjustment of the interior door, due to air diffusion between the two connecting rooms.

Similar conclusion was found in the research of Shi&Zhao (2016) [10]. They analysed occupants' interactions with windows in 8 residential apartments in two different cities in China. They examined relationships between the probability of window opening and explanatory variables, including outdoor air temperature, outdoor relative humidity, outdoor wind speed and ambient $PM_{2.5}$. And in fact, they found that outdoor climate has significant role occupant behaviour for window opening. They noticed that daily window opening period in summer was almost twice longer for Beijing city than Nanjing, due to fact that Beijing is a much dryer city with higher outdoor temperatures.

2.3. Indoor and outdoor environment control

The third category of sensors are sensors to control indoor and outdoor environment control. There are most spread type of sensors.

Relative Humidity Sensors (RH)

Relative humidity is important because it indicates the possible evaporation rate (release of latent heat). In a near comfort temperature situation, RH may vary in a wide range, as long as extremes are not obtained. Above 80% there is no room left for skin evaporation. If lower than 20%, it increases the spread of viruses and causes dry nose, throat, eyes, etc. The dryer the air, the better people tolerate higher temperatures. It is defined as the ratio of the partial pressure of water vapour in a gaseous mixture of air and water vapour to the saturated vapour pressure of water at a given temperature.

The simplest way to measure humidity is to use instruments called *hygrometers*. To detect moisture contents, a sensor in a hygrometer must be selective to water, and its internal properties should be modulated by the water concentration [37].

Humidity sensors work by detecting changes that alter electrical currents or temperature in the air. It is possible to distinguish types of humidity sensors: capacitive, resistive and thermal. All three types of sensors monitor minute changes in the atmosphere in order to calculate the humidity in the air [56].

The relative humidity can also influence the energy consumption. It was investigated by Wan et. al. (2009) [57]. They have found that the influence of indoor relative humidity on energy consumption is greater than that of indoor temperature for a required indoor thermal environment; hence energy consumption in an air-conditioning building may be reduced by choosing larger relative humidity and lower indoor temperature.

Combined data acquisition (T, RH, CO_2)

When it necessary to measure wide range of environmental data, it is possible to use devices which use the multiple sensors. Among them, the most common are devices which include sensors to measure temperature, relative humidity and carbon dioxide concentration.

One of the examples of modern tools is Indoor Climate Meter. IC-Meter measures, analyses and visualizes 'online' indoor climate in a room or building. The concept consists of a plug in measuring box, a server solution, an app and a website. By combining the indoor climate measurements with the local weather anywhere on the globe IC-Meter calculates a number of key parameters for the indoor climate and air changes. All data is stored in a Cloud solution – the buildings 'Black Box' – the results are communicated to the user through smartphone and/or PC. If the IC-Meter is combined with a remotely read heat meter, the heat loss to outside and gain from 'passive solar heat' can be derived. IC-Meter box The IC-Meter box is equipped with high accuracy sensors which measure temperature, humidity, CO_2 and noise every 5 minutes. The unit uploads the data through the users' internet (Wi-Fi or Ethernet) or GSM connection [58].

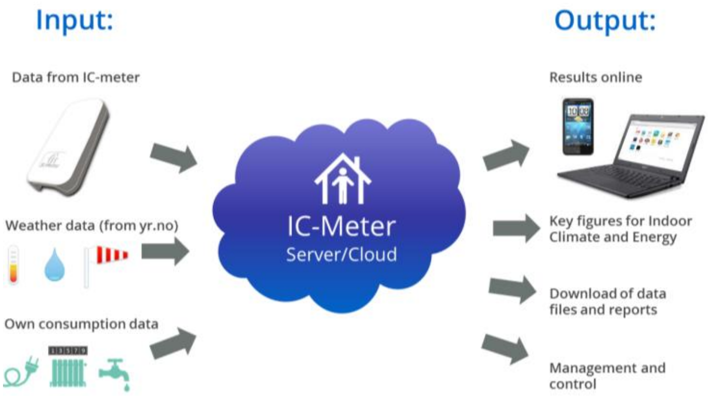

Fig. 16, IC meter concept, source: [*http://www.ic-meter.com/what-is-ic-meter/*](http://www.ic-meter.com/what-is-ic-meter/)

In the research field, the environmental control sensors can be used also for the occupant detection. For example, Lam et al. (2009) [59] were one of the first who proposed the use of environmental sensors to estimate occupancy. They measured environmental parameters like CO_2, temperature, humidity and acoustics. They extracted several features from the measurement data and shortlisted the most relevant ones using a feature selection algorithm based on Relative Information Gain (RIG). The best features were used to train three machine learning algorithms, namely Artificial Neural Network (ANN), Support Vector Machine (SVM) and Hidden Markov Model (HMM) to estimate occupancy. The accuracy of their estimation ranged from 58% to 75% for various testing periods.

More recently, Masood et al. (2015) [60] monitored the CO_2, temperature, humidity and pressure levels in Tutorial Room at Nanyang Technological University in Singapore. A wireless IP camera was used to take snapshots of TR45, which were used to establish the ground truth of occupancy. The collected data were used for the wrapper model of feature selection supported by Extreme Learning Machine (ELM). The ELM tracked the occupancy with the accuracy of 81.37 % for five levels (based on the number of occupants). The estimation tracks the rise in occupancy level to the peak (22 occupants) very closely and without fluctuations. It also detects relatively abrupt changes quite well. The results didn't show false detections for the unoccupied period, except for an instantaneous change that is not captured in the full-resolution case. The issue with the estimation is that the trend falls prematurely when there is a dip from maximum occupancy to zero occupancy. This occurs even with the five-level occupancy resolution.

Szczurek at al. (2017) [61] analysed the effectiveness of relative humidity, temperature and CO_2 sensors applied in an university room in Poland, naturally ventilated. The collected data about T, RH and CO_2 concentration were used as inputs of occupancy determination algorithms. The information about room occupancy was acquired from a survey. Everyday all teachers were asked to indicate the moment when their classes begun and finished as well as to quote the number of attendees. In the first step, they analysed the effectiveness of every sensor individually. The best results were based on CO_2 concentration data (with the misclassification rate 1.68 %). Comparable performance was achieved when was used the temperature data. The worst results were obtained when applying relative humidity data (MCR= 3.27 %). In the second part, the researchers examined the occupancy determination using measurement data on CO_2 concentration, temperature and humidity jointly (CO_2- T, CO_2-RH, T-RH and CO_2-T-RH). The results showed that combination of temperature and relative humidity sensors is an opportune solution for occupancy detection (MCR=??). The improvement was lowest in case of CO_2-T sensor combination. This fact reveals that CO_2 concentration and temperature displayed a substantial convergence of information which refers to room occupancy. However, the best result was obtained using tree of sensors together, with the (finish)

2.4. Energy Consumption and usage patterns

Considering Smart home as a building completely electric, the energy consumption measurement can be focused on electricity usage. They are many ways to control electricity consumption. Some methods allows to monitor only the appliance that is connected to the monitoring device, while other systems take a whole-house approach. The section below analyses some of them.

Smart energy meters

The most common way to measure electricity consumption is use of smart meters. A smart meter is an internet-capable device that measures energy, water or natural gas consumption of a building or home. Whereas traditional meters only measure total consumption, smart meters record when and how much of a resource is consumed [62].

Smart meters use a secure national communication network (called the DCC), which automatically and wirelessly send the actual energy usage to the supplier. In this way, households are not compelled to provide their own regular readings and they don't have to rely on estimated energy bills.

Use of smart meters has many benefits. They can improve the operational efficiency of the grid and allow for proactive maintenance. For occupants, the benefits of this improvement might be realized through the reduction of such adverse events as blackouts. As found by Pratt et al. (2010) [63], automation enabled by smart meters can reduce blackout times from hours to seconds by identifying faults and compensating remotely. Indeed, without smart meters, customers must notify their utility about outages, whereas smart meters allow for immediate outage detection. Moreover, smart meters can help occupants to save money. There are several ways in which smart meters may directly contribute to customer savings. Specifically, smart meters are expected to increase energy efficiency and improve operational efficiency and reliability. Moreover they reduce labour costs. Faruqui and Wood (2011) [64] have found that savings can be up to $24 per meter over a 20-year horizon, as it is not necessary to get involved an employee physically to read the meter.

Smart Plugs/Outlets

Smart Plugs are single-appliance energy monitoring and control devices. They principal scope is not the energy tracking- their focus is more on app control and setting schedules. However, many of them monitor also electricity. It is possible to plug them into a normal outlet, plug in any appliance, and see how much energy it uses without any extra work. It is also possible to turn the appliance on/ off basing on a time schedule designed to save energy. However, this solution works best when only a few energy-hungry appliances are tracked, instead of whole house monitoring [65].

3. Observations and conclusions

Occupant behaviour can greatly influence the performance of a building, with respect to both energy consumption and indoor environment. Many researchers have found that discrepancy between estimated energy consumption simulated by a software and the real one can be even up to 50 %, due to occupant behaviour. However, there are not many studies yet that have investigated the interactions of the occupant in real indoor environment in detail. Good knowledge of occupant behaviour is crucial for an accurate prediction of building and effective operation of building systems.

Occupants can influence the indoor environment in direct (adjustment of control systems) and indirect way (change of position or amount of clothes worn).

This paper takes into account different energy end-uses, in particular referring to window opening behaviour and heating adjustment. The analysis is conducted to highlights the most important factors which are influencing occupant behaviour. It can be noticed that many parameters overlaps and can be distinguished for more than end-use.

In the second section (data acquisition technologies) was compare the performance of various sensors for occupancy detection within buildings and systems which can help to assess potential energy savings due to activity and building occupancy and energy use. The optimal sensor in the domestic ambience should be discreet to avoid influence on occupants' activities and behaviours and private to do not reveal sensitive information about occupants. For the researches the devices should be cheap, easy to install, well documented, easy to replace and maintain, robust to damage, wireless connected to avoid use of cables, should require minimal computational resources, low-power, requiring no external power or able to run as long as possible on batteries.

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