UBIQUITOUS SENSORS TO ASSESS PEOPLE'S ENERGY CONSUMPTION AND WELLBEING IN DOMESTIC ENVIRONMENTS

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Keywords: Energy demand reduction; Health; Occupancy patterns; Non-intrusive monitoring system; User location and tracking.

SUMMARY

There is a complex link between building internal conditions, occupants' health, expectations and their behaviour, and energy consumption. Homeowners exert total control of their homes and how people actually use buildings is not as how we think they do. Therefore, mapping occupants' behaviour, and understanding how it relates to comfort and energy consumption is essential. To address this necessity, the paper discusses the finding of a case study with the use of (1) different monitoring systems for occupants, (2) technologies for their energy use through time and space. Furthermore, it assesses the complexity, robustness, accuracy and performance of each method. To support this review, monitored data were collected to assess occupants' wellbeing in their home. These could be supported by fix building sensors, or/and wearable sensors. Results from this study established that systems, using ultra wide band technology and radio-frequency identification hold the highest precision and accuracy, being a non-intrusive method in everyday domestic settings. In conclusion, gathering occupancy data may lead to better and more energy-efficient control system of indoor environment and understanding their health and comfort.

I. INTRODUCTION

Across the world there are targets imposed by Governments to reduce the carbon emissions from existing buildings and to improve their energy efficiency. Scientists showed that the energy use in homes as a result of human activities have contributed to the increase of carbon emissions. If the electricity consumption continues to increase, and people do not change their behaviour and the way they use energy, it is likely that the targets imposed by the Government may not be reached. As highlighted by Spataru (2010), Spataru and Gillott (2011) and Ekins and Spataru (2012), behavioural changes can be more important in reducing electricity consumption than any energy efficiency intervention relating to household equipment. Therefore, it is important to understand individual behaviour and to gather comprehensive evaluations of people's behaviour and activities in order to see how this can be change at a national level in order to help reduce energy consumption and carbon emissions from existing buildings. Moreover, information on occupancy, may lead to very fine delivery of lighting and heating, ventilation and air conditioning (HVAC), and visualization of the use of space.

Vale and Vale (2010) revealed the complex linkages between building fabric, inhabitants' expectation and behaviour, energy consumption and actual internal conditions. They have shown how people actually use buildings, rather than how we think they do. A Danish study investigating the heat consumption in 290 identical homes found that the highest heat consumption was up to 20 times higher than the lowest (Fabi et al., 2012). Toftum et al. (2009) determined that the energy usage depends on the occupant behaviour. In addition, significant savings can be achieved through consciously use of appliances, electronics and lights. Such studies are necessary in order to understand, for example, why housing occupants use more energy for heating as their neighbour, while living in exactly the same type of home. Also, information of occupants' patterns is useful in determining the required building's heating and for thermal control. The building heating system can be adjusted relative to the body heat output of the occupants' number. Multiple electronics lead to an increased temperature of the room. When this happens, the heating system can be automatically lowered. The same principle can be applied to adjust building's ventilation needs and decrease CO_2 emissions. This is important because respiratory diseases can occur in an improper ventilated space, but also this may lead to better and more energy-efficient indoor environment control.

In order to understand better how occupant behaviour relates to energy consumption, options for monitoring people within dwellings needs to be researched. Therefore, the authors tested over the past few years various techniques and monitoring systems. This paper investigates the use of different methods to measure building occupant activities in order to develop metrics related to total building occupancy and assess the impact of occupancy on energy use in buildings. Occupancy data and metrics related to building occupancy and comfort can be valuable in forecast models of building power draw. Moreover, information on occupancy may lead to more energy-efficient indoor environment control and improve the wellbeing of occupants.

II. THE CASE STUDY

The case considered was a one-bedroom flat in Central of London with two occupants; refer to Figure 1. The test period was two weeks in different seasons. This study shows the different methods tested during a 2-week period. Environmental factors, including: air temperature, relative humidity in different locations in the case study has been monitored using HOBO-U12 devices. In addition, the total electricity and water consumption were monitored, as well as electricity use with different electronic devices. The novelty of this case study was the monitoring of occupants with different techniques during the 2-weeks period to assess their energy consumption, as well as their wellbeing.

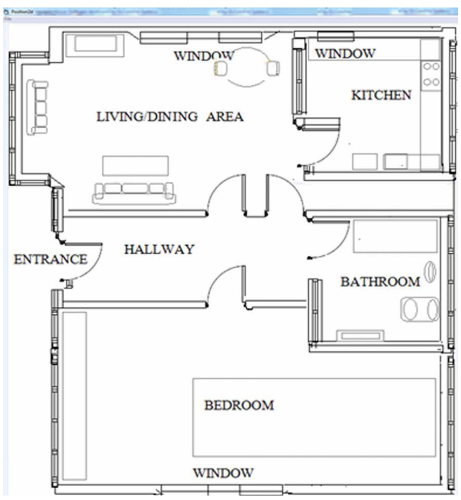

Figure 1. A print-screen of the case study floor plan.

III. METHOD AND RESULTS

3.1. Non-wearable sensors and devices

PIR Sensors

PIR sensors have been used to analyse the expected trends, looking at weekly and weekend profiles. PIR radiation motion sensors can be used to count the number of times people move through a space. Figure 2 shows PIR measurements in all rooms versus overall presence of the occupants during 1-day. Results show that when the room was occupied sometimes PIR shows no measurements. This is caused by a reduced amount of movement of the occupant. Moreover, when more than one person is present in the same space, the results do not show greater PIR peaks. So, PIR can provide information on the amount of movement, but not the number of people.

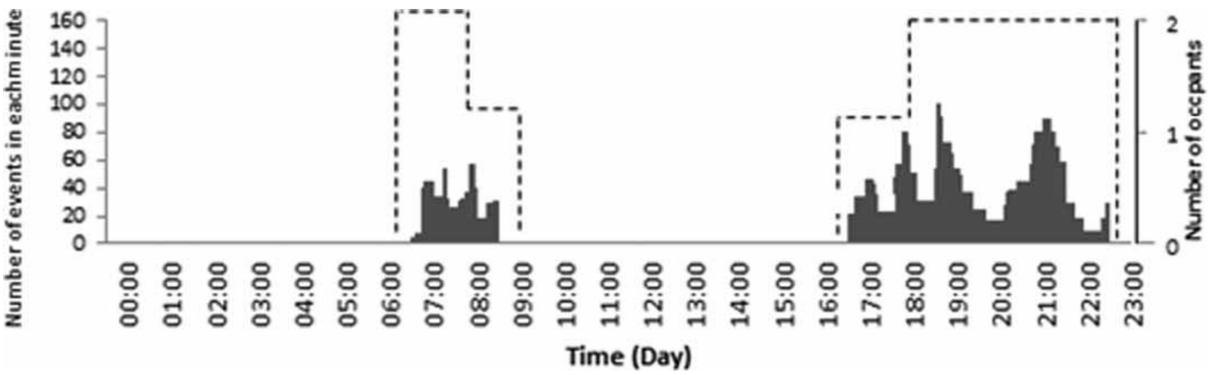

Figure 2. PIR measurements in all rooms versus overall human presence during a day.

Carbon-dioxide Sensors

A carbon-dioxide (CO_2) sensor was connected to a transmitter and included in the wireless network to record activity in the building. The CO_2 sensor used (Vaisala GMW21) was a commercially available sensor. The output was capped at 4 V and then stepped this down to 2 V for transmission to ensure that the sensitivity of the device to the concentrations expected is maximized. Figure 3 shows the CO_2 content versus number of occupants.

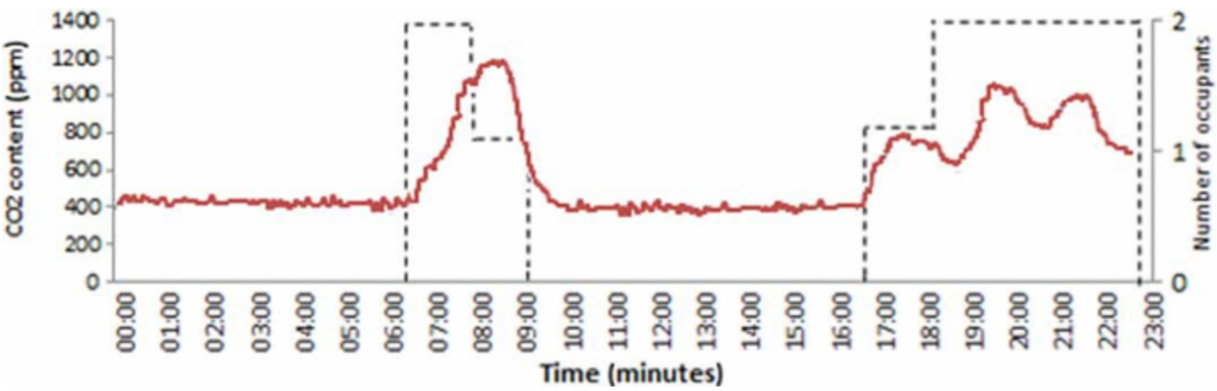

Figure 3. CO_2 content in all rooms versus overall occupants' presence during a day.

As it is shown in Figure 3, when the flat is occupied there is an increase in the CO_2 content, with a fast increased when a door has been closed or with slightly decreased in unoccupied spaces or when door has been opened again due to air being mixed with the one from the unoccupied space. Unfortunately, this can conduct to misinterpretation of the results on actual change of location of an occupant. The sharp rise could be related to an increased in metabolic rate due to physical exercise, since the occupants own a static exercise bike. It was observed that CO_2 could provide wrong information on the number of occupants.

3.2 Wearable sensors/devices performance

Wearable device may have built-in sensors that monitor motion, position, physiological, and environmental variables. These sensors provide data, which may be used to monitor changes in location or activity.

Active RFID Tracking System

Cost-effective sensors from the shelf has been used and put together to create our own monitoring system. A hybrid localization method using a combination of *angle-of-arrival* (AOA) and *time-difference-of-arrival* (TDOA) location methods to determine the location has been used. Mathematical expressions have been generated as a combination of an exponential distribution (RSS location method) and Gaussian distribution (TDOA location method). First the RFID reader gets the metric, and then locates the RFID tag in the space. This can be done by using the metrics, and converting those into distances to estimate the target position. The difficulty in using such a method consists of synchronized RFID readers in time. Literature provides us with different methods to achieve the solution. One method is Fan's (Elkamchouchi, 2005; Stefanski, 2009). This method transforms the nonlinear expressions into a linear system of equations. The distance was calculated by the time a signal travels from the sender to the receiver. Information about each tag (ID, time and date, and position) were stored by the software.

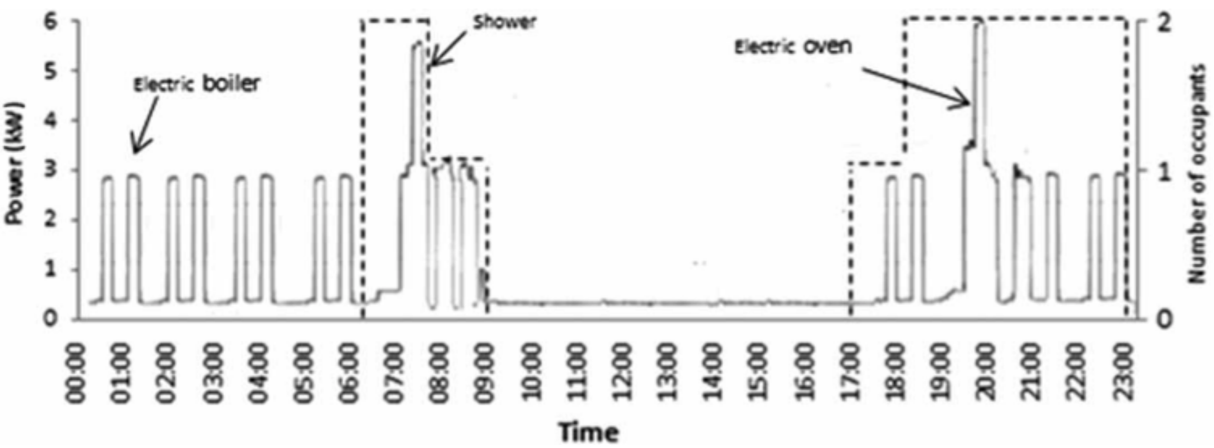

Figure 4. The occupancy patterns and power consumed during a day.

General trends can be draw from combining information on occupants' position and on power used through the use of soft computing logic algorithms. As depicted in Figure 4 from the total power used and from occupancy time patterns, the power use for main activities during the 24 h was deducted. This includes the use of electric boiler, shower and electric oven. Further applying logical algorithms attributed to the use of different electronics, the data could be translated into activities.

SenseCam

The SenseCam was first developed by Microsoft Research labs in Cambridge to assist people with memory impairment (Hodges et al., 2006). Of similar size to a badge and wear around the neck of the participant, it provides two types of outputs: (1) a record of the measurements taken by the five sensors (2) a visual photographic diary. Different types of hardware-based sensors are used in wearable devices to monitor specific physical properties, such as acceleration, heart rate or temperature; data that may be used to monitor changes in location and activity.

Motion sensors include accelerometers, gyroscopes and gravity sensors. They measure the acceleration of the device along two or three axes. Acceleration is defined as the change in speed over time; it is influenced by the frequency, the duration and the intensity of the body movement. The SenseCam device used in this study contains a three axes piezoresistive accelerometer, Kionix KXP84. Figure 5 shows an example of its output; during this 1-day sequence, we can observe that the occupant was very active during the lunch period (12–2 pm) and the early part of the evening. Also it is interesting to note the change in the y-axis around 7.20 pm, the visual diary confirmed that the occupant took the device off, and left-it facing downward. The occupant motion was analysed using a two steps process (Kim et al., 2012):

- Analysis of the y-axis output, identifying a forward or backward movement, where three types of activity would be discerned, as motionless, walking or running.
- Analysis of the z-axis, identifying an upward or downward movement, which could be recognized as walking, going upstairs or going downstairs.

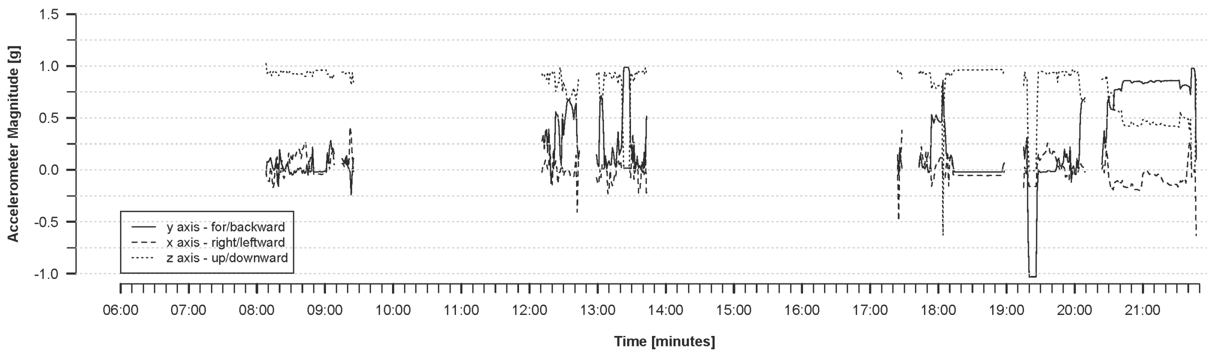

Figure 5. Example of motion sensor output from SenseCam accelerometer during a day.

Physiological sensors measure occupants' physiological characteristics, such as heart rate. The monitoring study included two devices manufactured by Kalenji to monitor HR: the sensor and transmitter (Kalenji 300 coded) fitted into a chest-strap belt and the receiver and data logger (Kalenji Cardio Connect) fitted into an independent device, which can be attached to the belt or kept in the occupants' pocket. The sensor is recording heart electric activity, using electrocardiography as shown in Figure 6. It was observed that records exceeding 95 bmp are matched with most of the peaks of the normalized magnitude of the accelerometer vector. By combining the output of the heart-rate monitor and accelerometer, an occupant's activity patterns can be determined with relatively a high level of accuracy. (Gauthier and Shipworth, 2013).The output from the heart-rate monitor can be analysed with the ISO 8996, level-3 approach and associated set of equations, to estimate metabolic rate. This method uses an indirect determination, based on the relationship between oxygen uptake and heart rate under defined conditions. This method holds some limitations, for example emotions or small movements while resting can increase the occupant's heart rate, while the energy expenditure remains almost the same (Jeukendrup and Gleeson, 2004).

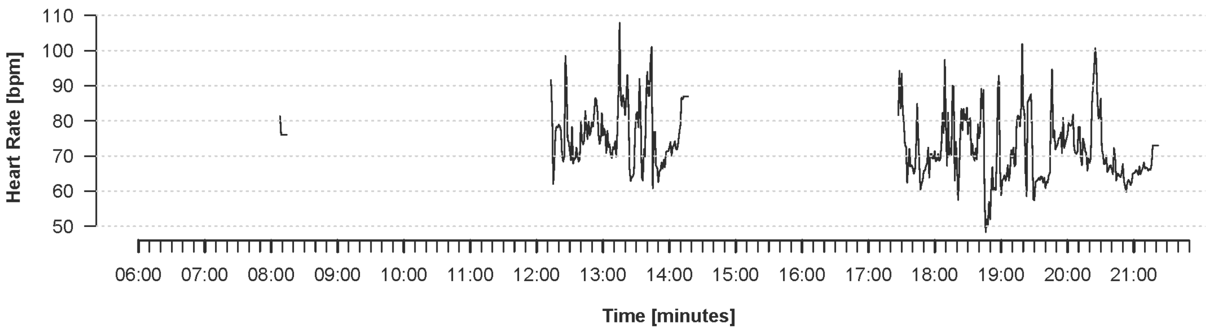

Figure 6. Example of physiological sensor output from Kalenji heart-rate monitor during a day.

Environmental sensors measure various environmental variables, such as air temperature, relative humidity and illuminance. This includes barometers, photometers and thermometers. Also temperature and relative humidity in the living area and bedroom have been monitored.

The four HOBO-U12 devices were attached to a wooden pole and positioned at 0.1, 0.6, 1.1 and 1.7 m from the ground to comply with the requirements set by EN ISO 7726. The poles were positioned according to the room layout (cold/warm places) and the most likely occupied places. It has been noted as shown in Figure 7 that the peaks in the internal living room temperature occur when the flat is occupied. Future studies might explore the relationship between the activity level and the variation in the indoor temperature through time and location.

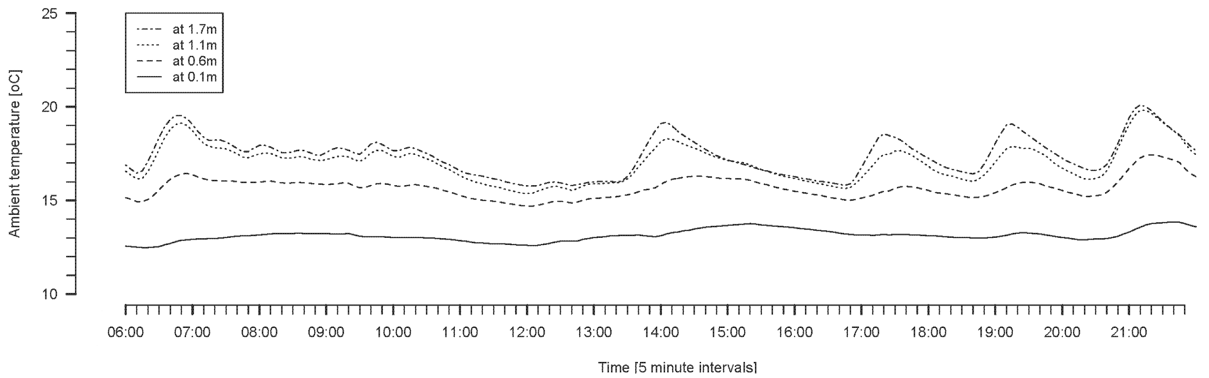

Figure 7. Example of environmental sensor output from living room thermometer during a day.

IV. DISCUSSIONS AND CONCLUSIONS

Lessons learnt from the use of methods and the assessment of wellbeing

The aim of this paper was to compare the performance of various sensors for monitoring people within buildings, systems which can help us to assess potential energy savings and occupants' wellbeing as a function of activity, building occupancy and energy use. Occupant location was tracked during 2- weeks, but due to the focus of this paper on different methods, only examples of output for 24 h are presented.

It was concluded that the ideal sensors when used in an indoor environment should be: 'discreet' to not influence occupant's activities; private – not revealing sensitive information; invasive; for researchers should be: inexpensive, 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.

Each technology as shown in the review has intrinsic restrictions. CO_2 sensors are highly depending on air circulation patterns and PIR sensors are prone to negative false outputs. Both methods the SenseCam and the method based on RFID tags can be improved significantly by adding more sensors and make it more comfortable to the users through the use of bracelets instead of necklace tags or through the integration of the tags within a home security system. For example, in the future, people localization may be determined through TV remote control. The authors will continue to further develop the method and search for new challenges and combinations.

Gathering information on occupants' behaviour and their energy consumption will help to understand better how to reduce energy consumption in buildings while keeping occupants comfortable. Compared to social surveys, actual monitoring shows exactly how people behave. Occupancy data are often an assumed variable in energy models. Therefore, more data should be collected to validate existing models.

Moreover, such studies help in understanding various relationships between occupants and buildings, for example, by looking at energy use variations when identical homes and different occupants are considered. In the future, within smart homes and smart grids, these methods could potentially be used to forecast energy demand for heating and to manage power distribution peaks automatically, as well as to address conservations alongside energy management and providing for rising expectation toward comfort.

ACKNOWLEDGEMENT

The research presented in this paper was published in Architectural Engineering and Design Management, citation as follow: Spataru, C. and Gauthier, S., (2014). How to monitor people 'smartly' to help reducing energy consumption in buildings?, Architectural Engineering and Design Management, 10:1-2, 60-78.
Available at: http://dx.doi.org/10.1080/17452007.2013.837248

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