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Occupant behaviour related to energy use in the residential sector: results from the Ecommon monitoring campaign.

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Abstract
Buildings in Europe are the largest end use sector and especially residential buildings account for two thirds of this energy use. Despite the fact that building characteristics play a major role in a dwelling's energy consumption, occupant characteristics and behaviour significantly affect this energy use as well. The Ecommon campaign monitored 32 residential dwellings for 6 months in the Netherlands, capturing quantitative (temperature, CO_2, humidity, movement, boiler and ventilation electricity consumption, real time and total electricity and gas consumption on the meter) and quantitative data (comfort perception, actions taken like closing and opening windows, thermostat use, use and type of clothes, and metabolic activity). Additionally in the beginning of the campaign a survey was given to the tenants with questions on income, gender, education level, thermostat and ventilation preferences, bathing patterns and other related data. This paper describes the experimental set up of the campaign, the temperature and occupancy profiles for each type of room for the 32 dwellings and the findings on the clothing patterns and metabolic activity. Temperature profiles show that these dwellings have higher temperatures through the whole day than the common assumption of the daily average of 18 ^{o} C suggested for the calculations of the national simulation software. A method is demonstrated on how a combination of motion detection and CO_2 can lead to reliable occupancy profiles.

Keywords – occupancy behaviour, energy consumption, residential buildings, wireless monitoring

1. Introduction

The built environment is responsible for about 40% of the total energy use in Europe[1]. Residential sector alone is responsible for 22% of the total energy consumption[2]. European and national regulations like EPBD and specific parts of building codes aim at reducing the energy consumption of buildings.

This paper presents the first outcomes of the Ecommon monitoring campaign in 32 Dutch residential dwellings for a period of six months. The long term aim of the Ecommon project is the development of better prediction models for the energy consumption of residential dwellings. Energy labelling calculations as well as energy consumption forecasts on which energy policies rely, are based on models. In the past years several studies have demonstrated that these models show large non-linear deviations from reality, making the prediction of possible energy savings biased. It has been shown that these poor predictions can be hypothesised – on the basis of a sensitivity analyses- to be the result of poor estimation of the U–values of walls, poor estimation of the infiltration and ventilation flow rates and poor estimation of the heated surface area leading to a poor estimation of the average indoor temperature[3]. Additionally, there is very little knowledge on how occupant's perception of comfort and behaviour influences the energy use for heating. A Monte Carlo analysis performed by Ioannou and Itard showed that behavioural parameters like the thermostat setting and ventilation patterns can significantly influence residential energy consumption, while clothing and metabolic activity have a big impact on the PMV comfort index of the tenants[4].

2. Methodology

2.1 Research Questions

The goals fo this study are:

- to define the 24-hour temperature profiles for the residential dwellings participated in the campaign.
- establish a relationship between CO_2 concentrations, movement and occupant presence by creating daily occupancy profiles.

2.2 Ecommon Campaign Set Up

In the Ecommon monitoring campaign we chose to restrain the sample to social housing in order to match this research to earlier research in which most of data was collected for social housing[5]. Furthermore the sample had to be divided into A and F labels and most of housings associations have labelled their dwellings, which is not the case of individual owners. We contacted tenants individually by a letter of intent. More than 2000 such letters were sent to individual homeowners in the greater Den Haag area (including the neighbourhoods of Rijswijk, Voorburg, Leidschenveen, Leidschendam and Zoetermeer). The response rate was about 10% and then a careful selection had to take place in order to maximize the amount of useful data that we could collect. For this selection, we made use of the SHAERE database from Aedes[6], to select respondents on the basis of their heating system. In total 32 houses were selected and were monitored for a period of 6 months. The final sample of the dwellings can be seen in table 1. Furthermore the dwellings were categorized based on their ventilation systems and in that sense there were 7 dwellings with balanced ventilation, 9 dwellings with completely natural ventilation (supply and exhaust) and 14 dwellings with natural supply and mechanical exhaust (usually in wet rooms, and kitchen).

Table 1. Number of dwellings per label category and type of space heating system.

Heating system / Energy Label	Heat Pump	Condensing Boiler	Local Stove
A/B	4	9	
F		17	2

2.3 Quantitative Data Acquisition Equipment

The system that was used to gather temperature, relative humidity, CO_2 and presence data was a custom made combination of sensors developed by Honeywell. The sensors for temperature, humidity and CO_2 were all fit in a single box that was installed in every habitable room (living room, bedrooms, study room and kitchen) of each of the houses that participated in the measuring campaign.

The CO_2 was an NDIR type sensor with +/- 50 ppm accuracy. NDIR sensors (non dispersive infrared sensors) are simple spectroscopic sensors that are widely used as gas detectors[7]. The humidity sensors were based on the capacitive sensing principle. They consist of a hygroscopic dielectric material (in this case thermoset polymer) placed between a pair of electrodes forming a small capacitor. In absence of moisture, the dielectric constant of the hygroscopic dielectric material and the sensor geometry determine the value of capacitance. At equilibrium conditions, the amount of moisture present in a hygroscopic material depends on both the ambient temperature and the ambient water vapour pressure. This is true also for the hygroscopic dielectric material used on the sensor. By definition, relative humidity is a function of both the ambient temperature and water vapour pressure. Therefore there is a relationship between relative humidity, the amount of moisture present in the sensor, and sensor capacitance. This relationship governs the operation of a capacitive humidity instrument. The temperature sensors used were silicon temperature sensors. These are common forms of sensors used in electronic equipment. It can be integrated into an silicon integrated circuit and the principle behind the sensor is that the voltage of a silicon diode is temperature dependent. For the presence detection a PIR (passive infrared sensor) sensor was used similar to the ones that are commercially available for home security.

Parallel to the Honeywell sensors, another type of wireless sensor was installed in each dwelling. This sensor was developed by Eltako Electronics for measuring electricity consumption of specific installations. Although in principle the device could measure the consumption of every appliance (television, coffee machine, etc.) its large size made it more suitable for measuring the consumption of larger home installations such as a balance ventilation system or a boiler. In our case the sensor was used for measuring the electricity consumption of the pump of the combined heat and hot water boiler, and the consumption of the mehanical ventilation system (where available).

Finally, apart from the atmospheric data (T, Hu and CO2), presence, and electricity of the combi-boilers the total electricity consumption of each dwelling was monitored in real time with the Youless system. The Youless energy meter can be attached on the electricity meter and its sensor can count the number of pulses that the meter is emitting. Its technology allows it to work with analog, dial gauges, as well as newer digital meters, which was very important in this project, as we expected to have almost no smart meters in the sample. A specific number of meter pulses each time interval (minute, quarter, hour etc.) is related to a specific number of kWh. The Youless sensor counts the amount of pulses, translates them into kWh of electricity consumption and then stores the data online. All parameters were measured with a 5 minute interval for the whole mesurement campaign period.

2.4 Qualitative Data Acquisition Equipment

The Ecommon measurement campaign was not limited in gathering only quantitative data but quantitative ones as well. Data on the comfort perception were gathered with the help of a device developed by TU Delft Department of Industrial Design under the umbrella of the European Interreg project Sustainable Laboratories North West Europe (www.SusLabNWE.eu). This Comfort Dial, figure 1, was allowing the tenants to record their thermal comfort perception in different hours of the day by choosing between a 7 point scale, from -3 to +3 with -3.

Parallel to the comfort dial, a paper log book was given to the tenants, see figure 1. In this log book tenants were able to record various qualitative data such as: comfort perception, clothing combination, actions last half hour, metabolic activity. All these data were timestamped in the same timeline as the quantitative data.

Figure 1: Comfort dial used to capture comfort perception of the tenants and qualitative data paper log book.

All data were wirelessly transmitted to the local mini pc that was equipped with all the necessary software for the management of the sensors and from these mini pcs the data were reguraly coppied to the TU Delft SQL database.

In this paper though, no qualitative data results are presented. This section was made in order to give the reader the greater picture of the Ecommon project campaign and the data that were aquired.

3. Results from Quantitative Data

3.1: Temperature Profiles

In figures 2 and 3 we can see the average temperature profiles from each of the 24 hours of the day for the dwellings with natural supply and mechanical exhaust. For the living rooms temperature drops during night sleeping hours and increases again in the morning when people wake up. Then it steadily keeps increasing until dinner time when it stabilizes or keeps slightly increasing until night hours when people go again to bed.

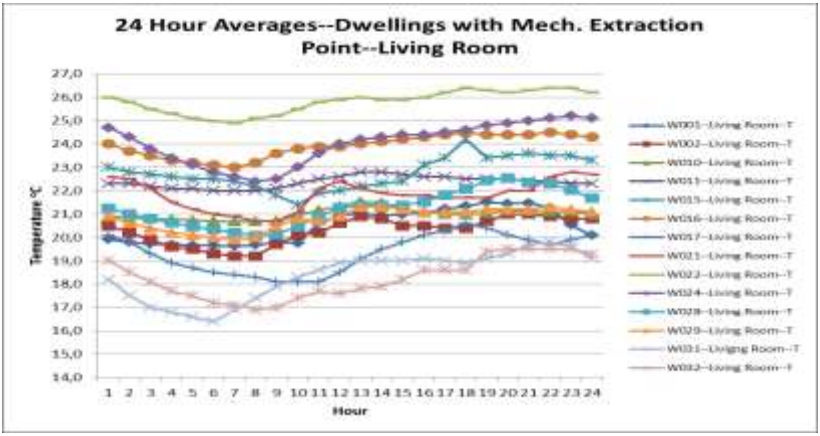

Figure 2: 24 hour temperature profiles for the living rooms of the naturally vent. dwellings with mechanical exhaust points.

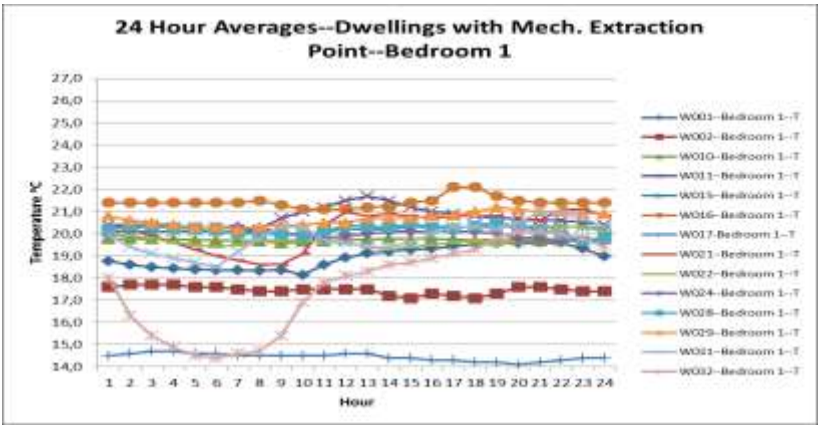

Figure 3: 24 hour temperature profiles for the bedroom 1 of the naturally vent. dwellings with mechanical exhaust points.

The range of temperature between the dwellings is very big. In dwelling 31 it fluctuates between 16.5 º C and 20 º C while in dwelling 22 it fluctuates between 25 º C and 26.5 º C. These differences in living room temperatures show the huge differences in the tenants' occupancy patterns concerning energy consumption and especially comfort perception. Very characteristic is the case of dwellings 10 and 11. These two dwellings were identical and adjusted to each other. One was inhabited by a young couple and one by a couple of pensioners. As we can see in figure 59, dwelling 11 has 1 ^{o} C higher temperature for each hour of the day.

In figure 3 we can see the results for the master bedrooms. There are two patterns that can be recognized. In the first temperature stays stable (with minor fluctuations) for the whole day and in the second one temperature drops during the night and increases again in the morning until the hours after dinner when it peaks. Then it starts dropping again till the next morning. With the exception of dwelling 17 where the temperature is constantly around 14.5 ^{o} C and dwelling 32 where the temperature during the sleeping hours drops gradually to 14.5 ^{o} C all other dwellings have 24 hour temperature profiles between 18 ^{o} C and 21.5 ^{o} C.

4. Occupancy Profiles

4.1 Determination of the Presence of Occupants by Analysis of Movement and CO_2.

To determine the presence of occupants, motion sensors are commonly used. Such a sensor, as the name illustrates, however only detects motion. Thus it is not clear if somebody has entered or left the room. If after motion detection, no further motion is detected, this can mean that the person is no longer present or is seated at rest or , in case of a bedroom, is sleeping.

In case of a bedroom, things can however be reasonable clear. If during the course of the evening, motion is detected and later on motion is detected in the morning, one might assume that a person has slept in that bedroom. For a living room however it is not that clear if somebody is present or not in between motion detection. The same goes for bedrooms used as study rooms.

Within this project a program is written to define the presence of occupants based upon (1) the motion sensor, (2) the fact that somebody was assume present or not previous and (3) the CO_2-course.

In general, determination is done in the following way:

- if motion is detected, at that moment somebody is considered present.

This is unquestionable and also regardless the fact if somebody was assumed present or not previous.

- if no motion is detected, while previous somebody was assumed present, there is checked if the CO_2-course decreases in a way as might be expected when nobody is present.

If this is the case, it is assumed that no longer somebody is present, while otherwise somebody is assumed still to be present.

- if no motion is detected, while previous also nobody was assumed present, there is checked if the CO_2-course nevertheless increases as might be expected when present.

It states ‘nevertheless’, while this situation (no motion and no previous presence) does not contradict. However situations were found in which the motion sensor misses the motion, which makes this consideration necessary.

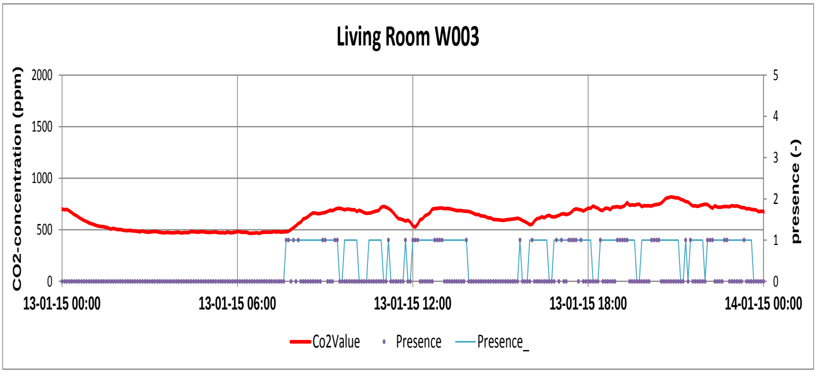

Figure 4: Predicted presence (Presence_) based upon motion sensor (Presence) and CO_2-course for the living room in dwelling W003 on the 13th of January 2015.

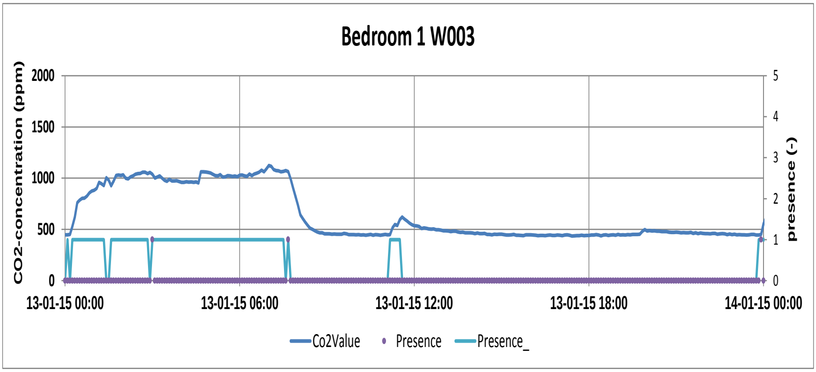

Figure 5: Predicted presence (Presence_) based upon motion sensor (Presence) and CO_2-course for bedroom 1 in dwelling W003 on the 13th of January 2015.

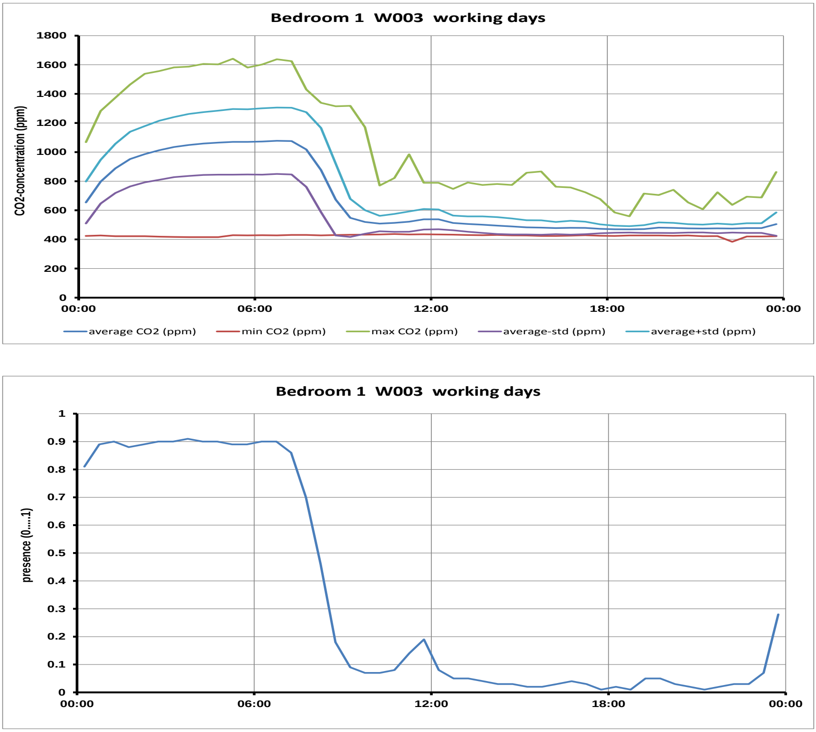

Figure 6: CO_2-profile and presence profile for bedroom 1 in dwelling W003 for working days based upon the complete measuring period

In figures 4 and 5 the predicted presence (blue line indicated with 'Presence_') is given, based upon the motion sensor signal (purple dots indicated with 'Presence') and the measured CO_2-curve, for the living room and bedroom 1 in dwelling W003. In this paragraph, for a couple of the considered rooms, the presence profile per day is given plus the CO_2-profile. It is noted that all these figures concern the working days within the measuring period. But the figures for the weekend were also determined and, as already state for the CO_2-profiles, the differences between workings days and weekend are minimal. In figure 6 the presence profile over a working day. This means all Monday's to Friday's within the complete monitoring period. This shows that during the night, from about 23 hour in the evening until 7:15 in the morning, the program predicts for about 90% of the time presence. During the day hardly presence is predicted. This meets the CO_2-profile (figure 5) which clearly indicates that this bedroom is used only for sleeping at regular times.

5. Conclusions

From the temperature profiles it is shown that there is a big spread in the temperature that tenants prefer in their living room in dwellings with natural supply of air and mechanical exhaust. This spread appears to be smaller in the bedrooms which leads to the conclusion that simplified one zone models for the energy calculations of dwellings are flawed. With the exception of a few hours in two living rooms (W031 and W032) all other living rooms and for the whole day the temperature lies above 18 C^o which is the temperature suggested for the calculations of the national simulation software. Another conclusion has to do with the dutch notion that bedrooms are not heated during the night. In figure 3 we can see that apart from 3 bedrooms (W002, W017 and W032) the other bedrooms have either a more or less constant temperature profile or a fluctuating one with temperatures well above 18 C^o. Given the fact that more than half of these dwellings are F labeled this mean that there must be heating during the night.

Based on the combination of motion detection and CO_2 a good prediction of the presence can be made. This can be expanded based on the monitoring data and can give further possibilities for analysis of this monitoring data. The occupancy profile calculations focus on the presence and not on the number of persons present. In case the number of persons in the household is known, rules can be added for this purpose. For instance if a person is detected in a bedroom, there should be at least one occupant less in for instance the living room. Furthermore 1 and 2 person bedrooms can be defined. This gives additional information about the possible number of persons when there is presence predicted in a room.

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