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A B S T R A C T

Reducing energy consumption in the residential sector is an imperative EU goal until 2020. An important boundary condition in buildings is that energy savings shouldn't be achieved at the expense of thermal comfort. There is, however, little known about comfort perception in residential buildings and its relation to the PMV theory. In this research an in-situ method for real time measurements of the quantitative and qualitative parameters that affect thermal comfort as well as the reported thermal comfort perception was developed and applied in 30 residential dwellings in the Netherlands. Quantitative data (air temperature, relative humidity, presence) have been wirelessly gathered with 5 min interval for 6 months. The thermal sensation was gathered wirelessly as well, using a battery powered comfort dial. Other qualitative data (metabolic activity, clothing, actions related to thermal comfort) were collected twice a day using a diary. The data analysis showed that while the neutral temperatures are well predicted by the PMV method, the cold and warm sensations are not. It seems that people reported (on a statistically significant way) comfortable sensation while the PMV method doesn't predict it, indicating a certain level of psychological adaptation to expectations. Additionally it was found that, although clothing and metabolic activities were similar among tenants of houses with different thermal quality, the neutral temperature was different: in houses with a good energy rating, the neutral temperature was higher than in houses with a poor rating.

1. Introduction

The built environment is responsible for about 40% of total energy use in Europe. Of this 40%, 63% is related to residential energy consumption [1]. European and national regulations like the Energy Performance of Buildings Directive EPBD and specific parts of national building codes aim to reducing the energy consumption of buildings in order to achieve the goals set for emissions and resource consumption by 2020.

The prediction and assessment of the energy consumption of residential dwellings is an important means to this end. Building performance simulation is a widely accepted method for this purpose. Buildings are highly complex systems in their own right. Both new buildings and renovated ones that are equipped with new heating and ventilation systems have high performance requirements that are closely related to EU sustainability goals for 2020. Increasing the reliability of building performance simulations can make an important contribution to reduction of the energy consumption of residential building stock.

The need for increased reliability of building simulations is also closely related to the discrepancy between actual and predicted energy use in the residential building sector. Researchers in the Netherlands and elsewhere have found a substantial gap between actual and predicted energy use in residential dwellings, with the worst dwellings (those with an energy rating of F or G) consuming significantly less energy than expected while dwellings with a higher energy rating consume more [2]. One reason for this discrepancy could be limited information on the building's thermal envelope and installations (more obvious in older dwellings where no records are available on the materials used). Another important reason is related to a misunderstanding or underestimation of the role of the occupant's behaviour [3,4,5]. Simulation software in its current form has very limited capabilities for taking the energy-related behaviour of the occupant into account. There is a clear need to take this behaviour into account during the design phase of new residential buildings or the renovation phase of older ones [3,4,6,7].

An important requirement both for new dwellings and for the refurbishment of older ones is that thermal comfort should be maintained or improved. Many commercially available simulation

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packages for the calculation of the energy consumption of buildings such as ESP-r, TRNSYS and Energy+ use the ISO 7730 method [8] for the assessment of occupants' thermal comfort. This seems to work well for office buildings, but not for residential buildings [9]. The ISO 7730 method, developed by P.O. Fanger, predicts perceived thermal comfort as a function of metabolic activity, clothing level and the four classical environmental parameters air temperature, mean radiant temperature, air velocity and humidity. Although Fanger's formulations were based on a sound physical model, the general validity of the statistically derived parameters is doubtful [9]. The thermal responses of occupants of residential and office buildings recorded in various countries differ from the predicted values [10,11,12,13,14,15] though Humphreys showed, in a world-wide data set of 16,762 cases with various settings, that the perceived thermal comfort agreed quite well with the model's predictions [15]. This means that it is very difficult to draw general conclusions for specific local settings, despite the model's strong physical basis.

Residential dwellings, unlike office buildings, include zones with variable thermal comfort requirements, are characterised by less predictable activities and provide more ways for the tenant to adapt to his thermal environment in order to reach the desired comfort level [16]. These conditions in these residential settings differ greatly from those applying in the climate chamber Fanger used to develop the PMV thermal comfort index.

Temperature levels and profiles in dwellings are expected to have an important effect on the energy consumption for heating and tenants' thermal comfort [17,18,19]. Furthermore, the operative temperature is a critical component of the PMV comfort index.

Various studies have derived indoor temperature profiles for the residential built environment but they differ in the methods used, the length of the monitoring period and the season when measurements were made. In many cases, temperature sensors with data recording intervals of 15, 30, 45 or 60 min were used [20–30]. The duration of the measurement campaign varied from 1 to 4 weeks [25,31] in some studies, while in others it covered the whole heating period (December to April in one northern European country (Belgium) [31]; a study in one southern Mediterranean country (Greece) [24] also covered the whole heating period –one that is much shorter than northern European countries like the Netherlands or Belgium. In one study the tenants were given the temperature sensor together with the operating manual and were invited to install it themselves [26], which could lower the accuracy of the measured data. In all these studies the data were collected locally in data loggers and had to be retrieved manually. Other studies used questionnaires or diaries for recording the temperatures where the tenants had to fill in the required information [32,33]. This probably led to large uncertainties, as no measurements were performed.

The aim of the present paper is to provide information on a kit for in-situ real-time measurement of the quantitative and qualitative parameters that affect thermal comfort on the reported tenant's thermal sensation and finally to present the resulting analysis of energy-related occupant behaviour (in particular the parameters that affect the PMV comfort index). This is important because thermal comfort may affect largely occupant behaviour, which relates to energy consumption and which in turn is an important factor for the discrepancy between actual and theoretical energy consumption in the residential dwellings.

The results presented here are taken from the Ecommon (Energy and Comfort Monitoring) campaign which took place in the Netherlands as part of the Monicair [34], SusLab [35] and Installaties 2020 [36] projects. Thirty-two residential dwellings (classified by energy rating and types of heating and ventilation system) were monitored for a 6-month period, from October 2014 to April 2015, which is the heating season for north Western Europe. Quantitative data (air temperature, relative humidity, CO_2 level and movement) for each room in the dwellings (living room, kitchen, bedroom 1 and bedroom 2 or study) were collected wirelessly at 5-min intervals. In addition, qualitative data (thermal sensation, metabolic activity, clothing, actions during the previous half hour related to thermal comfort) were collected over a 2-week period by two different methods, wirelessly and by entries in a manual log (see Section 2.3.2). The wireless device used to capture the thermal sensation of the tenants was time-coupled with the sensors for the quantitative data. This allowed the thermal sensation of the tenants at any given time to be time-coupled with the exact atmospheric conditions (temperature T, relative humidity RH and CO2 level), which could improve the reliability of the PMV calculations (see Section 2.3.1). All data (quantitative and qualitative) were available for inspection and analysis in real time throughout the whole campaign via a remote desktop application.

The next chapter describes the research questions, the design of this study, the way the campaign was set up, the data acquisition equipment and the data management system. The results follow in chapter 3 which first presents the neutral operative temperatures, per room type, derived from the PMV calculations and the recorded thermal sensation of the tenants. Further on, the relationship between the reported thermal sensation and the calculated PMV is explored in order to further validate the ability of the PMV index to predict the tenant's real thermal sensation. The next two sections (3.4 and 3.5) describe the clothing and metabolic activity of the tenants during the measurement campaign against the operative temperature and thermal sensation. Further, the clo and met values that correspond to the neutral thermal sensation of the tenants were calculated and the effect of the inaccuracy of these values was researched. Finally, a section with discussion, conclusions and recommendations conclude the present study.

2. Study design

Comfort has seldom been researched on site in actual conditions, and even more rarely has been measured in other ways than using surveys. The main research questions in this paper aim to determine whether it is possible to make such measurements and how the results of these measurements compete with already existing insights from PMV theory.

2.1. Research questions

The goals of this study are:

1) To perform in-situ real-time measurement of quantitative and qualitative data on comfort and occupant behaviour and their underlying parameters in an easy, unobtrusive way, in a residential environment.
2) To determine the tenants' temperature perception in relation to the energy rating and the ventilation and heating systems used in the dwellings.
3) To determine the type of clothing worn by the tenants and their activity levels in relation to the thermal sensation of the occupants.
4) To determine the neutral temperature levels calculated by the PMV method and to compare them to the neutral temperatures derived from the measurements thermal sensation.
5) To determine to what extent the PMV comfort index agrees with the thermal sensation reported by the tenants.
6) To determine if there is a relationship between the type of clothing and metabolic activity with thermal sensation and the indoor operative temperature.

2.2. Ecommon campaign set-up

The original design of the study was to have stratified random sampling. The dwellings were grouped according to the various heating systems, to their energy label and their ventilation system. However for practical reasons we deviated from that. This is also why we do not claim universality in our results but we instead show the methods that can be applied in order to measure in situ the qualitative and quantitative parameters of the PMV.

The sample used in the Ecommon monitoring campaign was restricted to social housing, in order to match this study with a previous one in which most data were collected for social housing [37]. Social housing in the Netherlands represents approximately one-third of the total residential housing stock and is quite representative of the residential housing stock as a whole [2,38,39]. Furthermore, housing associations have the energy rating of all their housing stock determined, which is not the case with all individual owners. The sample had to be divided into A-rated and F-rated dwellings, in order to address issues of current energy rating models. In fact, A-rated and B-rated dwellings were selected at one extreme and F-rated dwellings at the other. F-rated dwellings were selected in preference to G-rated ones, since previous studies [2,37] had shown that there are few dwellings in the Netherlands with a G energy rating.

The method used to calculate the energy rating is described in Dutch building code ISSO 82.3 [40]. The energy survey used as a basis for the energy performance certificate (EPC) rates each dwelling on a scale from 'A++' (the most efficient) to 'G'. The categories are determined with reference to the energy index, which is calculated on the basis of the total primary energy demand (Q_{total}); this represents the primary energy consumed for heating, hot water, pumps/ventilators and lighting, after subtracting the energy gains from PV cells and/or cogeneration.

We sent a letter to more than 2,000 addresses, inviting them to participate in the study and the response rate was 8.6%. Surveys that are intended for external audiences usually have a return rate of 5–10%. Considering the long length of the measurement campaign, the amount of equipment that had to be placed in each dwelling, the frequent intrusion of TU Delft personnel into the tenants' privacy (installing the equipment, handing over and retrieving the comfort dial, calling tenants to restart the data gathering mini pc, retrieving the equipment) and finally the fact that the data gathered could compromise the tenant's privacy and potentially their security (tenants were notified for all these issues in the initial letter they received), the return rate of 8.6% is considered very successful. Furthermore compensation was offered to the participants for the electricity costs of the equipment for the period of the six months, two gift cards of 20 euros each was offered to them and the feedback we received for this present was very positive.

A careful selection had to be made from among the households willing to participate in order to maximise the amount of data that could be collected. We used the SHAERE database developed by Aedes [41], the federation of Dutch housing associations, to select respondents on the basis of their energy rating and heating system. A total of 58 dwellings were selected. Finally, due to limitations in the monitoring equipment used, 32 dwellings were monitored over a 6-month period, from October 2014 to April 2015. The final sample may be seen in Table 1. The A-rated and B-rated dwellings were divided into those with an electrical heat pump coupled with low hydronic floor heating and those with efficient condensing gas boilers. The F-rated dwellings all had their old inefficient boilers replaced by new condensing gas boilers, apart from three that were still equipped with old gas stoves connected to the radiators in the various rooms to provide a central heating system.

The dwellings were also classified on the basis of their ventilation systems. Eight had balanced ventilation, 10 had completely natural ventilation (supply and exhaust) and 14 had natural air supply and mechanical exhaust (usually in wet rooms and kitchens). Dwellings 9 and 30 have been excluded from the analysis due to unavailability of data. Technical reasons related to the wireless transmission of the temperature, humidity and CO_2, resulted in

Table 1
Dwellings participating in the Ecommon campaign.

No.	Energy rating	Heating system	Ventilation system	No. of rooms	No. of occupants	Average age
W001	F	Condensing gas boiler	Natural supply Mech. Exhaust	6	1	67
W002	F	Condensing gas boiler	Natural supply Mech. Exhaust	5	3	39
W003	A	Heat pump	Balanced Vent.	4	2	73
W004	A	Heat pump	Balanced Vent.	4	2	67
W005	A	Condensing gas boiler	Balanced Vent.	4	1	92
W006	A	Condensing gas boiler	Balanced Vent.	3	2	77
W007	A	Heat pump	Balanced Vent.	4	4	31
W008	A	Heat pump	Balanced Vent.	4	2	25
W010	A	Condensing gas boiler	Natural supply Mech. Exhaust	7	2	29
W011	A	Condensing gas boiler	Natural supply Mech. Exhaust	7	2	69
W012	F	Condensing gas boiler	Natural Vent.	5	4	40.5
W013	F	Condensing gas boiler	Natural Vent.	5	3	53
W014	F	Gas stove	Natural Vent.	5	1	83
W015	B	Condensing gas boiler	Natural supply Mech. Exhaust	3	2	25
W016	B	Condensing gas boiler	Natural supply Mech. Exhaust	4	2	70
W017	B	Condensing gas boiler	Natural supply Mech. Exhaust	3	1	66
W018	B	Condensing gas boiler	Natural supply Mech. Exhaust	3	1	61
W019	F	Condensing gas boiler	Natural Vent.	5	3	29
W020	F	Condensing gas boiler	Natural Vent.	6	2	74
W021	F	Condensing gas boiler	Natural supply Mech. Exhaust	4	2	73
W022	F	Condensing gas boiler	Natural supply Mech. Exhaust	3	2	64
W023	F	Condensing gas boiler	Natural Vent.	4	2	66
W024	F	Condensing gas boiler	Natural supply Mech. Exhaust	5	1	72
W025	F	Gas stove	Natural Vent.	5	3	43
W026	F	Condensing gas boiler	Natural Vent.	4	4	21
W027	F	Gas stove	Natural Vent.	5	1	67
W028	F	Condensing gas boiler	Natural supply Mech. Exhaust	6	2	72
W029	F	Condensing gas boiler	Natural supply Mech. Exhaust	3	1	62
W031	F	Condensing gas boiler	Natural supply Mech. Exhaust	6	3	43
W032	B	Condensing gas boiler	Natural supply Mech. Exhaust	4	3	39

Fig. 1. T, CO_2, RH box (left) and movement sensor (right) as used during the Ecommon measurement campaign.

Table 2
Types, models and accuracy of sensors used during the Ecommon measurement campaign.

Sensor type	Model	Accuracy
CO_2	GE Telaire	400–1250 ppm: 3% of reading 1250 – 2000 ppm: 5% of reading
Relative Humidity	Honeywell HiH5031	+/– 3%
Temperature	KT Thermistor	1% per °C
Movement	Honeywell IR8M	11 × 12 m (range at 2.3 m mounting height)

Fig. 2. Comfort Dial used to capture perceived comfort levels of tenants during the Ecommon measurement campaign.

complete loss of data for these two dwellings. Details of the ventilation systems of the various dwellings are also given in Table 1.

2.3. Data acquisition and equipment

2.3.1. Honeywell equipment used to collect indoor climate data

The system used to collect temperature (T), relative humidity (RH), CO_2 level and presence data was a custom-built combination of sensors developed by Honeywell. CO_2 data were not required for the scope of the present paper, and are therefore not reported. The temperature, humidity and CO_2 sensors were all mounted in a single box that was installed in up to four habitable rooms (living room, bedrooms, study and kitchen) in each house participating in the measuring campaign. The type, model and accuracy of the sensors are shown in Table 2. The T, CO_2 and RH sensors were not battery powered and therefore had to be plugged into a wall socket. The PIR movement sensor, on the other hand, was battery powered. Fig. 1 gives an impression of the arrangement of the sensors.

The measuring frequency of all sensors was 5 min. The value recorded for each 5-min interval was the average of the readings during that interval. Temperatures were measured in °C, relative humidity in% and CO_2 levels in ppm (parts per million). The temperature sensor is fully compliant with the ISO 7726 standard for type C, measurements carried out in moderate environments approaching comfort conditions (comfort standard) specifications and methods. The humidity data were displayed as relative humidity (%) which was derived by the voltage output of these capacitive sensors and in terms of accuracy complies fully with the ISO 7726 [56].

The PIR sensor data were in binary form (0 and 1), 0 means that no movement was detected during the 5-min interval in question while 1 means that movement was detected at least once during the interval. The PIR sensor had 11 m × 12 mm detection range which was enough for all the rooms they were installed in. They had selectable pet immunity (0.18–36 kg) a patented look down mirror in order to detect movement exactly below the sensor, front and rear tampers and operative temperature range between −10 °C and 55 °C. The battery life was 4.5 years which was exceeding by far the time frame of this project and was ensuring that the data would be safely stored in case of wireless transmission problems. Finally they were compliant with the NEN standard for alarm systems [55].

2.3.2. Qualitative data: comfort dial and log book

The Ecommon measurement campaign collected qualitative as well as quantitative data. Data on perceived comfort levels were collected with the aid of a device developed by Delft University of Technology's Department of Industrial Design under the umbrella of the European Interreg project Sustainable Laboratories North West Europe (SusLab) [35]. This wireless device, called "comfort dial" (Fig. 2), allowed the tenants to digitally record their perceived thermal comfort level at any time of the day on a 7-point scale, from −3 (cold) via 0 (neutral) to +3 (hot).

The comfort dial is portable and relatively small in size and therefore tenants could carry it with them anywhere in the dwelling. That is why the data of the comfort dial had to be coupled to the PIR sensor data in order to determine the location of the tenant that particular moment.

Tenants also received a paper log book, shown in Fig. 3. This log book, like the comfort dial, was developed by Delft University of Technology's Department of Industrial Design. It was initially intended to be in online format so that people could log on to their computer, smart-phone or tablet and fill in various qualitative data such as:

- Perceived comfort level on the above-mentioned 7-point scale.
- The room they are occupying when filling in the log (kitchen, living room, bedroom etc.)
- Clothing combination worn: a choice of six combinations from very light to very warm clothing is available; see Fig. 3 and Table 4.
- Actions taken during the past half hour relating to comfort and energy consumption, such as opening or closing the windows, drinking a cold or hot drink, taking clothes off or putting them on, raising or lowering the thermostat setting and having a hot or cold shower.
- Activity level: lying/sleeping, relaxed sitting, doing light desk work, walking, jogging, running. These activities can then be related to the metabolic rate.

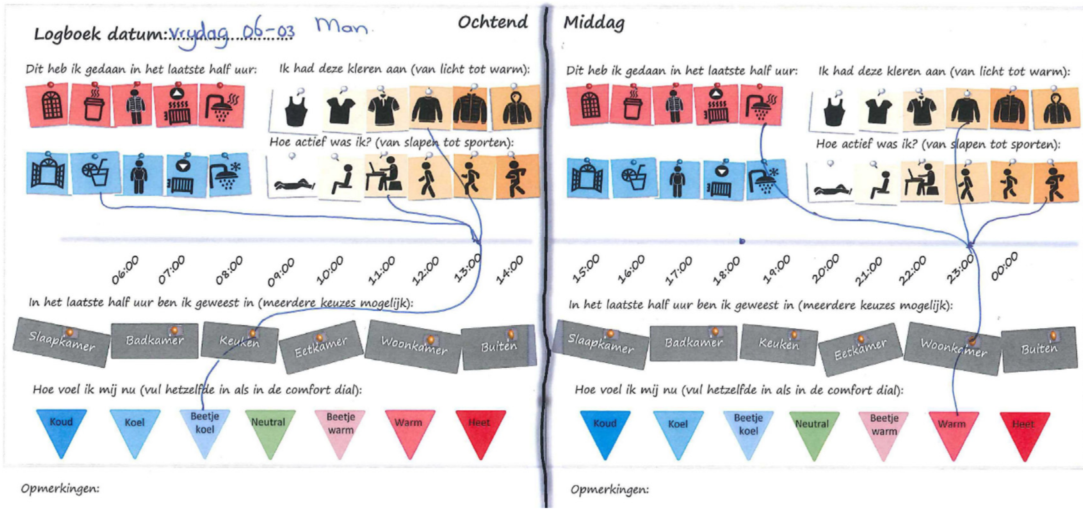

Fig. 3. Paper log book for entry of qualitative data.

However, we finally used a paper version of the log book due to a combination of financial limitations (not enough tablets available to provide all occupants of the 32 dwellings with one) and the fact that many participants were elderly and not well acquainted with digital technology.

The occupants of the houses were given the comfort dial and comfort log book for a 2-week period in March and early April 2015. The log book was given to them in 45 copies, 3 per day for the period of the two weeks that the tenants had to use the comfort dial. They had been instructed to use it at least 3 times per day (it was equipped with a time line, see Fig. 3) together with the comfort dial. The comfort dial on the other hand could be used as often as they wanted throughout the whole day.

The data from the comfort dial were wirelessly and in real time recorded to our database while the data from the comfort log book as well as the equipment (comfort dial) were retrieved in the end of the 2 weeks period. In that way we managed to obtain thermal sensation data (comfort dial), qualitative data related to the PMV (clothing and metabolic activity), and quantitative data related to the PMV (temperature and humidity) all universally time stamped. This enabled us to make calculations on the PMV with precision of 5 min which was the interval of the sensor quantitative data.

The main respondent (only one person per household was asked to use the comfort dial and log book) was asked to use it as often as he or she wanted, but at least three times a day (preferably in the morning, midday and evening). They also had to fill in the paper log, at least when they were using the comfort dial.

Furthermore, tenants had to fill in a questionnaire during the installation of the monitoring equipment, and all dwellings participating in the study were inspected at the same time. These two measures provided extra data in household characteristics, heating and ventilation patterns and perceived comfort levels.

2.3.3. Data storage and management

The data collected by the Honeywell sensors were managed by software developed by Honeywell. This software made it possible to select measurement frequency of 1, 5, 10 or any other number of minutes at any moment. A measurement frequency of 5 min was chosen for this project.

All the data were wirelessly transmitted from the sensors to a locally installed mini-PC on which the Honeywell software was installed. The data were regularly copied from this mini-PC to our SQL database at Delft University of Technology. This set-up allowed the data to be stored both locally, on the hard drive of the mini-PC, and centrally in the database at Delft.

Another point worth mentioning is that each Honeywell sensor box (containing the temperature, relative humidity and CO_2 sensors) also acted as a wireless transmitter for the adjacent sensor box, so that one mini-PC could collect data from neighbouring dwellings. This reduced overall equipment costs for the project. Data from the comfort dial were transmitted to the database at Delft University of Technology via a connect port and the local internet connection or a 3G network, if available.

2.3.4. Occupant survey and inspection list

Occupants were asked to fill in a questionnaire during installation of the sensors in their home. The questions asked fell into three categories: 1) general information on the participating households, such as household composition, income, age, education level; 2) the occupants' heating, showering and ventilation habits; and 3) overall perception of the comfort of the dwellings. The questionnaire was taken from an existing template that has been used in past projects, with different scopes, prior to Ecommon [57].

Furthermore, each dwelling was inspected during the installation of the monitoring equipment. The inspection covered the following items that were relevant to the present study: the type of space heating system used, the type of glazing, the types of ventilation present in the dwelling (extraction point in the kitchen, other mechanical ventilation usually present in the kitchen or bathroom and balanced ventilation) and information on the thermostat: type of thermostat, settings and control programme.

3. Results

3.1. Perceived dwelling temperature in relation to the energy rating and ventilation system

This section presents the results of this study starting with the tenant's overall perception of the dwelling temperature. The following part (3.2.3) presents the calculation of the neutral operative temperature, per room type and energy rating, according to the calculated PMV and the thermal sensation recorded by the tenants. In the two sections that follow (3.4 and 3.5) the clo and met values are displayed versus the recorded thermal sensation of the tenants and the operative temperature, for the living room, and a statistical analysis follows in order to determine the extent of possible bias in

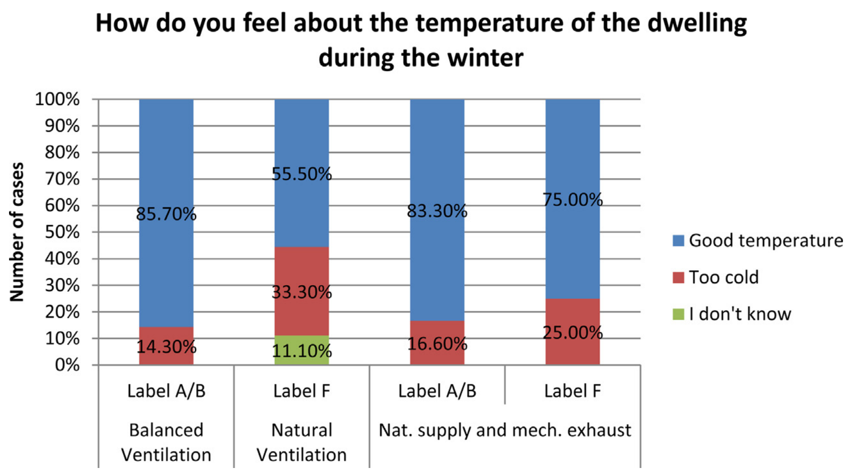

Fig. 4. Temperature perception in the winter per energy rating.

the calculations from potential mistakes in the gathering of the clo and met data.

Fig. 4 shows the answers to the question "How do you feel about the temperature of the dwelling during the winter?" as a function of the energy rating of the dwelling and the type of ventilation system used. It will be seen that the proportion of occupants who regard the dwelling as being too cold increases as we move from energy-efficient class A dwellings to class F dwellings, which have a poor energy performance. This finding is in agreement with the results reported by Majcen et al. [38], and is probably related to the insulation level and air-tightness of the dwellings.

The tenants of dwellings with balanced ventilation had the highest percentage (85.7%) of responses in dictating that the indoor temperature during the winter was all right. It should be noted that all these dwellings had energy rating A or B. In that sense, these results could be expected and relate more to the energy rating than to the ventilation system.

As may be seen from Table 1, some dwellings with mechanical exhaust ventilation had energy rating A/B, while others were F-rated. Fig. 4 shows that the proportion of "too cold" responses increases from A/B-rated dwellings to F-rated ones. Occupants of dwellings with completely natural ventilation were less likely to find the indoor temperature acceptable (55.6%). All dwellings with natural ventilation had energy rating F. It is noteworthy that this group included three dwellings with an old gas stove. The occupants of all three stated that they found the indoor temperature to be acceptable.

It might be expected that temperature perception during the winter is more closely related to the energy rating than to the type of ventilation. This was not however found to be the case in all dwellings with natural ventilation and mechanical exhaust. Some occupants of energy-efficient dwellings in this category stated that they felt too cold in the winter, while some occupants of less energy-efficient dwellings were satisfied with the indoor temperature. Further investigation of the actual energy consumption in these dwellings is required to determine whether these responses are related to excessive energy use in dwellings with low energy efficiency or very low consumption in the more energy-efficient dwellings.

3.2. Neutral temperatures in relation to PMV and reported thermal sensation

Fanger's method [14,42] for calculation of the predicted mean vote (PMV) is used worldwide to estimate the thermal comfort levels than can be achieved under various hydro-thermal conditions. This method uses the following parameters: air temperature (T_{air}), mean radiant temperature (T_{mrt}), air velocity (v), relative humidity (RH) and two parameters related to the thermal resistance of occupants' clothing [clo] and their metabolic activity [met]. During the present study, data for most of the above-mentioned parameters were collected with the aid of the sensors, the comfort dial and the log book. The parameters for which no direct data had been gathered were the mean radiant temperature T_{mrt} and the air speed; the latter in particular is a very difficult parameter to record since it has a very strong topical effect and its value may vary significantly from place to place in a given room. EnergyPlus simulations as described below were performed in order to estimate $T_{mrt,}$ sensitivity analysis for T_{mrt} and air velocity has been included in all further analyses in this paper.

3.2.1. Estimation of mean radiant temperature (T_{mrt}), indoor air speed, clo values and metabolic activity rates

A reference dwelling with a surface area of 75 m^2 divided in two zones (living room and bedroom) was simulated using the weather data for The Hague, the Netherlands, for the whole month of March 2015, which was the month when tenants were provided with comfort dials in order to record their thermal sensations, clothing values, actions aimed at modifying thermal sensation and metabolic activity. The size and characteristics of the reference dwelling were similar to the types of dwellings that were found in the sample of the Ecommon campaign. The dwelling was simulated in EnergyPlus in 3 different ways: as an A-rated dwelling with a condensing gas boiler for the heat generation and radiators for heat distribution in the rooms, as an A rated dwelling with a water-to-water heat pump, a ground heat exchanger and ground floor heating, and finally as an F-rated dwelling with condensing boiler and radiators. These three configurations cover all the dwellings used in the Ecommon measurement campaign.

Occupancy schedules, commonly available in simulation software libraries and adjusted to Dutch habits, were used for the simulations of the living room (presence early in the morning, and from 5 pm till midnight) and bedroom (presence/sleeping during the night hours). The number of people occupying the reference dwelling was set to 2 and the thermostat settings were 18 °C during daytime occupancy and 12 °C at night. The thermal transmittance (U) values used for A-rated dwellings were 0.251 W/m^2-K for the external walls, 0.346 W/m^2-K for the roof and 0.232 W/m^2-K for the ground floor. The corresponding values for F-rated dwellings (which were very poorly insulated) were 2.071 W/m^2-K for the external walls, 1.54 W/m^2-K for the roof and 3.11 W/m^2-K for the ground floor. Glazing for both configurations was set to standard

Table 3
EnergyPlus simulation results for March 2015, hourly average indoor air, radiant and operative temperatures.

	A-rated–boiler		F-rated–boiler		A-rated–Heat pump	
	Average	St. dev	Average	St. dev	Average	St. dev
Air Temperature (°C)	20.45	1.05	20.12	0.15	20.98	1.08
Radiant Temperature (°C)	20.09	2.16	16.21	1.48	22.20	1.46
Operative Temperature (°C)	20.27	1.54	18.17	0.77	21.59	1.22

Table 4
Range of clothing and metabolic activities available for selection in connection with entries in the comfort log book during the Ecommon measurement campaign, and the values used to calculate their thermal effects.

Clothing ensemble	Clo value	Metabolic activity	Met value
Very light (Sleeveless T-shirt, icon in Fig. 3)	0.5	Lying/sleeping	0.7
Light (Normal T-shirt, icon in Fig. 3)	0.55	Sitting relaxed	1
Normal (Knit sport shirt, icon in Fig. 3)	0.57	Light desk work	1.1
Rather warm (Long-sleeved shirt, icon in Fig. 3)	0.61	Walking	2
Warm (Long-sleeved shirt plus jacket, icon in Fig. 3)	0.91	Jogging	3.8
Very warm (Outdoor clothing, icon Fig. 3)	1.30	Running	4.2

double glazing with 6 mm glass thickness and 13 mm air filling with a U value of 2.7 W/m^2-K set in wooden window frames with a U value of 3.3 W/m^2-K.

The reason why the same double glazing was used for both A-rated and F-rated dwellings is that our inspection revealed that all F-rated dwellings had their outside glazing upgraded to double. Similarly, all the simulations made use of the same condensing boiler (variable flow, nominal thermal efficiency 0.89, maximum loop temperature 100 °C) and radiators with a constant water temperature of 80 °C, since nearly all the F-rated dwellings had new condensing boilers installed. In both cases the infiltration was set to 0.5 air changes per hour while the ac/h due to window natural ventilation was set to 3. The windows covered 30% of the wall and the lighting gains were set to 5W/m^2-per 100 lx.

Table 3 presents the averages of the hourly simulation results for March 2015, the month when tenants used the comfort dials to record comfort-related data. It will be seen that the difference between the radiant and air temperatures in A-rated dwellings with a boiler was only about 0.3 °C, appreciably less than the respective standard deviations. It was therefore decided that the radiant temperature for these dwellings could be set equal to the air temperature recorded by the sensors.

Table 3 further showed that the difference between the average radiant and air temperatures in F-rated dwellings with condensing boilers was about 4 °C. Finally, the simulated radiant temperature for A-rated dwellings with heat pumps and under floor heating was about 1.2 °C higher than the air temperature, due to the radiant heating effect of the hydronic floor heating system. The instantaneous value of T_{mrt} for these dwellings was therefore calculated as $T_{air} - 4$ °C and $T_{air} + 1.2$ °C respectively.

Thus, the EnergyPlus simulations made it possible to estimate the radiant temperature on the basis of the sensor readings of air temperature.

Furthermore, two values of the indoor air speed were chosen for the PMV calculations, a low one of 0.1 m/sec and a higher one of 0.3 m/sec [8,40].

Table 4 presents the values used to calculate the effects of clothing and metabolic activity, taken from the manual of the American Society of Heating, Refrigeration and Air Conditioning Engineers, (ASHRAE) [43]. Tenants were asked to note the clothes they were wearing and the metabolic activities they performed in the log book at regular intervals. All clothing ensembles include shoes, socks and briefs or panties. The insulating effect of chair (0.15 clo) was neglected.

3.2.2. PMV and reported thermal sensation as functions of the operative temperature

As mentioned above, tenants were asked to fill in the comfort log book at least 3 times a day to provide information about their clothing and the metabolic activities they performed. They also had to record how hot or cold they felt at the same time. All this information was time stamped and time coupled with the quantitative data collected by the sensors at 5-min intervals. This interval is assumed to be large enough to ensure that the comfort level is not related to prior comfort levels and conditions: an adaption time of approximately 4 min when people are submitted to temperature step changes was reported in the studies of Zhang et al. (2004) and Xiuyuan et al. (2014) [44,45], which implies that the comfort sensation may be assumed to have reached a steady state after 4 min under the same conditions.

The PMV was calculated for each room in the dwelling for all 5-min intervals for which a complete set of data was available. Further analysis of the data points (metabolic activity, clothing, actions, quantitative data etc.) was only performed if motion was detected in the room in question at any given time. This selection procedure resulted in a total of 194 data points for the 2-week period in which the tenants were provided with the comfort dial and the log book. The radiant temperature was assumed to be that derived from the EnergyPlus simulations (see Section 3.4.1), while, calculations were performed for two air speeds, 0.1 m/sec and 0.3 m/sec. The calculated PMV values and the reported thermal sensation were plotted against the operative temperatures, and regression analysis was used to determine the data trend line.

As most data were available for the living room, Figs. 5 and 6 show the scatter plots of the operative temperature versus the PMV (calculated for an air speed of 0.1 m/sec) and the reported thermal sensation for the living rooms of A/B-rated and F-rated. The samples used for determination of the PMV and for the reported thermal sensation are of different sizes because more records of quantitative parameters from the sensors were available than records of thermal sensation made with the aid of the comfort dial. Furthermore the number of cases for "All dwellings" is slightly different than the sum of cases for A/B and F dwellings; this is because in the regressions for the different rooms and energy labels, different outliers had to be excluded each time and because for the A/B dwellings kitchen and living room data were put together in the same regression.

Regression analysis showed significant correlation between the operative temperature and the PMV or reported thermal sensation (RTS) in both A/B-rated and F-rated dwellings. Significance levels of $p = 0.01$ and $p = 0.04$ respectively were found in A/B-rated dwellings, and $p = 0.02$ and $p = 0.001$ respectively in F-rated dwellings. It may be noted that the kitchen and living room were treated as a single room for the purposes of regression analysis on A/B-rated dwellings, since the kitchen and living room in these dwellings were in one continuous space with no doors or walls sep-

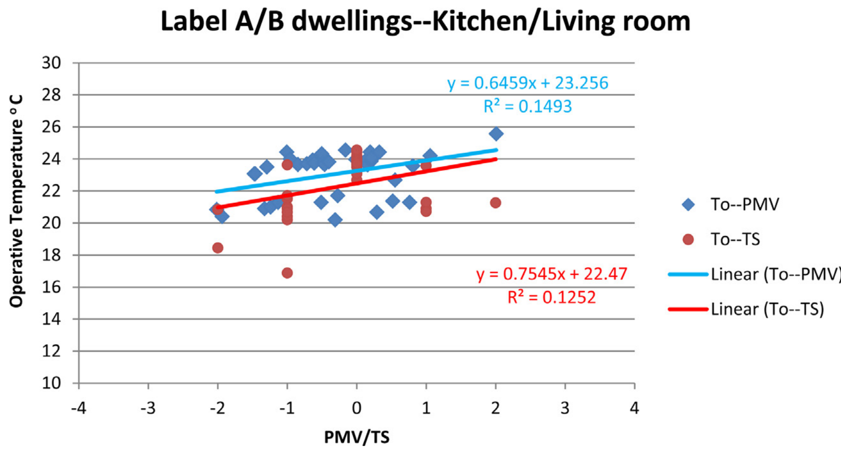

Fig. 5. Operative temperature versus PMV and RTS (reported thermal sensation) scatter plot and regression analysis trend line for the kitchen/living rooms of A/B dwellings at an air speed of 0.1 m/sec.

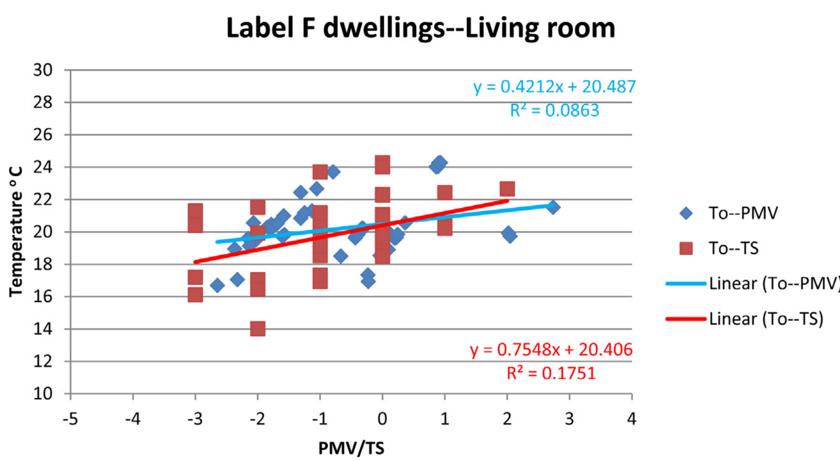

Fig. 6. Operative temperature versus PMV and RTS scatter plot and regression analysis trend line for the living rooms of F dwellings at an air speed of 0.1 m/sec.

arating them. The basic statistical data for all regression lines are given for each room in Tables 5 and 6.

As expected, both PMV and the reported thermal sensation increase when the operative temperature increases. The same trend was observed when the PMV calculation was carried out with an air speed of 0.3 m/sec, both for label A/B-rated and F-rated dwellings. It is noteworthy, however, that the full range of both PMV values and reported thermal sensations (from −4 to +3) is observed in A/B-rated dwellings at temperatures between 20 °C and 26 °C and in F-rated dwellings at temperatures between 14 °C and 24 °C. PMV and reported thermal sensation seem to be closer to each other in the F dwellings than in the A/B dwellings. The R^2 values are low (12.6% and 10.9%), meaning that the operative temperature explains only 12.6 and 10.9% of the variance in PMV or RTS.

In order to explore if there are significant differences between the neutral temperatures for the living room between the label A/B and F dwellings an analysis of variance was performed. The operative temperatures (per room type) of the A/B and F dwellings while the tenant's recorded neutral thermal sensation were gathered and an ANOVA was performed. The results were highly significant: for the living rooms p = 4.66E-10, F = 61.87 and F_{crit} = 4.05 while for the bedrooms p = 7.22E-06, F = 56.25 and F_{crit} = 4.74 and they are displayed in Fig. 7 and show that there are significant differences between the neutral temperatures of the living rooms of A.B and F rated dwellings.

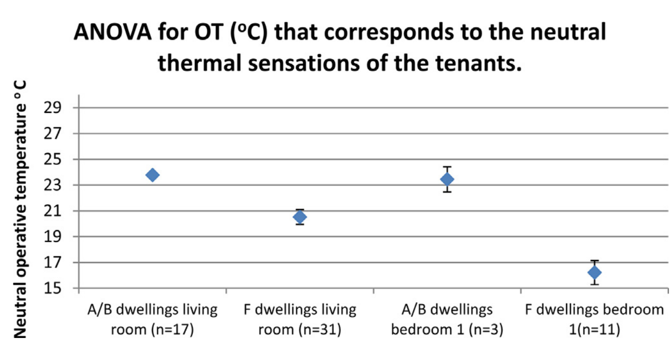

Fig. 7. ANOVA single factor for the operative temperatures that correspond to the neutral thermal sensations of the tenants.

3.2.3. *Neutral operative temperature (T_o) according to PMV and reported thermal sensation*

The neutral temperature, the temperature at which occupants feel neither hot nor cold, can be estimated by solving the regression equations of Section 3.2.2 for neutral thermal sensation. Solution of the equations in Figs. 5 and 6 for PMV = 0 or for RTS = 0 thus permits comparison of the neutral operative temperatures based on reported thermal sensation and on PMV index.

Only the significant regression lines (as indicated in Tables 5 and 6) were taken into account. Two of the regressions, for bedroom 2 in A/B dwellings were found not to be

Table 5
Basic statistical data for the regressions between operative temperature (OT) and PMV (significant results in bold), and calculated neutral operative temperature (see section 3.2.3).

Room	Neutral OT–all dwellings	p value	Number of cases	R^2	Neutral OT–A/B-rated dwellings	p value	Number of cases	R^2	Neutral OT—F-rated dwellings	p value	Number of cases	R^2
0.1 m/sec air speed												
Kitchen	19.47	0.010	34	0.189	23.08	0.025	37	0.149	18.78	0.04	23	0.19
Living Room	21.67	0.003	79	0.105					20.3	0.02	48	0.086
Bedroom 1	–	0.280	32	0.007	23.11	0.005	10	0.655	–	0.88	18	0.001
Bedroom 2	18.61	0.003	21	0.223	–	–	–	–	18.29	0.02	19	0.265
0.3 m/sec air speed												
Kitchen	19.61	0.008	32	0.211	23.4	0.038	37	0.117	18.99	0.01	21	0.302
Living Room	21.81	0.020	78	0.068					20.78	0.04	45	0.094
Bedroom 1	–	0.655	26	0.008	–	–	–	–	–	0.68	16	0.003
Bedroom 2	18.77	0.031	21	0.221	–	–	–	–	18.4	0.02	19	0.265

Table 6
Basic statistical data for the regression between operative temperature (OT) and reported thermal sensation (RTS) (significant results in bold), and calculated neutral operative temperature (see section 3.2.3).

Room	Neutral OT–all dwellings	p value	Number of cases	R^2	Neutral OT–A/B dwellings	p value	Number of cases	R^2	Neutral OT–F dwellings	p value	Number of cases	R^2
Kitchen	19.1	0.040	40	0.106	22.5	0.04	34	0.125	18.2	0.03	27	0.169
Living Room	23.2	0.001	89	0.121					20.4	0.001	57	0.175
Bedroom 1	18.1	0.006	39	0.188	22.5	0.04	10	0.429	16.3	0.01	25	0.136
Bedroom 2	–	0.578	24	0.014	–	0.30	3	0.797	–	0.92	21	0.000

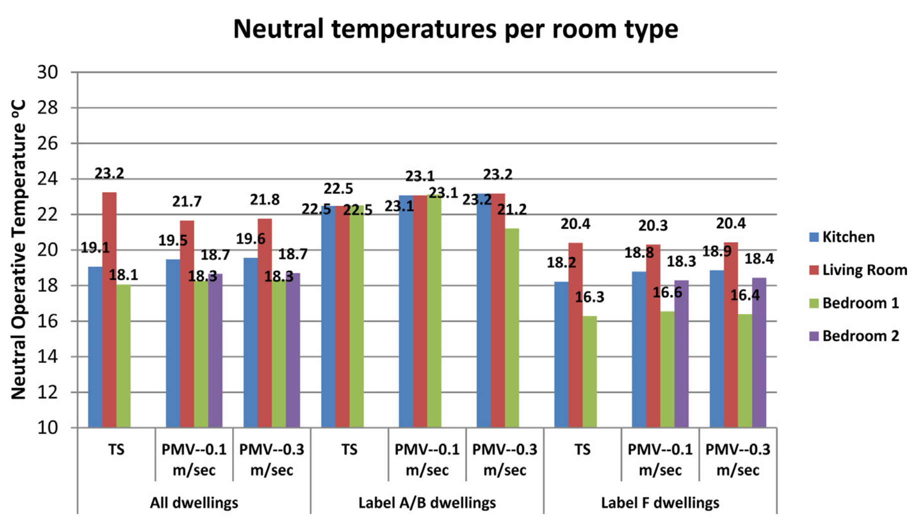

Fig. 8. Neutral operative temperatures calculated from RTS and PMV regressions for all room types and energy ratings.

significant, because of, the very small amount of data points (only three) involved in both case.

Fig. 8 shows the neutral operative temperatures for all room types and energy ratings derived from the calculated PMV and the thermal sensation reported by the tenants. Despite the uncertainties in the parameters needed to calculate the PMV (air speed and operative temperature) which were determined indirectly on the basis of assumptions and simulations, the neutral temperature (T_o) in both A/B and F dwellings is well predicted by the PMV model and closely matches the neutral temperatures obtained using the reported thermal sensation of tenants in different rooms of dwellings with different energy ratings. However, when all dwellings are considered together, the neutral temperature is less well predicted by the PMV model, especially for the living room. A/B and F dwellings give noticeably different results here. The average neutral temperature for the kitchen and bedroom 2 calculated for all dwellings is quite similar to that calculated for F dwellings only (the regressions for A/B dwellings were found not to be significant in this case, as explained above). On the other hand, there are marked differences between average neutral temperatures in the kitchen, living room and bedroom of A/B and F dwellings at both air speeds.

The regression predicts a neutral temperature for the living rooms of A/B dwellings that is about 3 °C higher than that for the living rooms of F dwellings. The difference is even bigger for bedroom 1, about 4 °C.

The lower neutral temperatures in F dwellings could indicate that air velocities are lower in these dwellings (this is possible, because the balanced and mechanical ventilation systems used in A/B dwellings are known to give higher air velocities). Other possible explanations are that people in F dwellings may wear warmer clothes or have higher metabolic activity. Finally, this difference could be attributed to different thermal expectations or age or gender differences between the tenants of A/B and F dwellings. The last-mentioned explanation seems unlikely, however, since the average age of the tenants of the A/B and F dwellings is 56 and 57

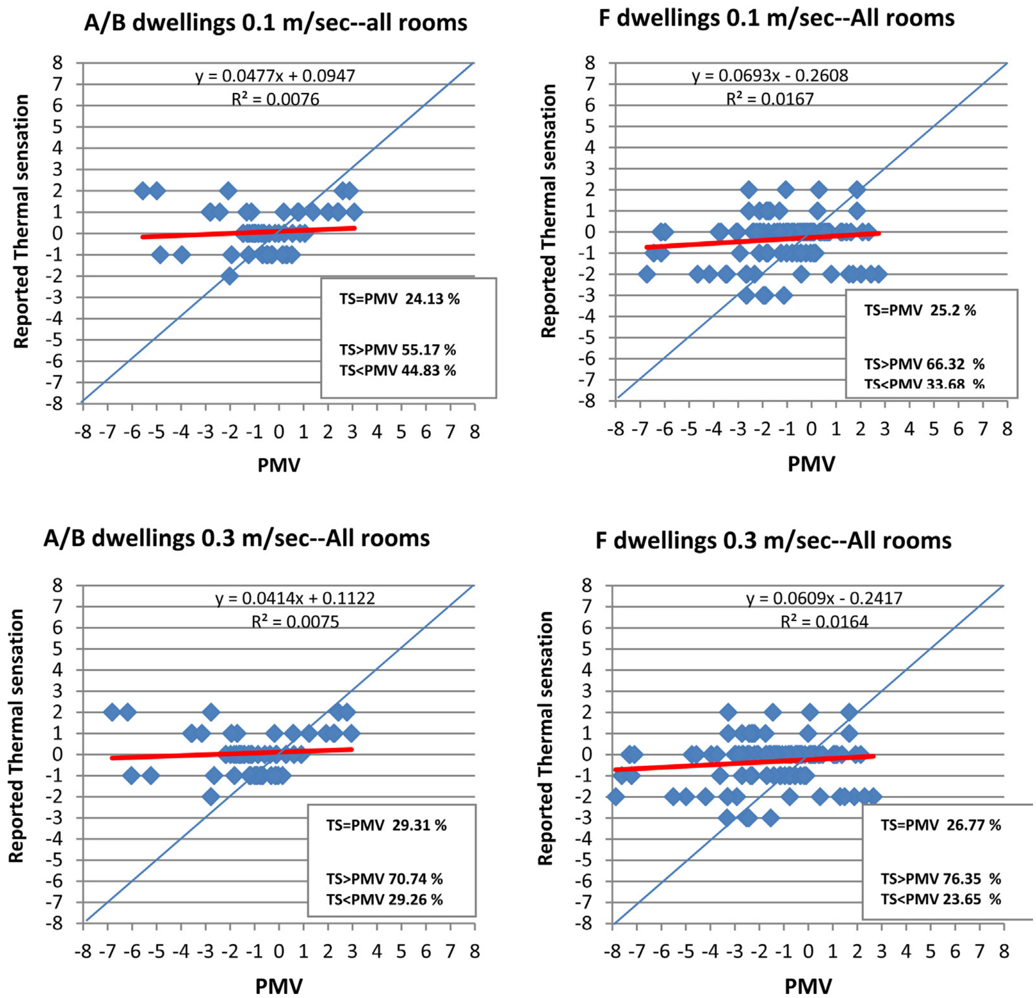

Fig. 9. Plots of reported thermal sensation against PMV for A/B and F dwellings, at air speeds of 0.1 m/sec and 0.3 m/sec (blue line TS = PMV, red line = regression line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

years respectively, and men and women were equally distributed between the two dwelling types.

3.3. Relationship between reported thermal sensation and PMV

To further validate the PMV index and its ability to predict tenants' real thermal sensation, all thermal sensation values collected during the campaign were compared with the calculated values of the PMV. The PMV values for all energy ratings, types of rooms and air speed scenarios were grouped in sub-sets around each integer value of PMV. For example, the sub-set around a PMV of −1 includes all PMV values between −1.5 and −0.5. The reason for this was that tenants were asked to record their thermal sensation on a scale of integer numbers from −3 to +3. The PMV calculations, on the other hand, lead to non-integer numbers. Furthermore, each PMV value between −0.5 and +0.5 is considered to be neutral. Values between −1.5 and −0.5 correspond to a rather cool thermal sensation, and so on. Fig. 9 show the plots of reported thermal sensation against PMV for all A/B and F dwellings, and for air speeds of 0.1 m/sec and 0.3 m/sec. The line on which RTS equals PMV separates the thermal sensation points that are warmer than the PMV points (above the line) from those that are cooler (below the line). The best fit lines are shown in red.

The prediction success of the PMV model never exceeds 30%. When the PMV fails to predict the thermal sensation correctly, it usually underestimates it especially at higher air speeds. These findings are in agreement with other studies from various countries [9,46,47] and are similar for each type of room (see Fig. 10 for a breakdown of the results by room). However, the PMV method never claimed to give accurate predictions on a case by case level, but only at a statistical level. The R^2 values given in Fig. 9 show that only less than 1.7% of the variations in the reported thermal sensation can be explained by the PMV; it follows, therefore, that the PMV cannot be considered as an accurate predictor of the actual thermal sensation and that other parameters must play a role.

However, the best fit lines in all four graphs cross the RTS = PMV line around the neutral level, which shows that neutrality is well predicted. Furthermore, the best fit line for A/B dwellings, is within the comfort band (corresponding to PMV values between −0.5 and +0.5) at all times, while it is somewhat lower in F dwellings. This shows either that the PMV does not perform well outside the climate chamber, or that people adapt to cooler conditions and take action to improve their thermal comfort. Another possibility that the clo and metabolic activity values used in our calculations were not accurate enough, due either to incorrect assumptions (wrong values attributed to qualitatively recorded clo values and activity levels from ASHRAE tables), or to inaccurate recording by the tenants. These possibilities are explored in Sections 3.6 and 3.7.

3.4. Clothing and reported thermal sensation

Fig. 11 shows the clothing types worn by tenants in A/B dwellings for each reported thermal sensation, while Fig. 12 gives the corresponding results for F dwellings. The different types of

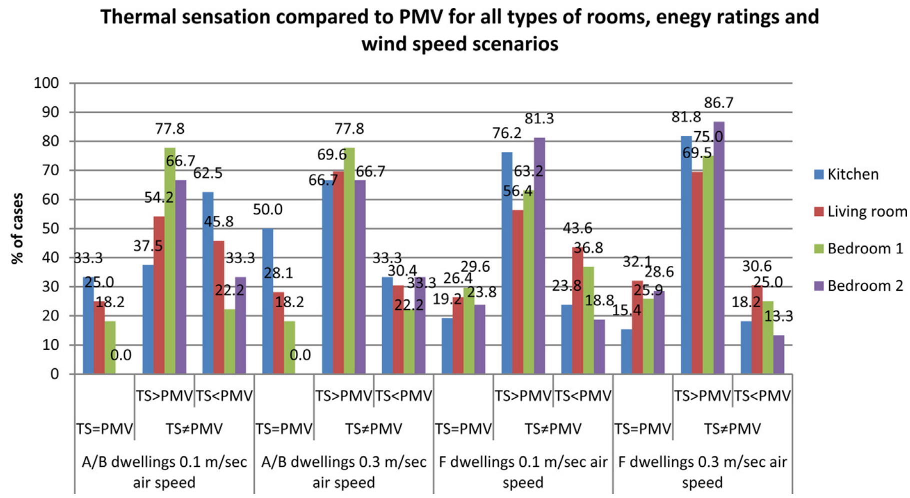

Fig. 10. Thermal sensation compared to PMV for all types of rooms, energy ratings and wind speed scenarios.

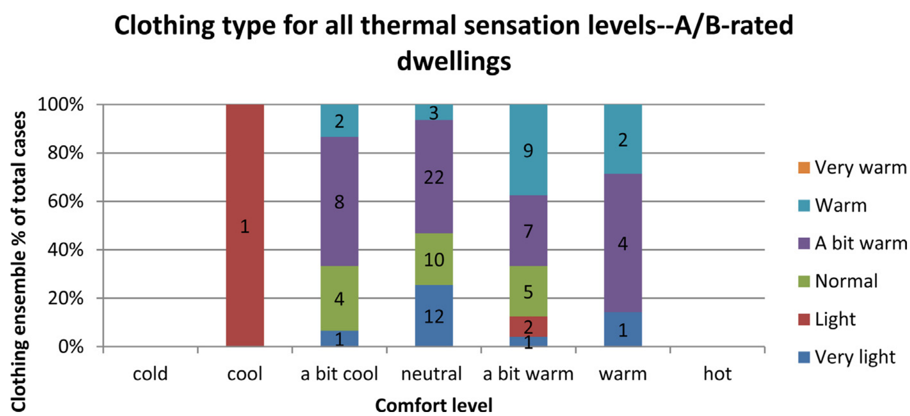

Fig. 11. Clothing types worn at all thermal sensation levels in A and B dwellings (n = 94).

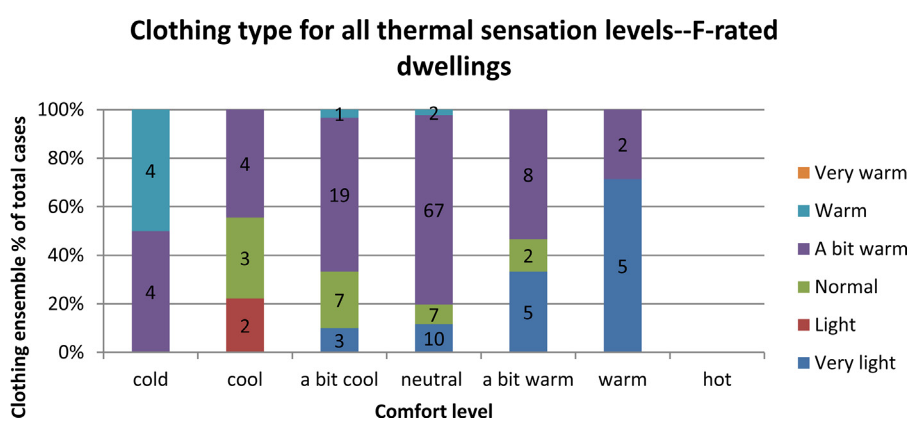

Fig. 12. Clothing types worn at all thermal sensation levels in F dwellings (n = 155).

clothing are colour-coded, while the numbers in each segment represent the number of times the type of clothing in questions is worn (total n = 94 for A/B dwellings and n = 155 for F dwellings).

These stacked graphs show first of all that no tenants in A/B dwellings reported feeling "cold" (in agreement with the thermal sensation graphs of Fig. 10), while 8 tenants in F dwellings made this observation. No tenants from either type of dwelling reported feeling "hot". The most preferred clothing ensemble for both types of dwellings is the warm ensemble, as defined in, Table 4. When tenants feel warmer, they replace the warm ensemble by lighter ensembles. The only instances when tenants report wearing the outdoor warm ensemble were in A/B dwellings, generally when they had just come in from outside and immediately filled in the comfort app/log book. They usually reported feeling rather warm or warm in these cases, probably because of the lower outdoor temperature.

The clo value corresponding to neutral thermal sensation can be determined by plotting the clo value against the reported thermal sensation and applying regression analysis to the resulting graph. Table 7 gives the basic statistical data for the regression calcula-

Table 7
Basic statistical data for the regressions between TS and clo values (significant results in bold), and calculated clovalues for neutral thermal sensation.

Room	Average clo value all dwellings	p value	Average clo value A/B-rated dwellings	p value	Average clo value F-rated dwellings	p value
Kitchen	0.58	0.050	–	0.119	0.59	0.019
Living Room	0.61	0.040	0.60	0.027	0.60	0.021
Bedroom 1	0.57	0.043	–	0.907	0.56	0.047
Bedroom 2	0.60	0.013	0.60	0.017	–	0.686

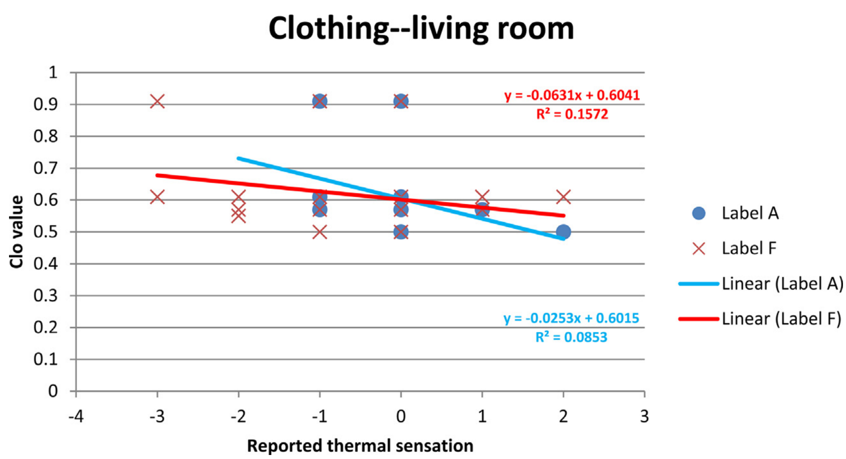

Fig. 13. Clo value versus thermal sensation scatter plot and regression analysis for the living rooms of A/B and F dwellings.

tion, and Fig. 13 shows the scatter plots and trend lines for the living rooms of A/B and F dwellings. Both regressions were significant with p = 0.02 and the total number of cases was 31 and 62 respectively. The regressions for bedroom 1 of A/B dwellings and bedroom 2 of F dwellings were found not to be significant.

Although the spread of the data is large, especially in A/B dwellings, the clo value was found to decrease with increasing thermal sensation in both cases. This confirms that clothing is an adaptive behavioural feature exercised in order to feel more comfortable. According to the regression analysis, 15.7% of the variance in clo relates to the thermal sensation. We see a fall in clo value from a little above 0.7 (warm ensemble) to somewhat below 0.5 (light ensemble) in A/B dwellings as the thermal sensation rises from −2 (cool) to +2 (warm. A similar effect is observed in F dwellings, though the drop in clo value on going from a thermal sensation of −2 (cool) to +2 (warm) is slightly smaller.

The data collected in this measurement campaign indicate that the tenants of both A/B and F dwellings seem to wear much the same type of clothing, which means that clothing does not seem to be the reason for the lower neutral temperatures found in F dwellings (see Section 3.2.3). The same trend was found for the other types of rooms (kitchen, bedroom 1 and 2) as the living room.

Table 7 displays the calculated clo values corresponding to neutral thermal sensation (zero on the horizontal axis of Fig. 13) for each type of room. Identical values were found for the living room (the room for which most data were recorded) in both A/B and F dwellings.

Fig. 14 shows the clo value plotted against the operative temperature for the living rooms of A/B and F dwellings. Both regressions were significant, with p = 0.0009 and p = 0.047 respectively. The trend line for the A/B dwellings is slightly ascending while for the F dwellings it is slightly descending. However, a closer look at the results for temperatures between 20 °C and 24 °C shows that the clo value for A/B dwellings starts around 0.5 (very light clothing) and ends around 0.6 (rather warm clothing). In F dwellings, the clo value is already 0.6 at 20 °C and ends up slightly below 0.6 at 24 °C. In other words, people in A/B dwellings actually tend to wear somewhat warmer clothing as the operative temperature rises from 20 °C to 24 °C, while people in F dwellings wear lighter clothing; the clo values converge at a temperature of 24°C. In both cases, the slope of the trend line is very shallow and the value of R^2 is small. At operative temperature below 23 °C, the occupants of F dwellings seem to be wearing warmer clothes than their counterparts in A/B dwellings. The rising trend for A/B dwellings is counter intuitive, but could be related to the higher air speed of the balanced ventilation system. Intuitively this could mean that when tenants turn up the ventilation in such cases to deal with temperature rises, the higher air speeds may cause then to wear warmer clothing.

The following procedure was used to gain an insight into the effect of the inaccuracy in clo values on the PMV: The reported RTS values and the calculated PMV values were collected and split into two groups, one for A/B dwellings and the other for F dwellings. The difference PMV-RTS, which is the most logical indicator of the quality of the PMV calculation, was then calculated and assigned to 5 groups by clo value. (Since no data were recorded for very warm clothing, the clo value 1.30 given in Table 4 was omitted). A one way analysis of variance was then used to calculate the 95% confidence interval of the difference PMV-RTS within the various clo categories. If the 95% confidence intervals of two categories overlap, this means that the quality of the prediction (PMV-RTS) cannot be assumed to differ significantly between the two clo categories. If the 95% confidence intervals do not overlap, this indicates significant differences in the quality of prediction; in other words, there are good reasons to suspect a bias relating to clo value in the behaviour of the PMV [15]. Figs. 15 and 16 display the mean difference PMV-RTS and the 95% confidence interval for each clo value category the closer to the zero line, the more accurate the prediction of the thermal sensation.

The confidence intervals of (PMV-TS) for A/B dwellings overlap in the categories clo = 0.5, 0.57 and 0.61, meaning that the quality of the TS prediction by the PMV is probably not different in these clo categories. The results for clo = 0.91 do however differ significantly from those for other categories.

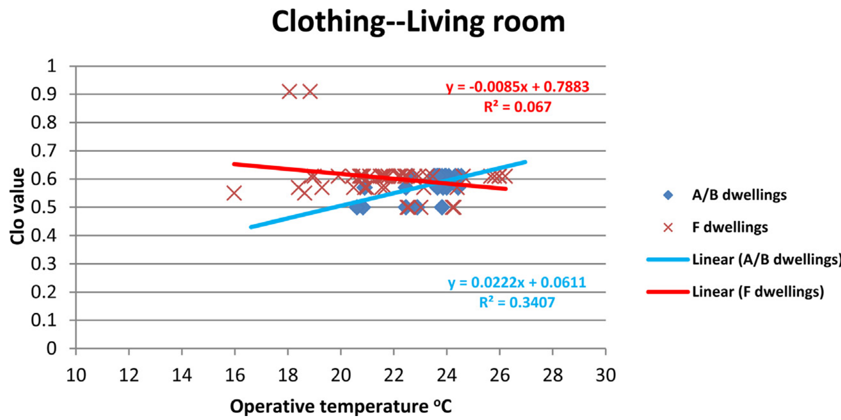

Fig. 14. Clo value plotted against operative temperature for the living rooms of A/B and F dwellings.

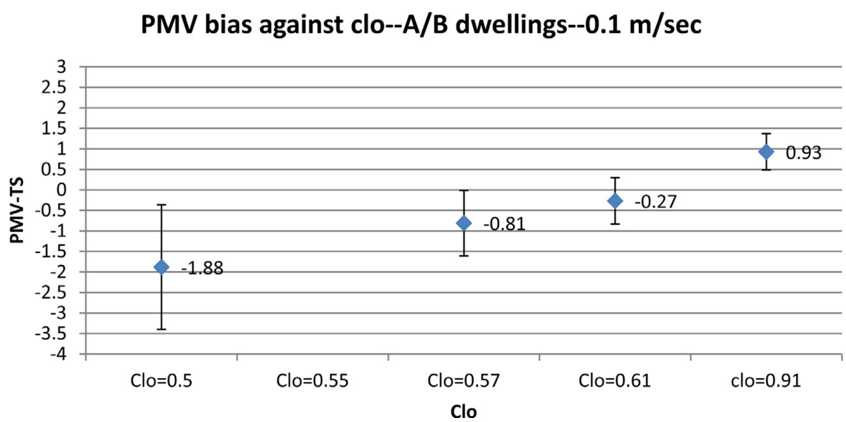

Fig. 15. Predictive bias (PMV-TS) of the clo value against the PMV for A/B dwellings.

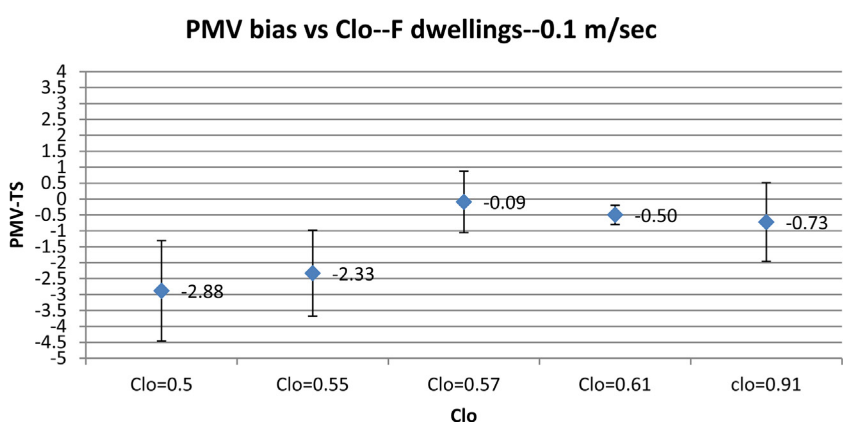

Fig. 16. Predictive bias (PMV-TS) of the clothing value against the PMV for F dwellings.

There seem to be two groups of clo categories for F dwellings with no difference in the quality of prediction. One is the group for clo = 0.5 and clo = 0.55 and the other for clo ≥ 0.57. The quality of the prediction is worse in the lower clo categories than in the higher. It might be though at first sight that this is because the low clo values were not accurately determined. Previous studies indicate that it is difficult to determine clo values precisely in situ [48,54].

However, closer examination of the above graphs does not reveal any evidence that the problem lies in the clo value. In order to reduce the possible bias at low clo values in Fig. 16, the average PMV-RTS value for the lower clo category would have to move vertically upwards towards the zero line. Since RTS has a fixed value reported by the tenants, this means that PMV (and hence the clo value) would have to increase: for example, the category clo = 0.5 might move up to 0.61 for A/B dwellings and 0.57 for F dwellings if the clo values were measured accurately. This is unlikely, however, since it would have the result of moving all clo categories closer together so that it would be impossible to distinguish between them.

Alternatively, the problem may not lie in the PMV calculation and the poor determination of the clo value but in the reported thermal sensation. We used the widely accepted 7-point scale, but this scale may be too detailed for the range of operative temperature found in the buildings that were monitored. People are accustomed to keeping their home as a comfort zone; in other words, they are used to a neutral operative temperature indoors but not to other comfort levels especially at the colder end of the scale. It may be impossible for people to make a real distinction between 'cold', 'cool', and 'slightly cold', or the results would have been different if they had been exposed to cold outdoor temperatures before using the comfort dial. In line with this, Fig. 9 shows that PMV ranges from −8 to +3 while RTS ranges only from −3 to +2.

The same technique (Anova: single factor) was used to determine if there are any significant differences between the clo value between A/B and F rated dwellings. The Anova was performed for the clothing level that corresponded to the neutral votes of thermal sensation of the tenants. The result was highly insignificant with $p = 0.993$ and $F = 6.23E{-}05$ and $F_{crit} = 3.94$ which means that we cannot reject the null hypothesis that the clo values in the living room for neutral thermal sensation between A/B and F rated dwellings are equal (Fig. 17).

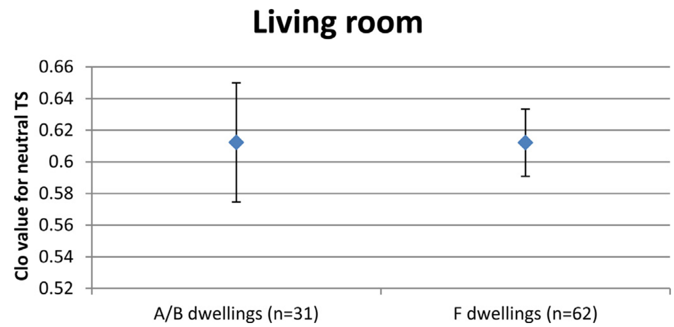

Fig. 17. ANOVA single factor for the clo values in the living rooms for neutral thermal sensations of the tenants.

3.5. *Metabolic activity and thermal sensation*

Fig. 18 displays the metabolic activity for each thermal sensation level recorded by tenants of A/B dwellings with the aid of the comfort dial and the comfort log book, while Fig. 19 gives the corresponding results for F dwellings. The metabolic activity shown here is the average activity level as defined in Table 4 reported for the half hour before use of the comfort dial. The activity levels are colour-coded, while the superimposed numbers represent the frequency of reporting each type of metabolic activity (in total n = 147 for A/B dwellings and n = 206 for F dwellings).

The metabolic activity most often reported in both A/B and F dwellings was "relaxed sitting". This was followed by "light desk work" and then "walking" in A/B dwellings. "Walking" was recorded than "light desk work" in F dwellings.

"Lying/sleeping" was the fourth metabolic activity level for both types of dwellings. The metabolic activity of the tenants can be calculated as a function of the reported thermal sensation, in much the same way as was done for the clo value above. Fig. 20 shows the scatter plots and trend lines for the metabolic activity value plotted against reported thermal sensations for the living rooms of the A/B and F dwellings. Both regressions were significant with $p = 0.008$ and $p = 0.04$ respectively, and the total number of cases was 56 and 82 respectively. The RTS explains 12% of the variance of metabolic activity in A/B dwellings, but only 5% in F dwellings. The statistical significance values for each regression are given in Table 8.

The regression for bedroom 2 was only significant in F dwellings. The regressions for all other types of room were significant at $p \leq 0.01$. The metabolic activity in the kitchen of A/B dwellings is

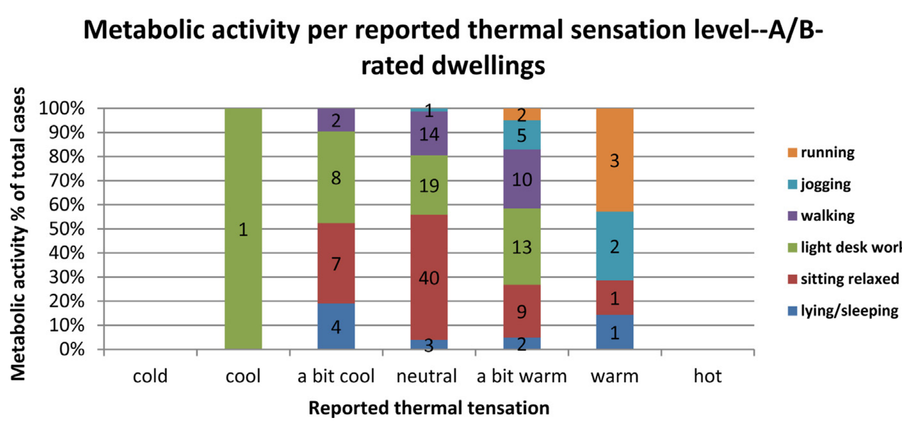

Fig. 18. Metabolic activity reported at various comfort levels in A/B dwellings (n = 147).

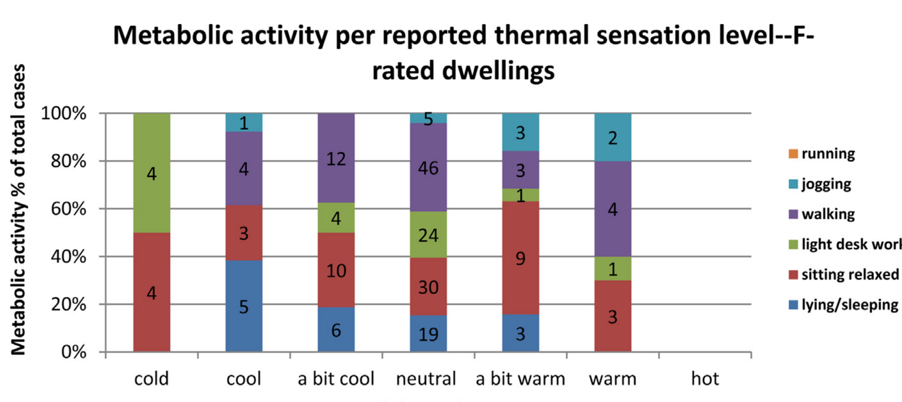

Fig. 19. Metabolic activity reported at various comfort levels in F dwellings (n = 206).

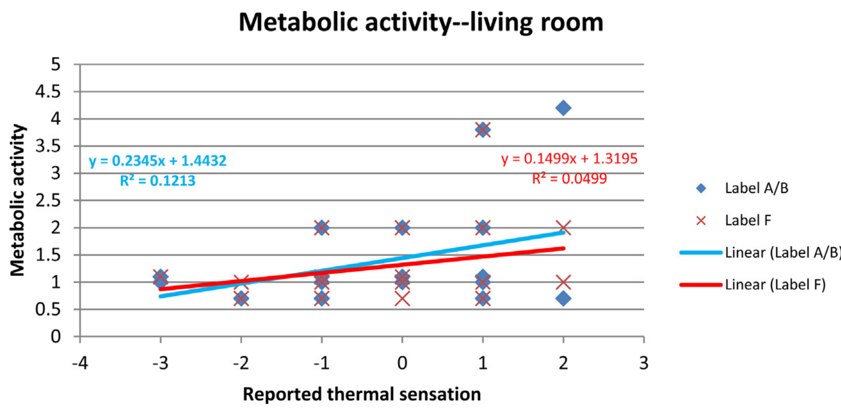

Fig. 20. Metabolic activity versus reported thermal sensation scatter plot and regression analysis trend line for the living rooms of A/B and F dwellings.

Table 8
Basic statistical data for the regressions between TS and met values (significant results in bold), and calculated met values for neutral thermal sensation.

Room	Average met value all dwellings	p value	Average met value A/B-rated dwellings	p value	Average met value F-rated dwellings	p value
Kitchen	1.53	0.002	1.88	0.01	1.38	0.01
Living Room	1.41	0.039	1.44	0.008	1.32	0.043
Bedroom 1	1.46	0.048	1.28	0.050	1.90	0.040
Bedroom 2		0.286		0.069	1.45	0.048

appreciably higher than in the living room and bedroom 1, which is to be expected since the kitchen is where dinner is prepared and where people usually have breakfast in the morning before they leave home. Both those common activities for kitchens are associated with higher metabolic activity levels. Furthermore, A/B dwellings all had their kitchens and living rooms combined in a single large space. This is likely to make for more frequent movement between the two halves of the space for example; breakfast may be prepared in the kitchen and eaten at the table in the adjacent living area, unlike the case with separate kitchens containing a breakfast Table Similar considerations apply to the metabolic activity levels in the kitchens and living rooms of the F dwellings. The metabolic activity is higher in the kitchen than in the living room, but a lot less than in A/B dwellings.

All the F dwellings in this study had separate kitchens, and the confined space could lead to lower metabolic activity. The highest metabolic activity for neutral thermal sensation was observed in the bedroom 1 of F dwellings. The data points for A/B dwellings in this case were for 3 dwellings; two of those belonged to elderly people who used the bedroom only for sleeping while the third house belonged to a young couple who also used the bedroom only for sleeping since they had a second bedroom that they used as a study. The F dwellings on the other hand provided enough data points for accurate calculation of the regressions; these households all had young family members (from small children up to teenagers) who used the rooms actively during the daytime, not just for sleeping.

Apart from the special cases analysed in the previous paragraph, similar levels of metabolic activity were found in the living room in both types of dwellings; this type of room was used in the same way in both A/B and F dwellings, and also provided most of the data points for the regression analysis. This is also evident from Fig. 20, where the reported thermal sensation ranges from −3 to +2 in both cases and the metabolic activity usually varies from 0.75 to 1.5.

Fig. 21 displays the metabolic activity as a function of the operative temperature for the living rooms of A/B and F dwellings. As in the case of the clo value discussed in Section 3.6, the trend line is rising for A/B dwellings and falling for F dwellings, converging to the same levels of metabolic activity as the temperature rises from 18 °C to 24 °C. Furthermore, the slope of the trend lines is very shallow and the R^2 values are even lower than for the clo trend lines. The increase in the metabolic activity of the tenants in A/B dwellings as the operative temperature rises may be due to the design of these dwellings. Most of them have the kitchens and living rooms combined in one continuous space. Cooking causes the temperature of the space and the level of metabolic activity to rise, since it requires more activity than typically found in the living room, which is normally associated with more relaxed activities such as watching TV, reading a book or listening to music. People who were recording their metabolic activity in the living room were more likely to be in a relaxed state, sitting on a couch or in a chair, while people recording their metabolic activity in the kitchen would be more active (cooking, using the dishwasher etc.).

As in the previous section, we explored the effect that inaccuracy in determination of the values of metabolic activity might have on the calculated PMV. The difference PMV-RTS was once again determined, grouped by the energy rating of the dwellings and categorised by metabolic activity value into 7 groups as defined in Table 4. One way analysis of variance was again used to test whether the different mean discrepancies for the various groups could be attributed to chance. Figs. 22 and 23 display the mean discrepancy (predictive bias) plotted against the met value (met value of 1.5 appears in the graph despite its absence in Table 4; that is because tenants many times recorded more than one type of metabolic activity for the past half hour and so an average met value of those activities was used), together with the 95% confidence interval for each category. If the PMV were free from bias relating to the met value, the confidence intervals of all categories would overlap.

It was found that the discrepancies were not attributable to chance and were highly significant at $p < 0.001$. A/B dwellings showed substantial bias for met = 0.7 (lying/sitting), met = 1 (relaxed sitting) and met = 4.2 (running), though the bias is much smaller in the last two categories. The PMV is however free from serious bias for met values of 1.1 (light desk work), 1.5 and 2 (walking).

The discrepancies in F dwellings were also not attributable to chance and were highly significant at $p < 0.001$. The bias in these dwellings was more substantial than in A/B dwellings. All

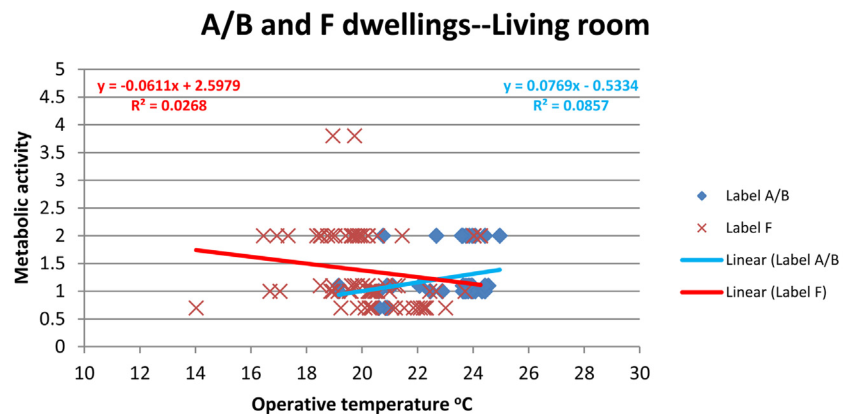

Fig. 21. Metabolic activity (met value) plotted against operative temperature for the living rooms of A/B and F dwellings.

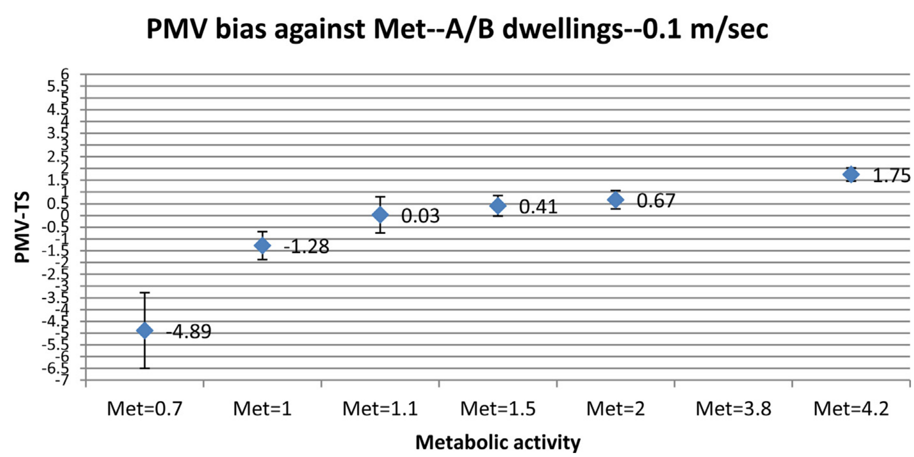

Fig. 22. Predictive bias of the met value against the PMV for A/B dwellings.

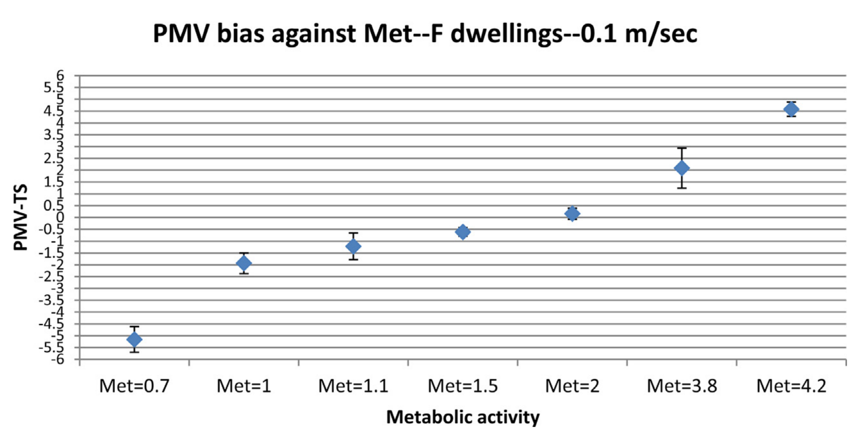

Fig. 23. Predictive bias of the met value against the PMV for F dwellings.

categories of metabolic activity showed marked bias, apart from met = 1.5 and met = 2.

Anova: single factor was used to determine if there are any significant differences between the metabolic activity value between A/B and F rated dwellings. The Anova was performed for the metabolic activity level for the living rooms that corresponded to the neutral votes of thermal sensation of the tenants for both A.B and F dwellings. The result was highly insignificant with $p = 0.488$ and $F = 0.483$ and $F_{crit} = 3.91$ which means that we cannot reject the null hypothesis that the metabolic activity values in the living room for neutral thermal sensation between A/B and F rated dwellings are equal (Fig. 24).

4. Discussion

Despite limitations on materials and equipment, the Ecommon measurement campaign successfully collected adequate quantitative and qualitative data on comfort and occupant behaviour in a relatively easy and unobtrusive way in the residential environment. The tenants were very interested in the comfort dial, and used it

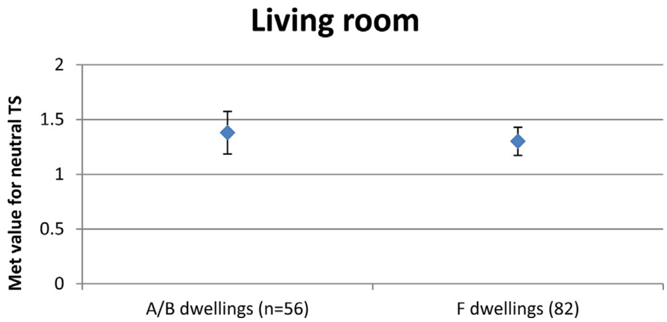

Fig. 24. ANOVA single factor for the metabolic activity values in the living rooms for neutral thermal sensations of the tenants.

much more often than the requested minimum three times a day. The high frequency (every 5 min) of the sensor measurements of quantitative parameters, the unobtrusive wireless method used to collect thermal sensation data and the remote management of the entire sensor system ensured minimal data loss over the whole six months of the measurement campaign.

Furthermore, the reported thermal sensation data used for the comfort calculations were collected electronically for the first time with a time stamp linked to the quantitative sensors; this approach compares favourably with the questionnaire tenants had to fill in by hand in previous monitoring campaigns. The precision of data collection is much higher in this approach: tenants no longer had to write down the exact time they filled in the comfort log book, and the 5-min interval used for quantitative data collection ensured that the quantitative data entered in the comfort log book could be easily and precisely linked with the qualitative data. At the same time, the motion sensors helped to identify where the tenants were when they were filling in the comfort log book, thus allowing the appropriate room type to be linked with the corresponding data entry.

One of the issues that arose during the analysis of the campaign data was the possible effect of direct solar radiation on tenants' thermal preferences. EnergyPlus accounts fully for the effects of direct and diffused solar radiation in the interior of a building when simulating air, radiant and operative temperatures [49]. However, these simulations were based on a reference building (described in Section 3.2.1) which may differ in architecture (placement, size and orientation of the windows) from the real buildings dealt with in the campaign. Furthermore, while the average hourly radiant temperature in each flat was approximated in detail in EnergyPlus simulations, we have no way of knowing whether tenants were sitting in front of a window while they recorded their thermal sensation. The Netherlands may not be the sunniest country in the world and monitoring did take place during the winter, but direct solar radiation could still have played a role in determining tenants' thermal sensation. Besides, the radiant temperature at a given time may differ from the average hourly value obtained from EnergyPlus simulations. However, Table 3 shows that the highest standard deviation found for the air temperature was 1.08 °C while that for the radiant temperature was 2.16 °C. In order to estimate the effect of temperature variations, the PMV equation was subjected to sensitivity analysis with reference values of 20 °C for air and radiant temperature. The maximum effect on PMV produced when the air and radiant temperatures were varied in 0.5 °C steps from 18 °C to 22 °C (in order to cover the entire possible range of twice the standard deviation) was 0.7. It follows that possible deviations of the radiant temperature from the average at a given time shouldn't have a dramatic effect on the PMV.

Another point of discussion is related to the 7-point scale used for the PMV. This scale was developed in climate chamber experiments where subjects were exposed to a variety of climatic conditions. It was validated by determining the regression between the calculated PMV values and people's reported thermal sensations. There is however no guarantee that a thermal comfort level of −3 reported by a Dutch subject corresponds to −3 on the PMV scale. Greater robustness could be achieved by collecting large scale data sets for a wide variety of subjects and areas in the Netherlands and using these data to define the PMV scale for the Netherlands together with the thermal sensation scale for Dutch subjects. It is claimed that the PMV model can be applied irrespective of climate and social convention, way of life and kind of clothing, though some distinction needs to be made between winter and summer [13]. In contrast with this, previous thermal comfort studies found that subjects' thermal sensations varied from individual to individual and were dependent on race, climate, habits and customs [50,51].

Furthermore, the thermal sensations recorded by the tenants in the present study ranged mainly between −2 and +2. Comfort levels of −3 (cold) were recorded very infrequently (only 9 cases out of 192, all in F dwellings), while comfort levels of +3 (hot) were never recorded. Most reported comfort levels were between −1 and +1. As discussed in section 3.6, the PMV shows little bias for clo and met values that are close to those for neutral comfort levels. These facts reflect the possible effect of psychological adaptation on the tenants in the present study. Thermal adaptation can cause people to perceive, and react to, sensory information differently on the basis of past experience and expectations [52]. Personal comfort set points are far from thermostatic, and expectations may be relaxed in a way that resembles the habituation found in psychophysics [53,54] where repeated exposure to a constant stimulus leads to a diminishing evoked response [52]. The tenants who participated in the Ecommon campaign might not even have a clear feeling of what a thermal sensation of −3 means. They are always in their own personal space, which they always try to keep as comfortable as possible, and this feeling of comfort is what they know and what they associate with their home. It follows that their response are more accurate around the neutral comfort level and less accurate at more extreme comfort levels approaching −3 or +3, which correspond to thermal sensations to which they are much less accustomed in their own homes. Similarly, our analysis of the bias in PMV due clo and met values showed that bias was low around the neutral point, but could be substantial at lower and higher clo and met vales.

5. Conclusions and proposals for further research

The PMV model predicts neutral temperatures for the various room types well, in line with those derived from the thermal sensations reported by tenants.

The thermal sensation reported by tenants ranged from −3 (cold) to +2 (warm), while the PMV calculations showed thermal comfort levels ranging from −8 to +3. This means that people feel more comfortable than indicated by the predictions. The PMV model underestimates the thermal comfort of the tenants in residential dwellings. Furthermore, people seem to have better perception of thermal comfort around neutrality. This could indicate a certain level of psychological adaptation and expectation since each person's home is associated with comfort, relaxation and rest, in contrast to office buildings for example that are associated with work and higher levels of stress, effort and fatigue.

Tenants of A/B and F dwellings seem to show no differences in clothing and metabolic activity patterns, even though, F-rated dwellings had lower neutral temperatures. Age and gender also seem to have no effect on neutral temperature levels, which leaves the indoor air speeds and psychological adaptation and expectations as possible explanatory factors for the difference in neutral temperatures between A/B and F dwellings.

Further research could include up scaling of the Ecommon project, with improvement in the equipment and data collection. The high level of automation of the quantitative and qualitative data collection tools has already made the data collected more reliable, robust and time accurate, though in the future it would be better to have everything on an app and not partly on paper. Moreover, data collection should be expanded to incorporate information on the thermal expectations of tenants during the measurement campaign.

Improved equipment could ensure the collection of more solid data (in particular clo and met values), which could further help to eliminate measurement bias and lead to more accurate calculation of PMV.

Further research on the actual energy consumption of the dwellings is also needed in order to discover the effect of the reported thermal sensation on the energy consumption in the dwellings. For example, do tenants in F dwellings turn up the thermostat before reporting "good" thermal sensation?

Finally, extended data collection from a variety of Dutch subjects with different demographic characteristics such as sex, age, income and ethnicity, different housing typologies (standalone houses, row houses, apartments) and different geographical locations in the Netherlands is needed as a basis for development of a national thermal sensation index leading to a better prediction model that could supplement or replace PMV.

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In-situ and real time measurements of thermal comfort and its determinants in thirty residential dwellings in the Netherlands

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