THERMAL COMFORT IN RESIDENTIAL BUILDINGS: SENSITIVITY TO BUILDING PARAMETERS AND OCCUPANCY.

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ABSTRACT

Dynamic simulation is widely used for assessing thermal comfort in dwellings. Simulation tools, though, have shortcomings due to false assumptions made during the design phase of buildings, limited information on the building's envelope and installations and misunderstandings over the role of the occupant's behaviour. This paper presents the results of a Monte Carlo sensitivity analysis on the factors that affect the PMV comfort index. The reference building was simulated as both Class-A and F according to the Dutch determination method for the energy performance of residential functions and buildings (ISSO 82.3, 2009), with three different heating systems. The study focuses on the heating period which is of main interest concerning residential energy use in the Netherlands. For the PMV the most influential parameters were found to be metabolic activity and clothing, while the thermostat had secondary impact.

INTRODUCTION

The international standard ISO 7730 is a commonly used method for predicting the thermal sensation (PMV) and thermal dissatisfaction (PPD) of people exposed to moderate thermal environments. The PMV model predicts the thermal sensation as a function of activity, clothing and the four classical thermal environmental parameters: air temperature, mean radiant temperature, air velocity and humidity. Activity means the intensity of the physical activity of a person and the clothing is the total thermal resistance from the skin to the outer surface of the clothed body. Many widely used building simulation programs such as ESP-r, TRNSYS and Energy+ use ISO 7730 (ISO 2005) to calculate comfort levels inside a building. There is a significant gap in the literature when it comes to sensitivity analysis of physical and occupancy parameters in the residential sector of areas with a cold climate such as North Western Europe. No studies have evaluated these parameters with a complete sensitivity analysis method which reflects the occupant's behaviour such as ventilation and thermostat settings as well as physical parameters for the PMV comfort index.

This paper presents the results of a sensitivity analysis study that was performed for a single residential housing unit in the Netherlands. The simulations were carried out with the following variations: multi-zone and single-zone versions of the building; two different grades of insulation; three different types of HVAC services; the occupant's behavioural characteristics (thermostat level, ventilation behaviour, metabolic rate, clothing and presence). The sensitivity of the above-mentioned parameters was gauged for the hourly PMV comfort index and the results focus on the heating period.

METHODOLOGY

The goal of the study is to make recommendations for:

1) Which parameters have the most critical influence on the PMV comfort index?

2) Is the sensitivity different for dwellings with different physical qualities and different energy classes?

Sensitivity Analysis

The goal of the sensitivity analysis is to study the response of the model simulated by EnergyPlus with respect to the variations of specific design parameters. It can be used to assess which set of parameters has the greatest influence on the building performance variance, and at what percentage.

Sensitivity analyses can be grouped into three classes: screening methods, local sensitivity methods and global sensitivity methods. Screening methods are used for complex, computationally intensive situations with a large number of parameters, such as in sustainable building design. This method can identify and rank in qualitative terms the design parameters that are responsible for the majority of the output variability e.g. energy performance. These methods are called OAT methods (one-parameter-at-a-time) and the impact of changing the values of each parameter is evaluated in turn (partial analysis). A performance estimation using standard values is used as control. For each design parameter, two extreme values are selected on either side of the standard value. The differences between the results obtained by using the standard value and the extreme values are compared in order to evaluate which parameters would affect the energy performance of the building the most (Heiselberg, Brohus et al. 2009).

Local sensitivity analysis methods are also based on an OAT approach, but the evaluation of output variability is based on the variation of one design parameter between a certain range (and not only on extreme values) while the rest are maintained at a constant level. This method is a useful way of comparing the relative importance of various design parameters. The input-output relationship is assumed to be linear and the correlation between design parameters is not taken into account (Heiselberg, Brohus et al. 2009).

In global sensitivity methods, output variability due to one design parameter is evaluated by varying all the other parameters at the same time, while also taking account of the effect of range and shape of their probability density function. Randomly selected design parameter values and their calculated outputs are the means for determining the design parameters' sensitivity. The influence of other design parameters is very important in a sensitivity analysis because the overall performance of the building is determined by all these parameters and how they interact. Distribution effects are relevant because parameter sensitivity depends not only on the range and distribution of the individual parameter but also on other parameters that building performance is sensitive to. Design parameter sensitivity often depends on the interaction and influence of all the design parameters (Heiselberg, Brohus et al. 2009). The method used in the present study is the Monte Carlo analysis; this is a variance-based method and a form of global sensitivity analysis.

Monte Carlo Analysis

There are several mathematical methods for sensitivity analysis that can be found in the literature (Morris 1991, Lomas and Eppel 1992, Hamby 1994, Lam and Hui 1996, Saltelli, Tarantola et al. 2000, Hopfe 2009). The Monte Carlo analysis (MCA) method was chosen for the purposes of this study. Under MCA, all the uncertain parameters are assigned a definite probability distribution. For each simulation a value is selected at random for each input based on the probability of its occurrence. For inputs that are distributed with a Gaussian (normal) distribution, a value close to the modal value is more likely to be selected than an extreme value. The predictions that are produced by this unique set of parameter values are saved and the process is repeated many times, using a different and unique set of values for each parameter every time. When the process reaches an end, all the values for the predicted parameter (e.g. energy performance or PMV) that have been calculated from each simulation are recorded. At the same time, all the values for each of the design parameters for every simulation are also recorded (Lomas and Eppel 1992).

The accuracy of the method is based on the number of simulations that have taken place and not on the number of the uncertain input parameters. This means that given enough computational power, the effect of a large number of parameters could be assessed simultaneously with MCA. Only marginal improvements can be obtained after 60-80 simulations (Lomas and Eppel 1992). For our study, 200 simulations were used.

Since all the inputs are perturbed simultaneously, the method takes full account of any interactions between the inputs and, in particular, any synergistic effects. Moreover any non-linearity effects in the input/output relationships are fully accounted for (Lomas and Eppel 1992).

Sampling

A study by McDonald (Macdonald 2009) which compared sampling techniques for Monte Carlo analysis suggests that the best combination for MCA in typical building simulation applications is simple random sampling with 100 runs. For the present study, simple random sampling was therefore chosen with, for the sake of accuracy, 200 simulation runs.

Statistics

The post-processing took place in SPSS after each of the 200 simulation sets was finished and the results were recorded. The parameters that were used in the simulations have different units and relative magnitudes and for that reason a standardisation process was needed. For this study, the standardisation of the regression analysis took place in the form of transformation by ranks. Moreover the ranking of the raw data allowed the exploration of non-linear relationships between predictors and dependent variables. The regression analysis was then performed on the rank transformed data rather than the raw original ones. The standardised rank regression coefficient (SRRC) was used for the sensitivity analysis in this study. The SRCC values that were obtained are the sensitivity indicator for each parameter and describe the effect that this parameter has on the dependent variables (PMV). Only statistically significant parameters are presented in the results, with the significance level being 0.05. The higher the value of the SRRC, the more sensitive the parameter is and thus the more impact it has on the PMV. A positive SRCC means that an increase in the parameter leads to an increase in the value of the dependent variables; a negative SRCC means that an increase in the parameter leads to a decrease.

Tools

The initial modelling of the reference building was carried out using the simulation software DesignBuilder, which is a user interface for the Energy+ dynamic thermal simulation engine. The building file was exported in the form of an Energy+ file and uploaded to the main Energy+ editor for the simulation of the installations. The parametric simulations for the Monte Carlo analysis took place with an Energy+ add-on that was created for that purpose, the jEPlus (Zhang 2009, Zhang and Korolija 2010)

Reference Building

The reference building for the simulations was based on a real building, the Concept House built by TU Delft in Rotterdam. Two variations of the concept house were initially chosen as reference cases, based on their energy class which represents the amount of energy consumed per m^2 in kWh/year. The first was a Class-A building (very well insulated) and a Class-F building (poorly insulated), according to the Dutch building code ISSO 82.3. The dwelling consists of a living room with kitchen, two bedrooms, a bathroom, a storage room and a hallway. The reference building was modelled in two ways, as a single zone and as a multi-zone (three zones: kitchen/living room, bedroom 1 and bedroom 2 were the heated areas in this case). The floor area of the house is $86.2m^2$ and its height is 2.7m. The shading system of both dwellings consists of blinds with high reflectivity slats, positioned outside the window system. The blinds are open while the occupants are awake and closed when they are asleep or absent. The blinds therefore also act as window insulation. Furthermore, modelling was carried out for three different heating systems: ideal loads, high efficiency boiler with radiators and floor heating coupled with a heat pump.

Independent variables and predictor parameters

The output (dependent) variable selected for this study was the hourly PMV. The predictor variables used were: thermostat setting, metabolic activity, clothing and ventilation (air flow rate), while the air speed in the rooms was held constant (0.14 m/sec). The reason for the choice of these variables was that they represent the factors that affect the thermal comfort index (PMV) most closely. In reality, air temperature and radiant temperature relate to the thermostat setting, while humidity and air speed relate to the ventilation of the building. However, in Energy+ the local air speed of the rooms that affects comfort is not dynamically calculated from infiltration and ventilation; instead it can only be defined using a schedule, which means that detailed and reliable comfort calculations can only take place if an extensive file with air speed patterns (produced from empirical data or from CFD calculation) is available.

Each simulation was performed for a whole day in the fall, the winter, the spring and summer. Figure 1 shows a complete picture of the simulations and combinations of type of buildings, class of buildings and parameters.

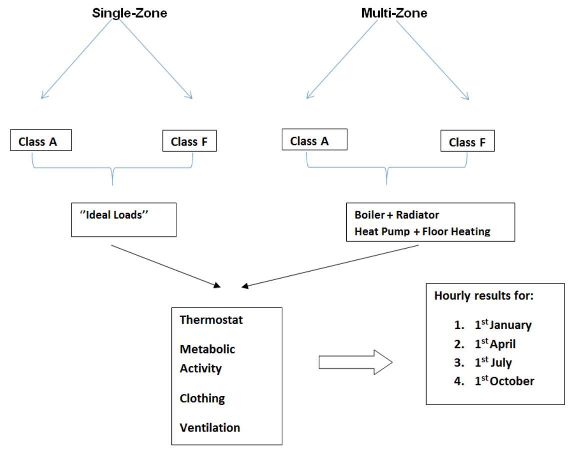

Figure 1: Schematic representation of simulations and combinations between buildings types and parameters

Each of the parameters was assigned a base case value and a normal probability distribution on the basis of which the parameter value changed randomly. Table 1 shows the base case values (mean) of the parameters, the standard deviation (10% around the mean) and the number of samples.

Table 1: Mean, std. deviation and number of samples for the predictor parameters for hourly PMV

	Class A			**Class F**		
Parameters	**mean**	**std. deviation**	**no. samples**	**mean**	**std. deviation**	**no. samples**
Clothing (clo)	1	0.1	10	1	0.1	10
Metabolism (met)	100	10	10	100	10	10
Thermostat [^oC]	20	1	10	20	1	10
Ventilation-Bedroom [m^3/s]	0.015	0.0015	10	0.015	0.0015	10
Ventilation-Living room [m^3/s]	0.04	0.004	10	0.04	0.004	10

Heating Systems

Both Class A and F dwellings were simulated with three different heating systems. The first heating system was based on the model of ''Ideal Loads Air System''. This model can be thought of as an ideal unit that mixes the air at the zone exhaust condition with the specified amount of outdoor air and then adds or removes heat and moisture at 100% efficiency to produce a supply air stream with the properties specified .

The second heating system is based on the transient model ''Low Temperature Radiant: Constant Flow'' of Energy+. This low temperature radiant system (hydronic) is a component of zone equipment that is intended to model any radiant system where water is used to supply/remove energy to/from a building surface (wall, ceiling, or floor). The low temperature radiant system is supplied with warm water from a water-to-water heat pump. The supply side of the heat pump is connected to a ground heat exchanger and the circulation pump is a constant speed pump [Energy+ Engineering Reference, Energy+ Input/ Output Reference]. This system will henceforth be referred as the floor heating system and includes the heat pump.

The third heating system is a transient model of a high temperature radiant system (gas-fired) that is intended to model any "high temperature" or "high intensity" radiant system where electric resistance or gas-fired combustion heating is used to supply energy (radiant heat) [Energy+ Input/ Output Reference]. This system will henceforth be referred as the Radiator system and includes the gas boiler.

Natural Ventilation

The natural ventilation for each of the thermal zones of the base case scenario is calculated from the directions given by the Dutch NEN 1087 standard (NEN 1087, Ventilatie van gebouwen. Bepalingsmethoden voor de nieuwbouw. NNi, Delft, 1997). The NEN standard provides the required flow for each room. The ACH when the rooms are not occupied is set to 15% of the ACH when the room is occupied. Infiltration was calculated based on the Dutch NEN 1087 standard and added to the ventilation.

Heating and Ventilation Controls

For all three systems, the temperature control type was the mean air temperature of the zone. The thermostatic control set point defines the ideal temperature (i.e. setting of the thermostat) in the space. During daytime and occupied periods, this heating set point is set to 20 ^{o}C for all rooms and for the whole year. Every time the mean air temperature falls below 20 ^{o}C the system is providing heat to the zone, if it is above 20 ^{o}C then the system will stop. The setback set point temperature, which is the temperature during the night and unoccupied periods is set to 16 ^{o}C. The thermostatic control set point determines whether or not there is a heating load in the space and thus whether the systems should be operating.

In the ideal loads system, the control is only through the thermostatic control set point. Heating control in the high temperature radiant system (radiator + boiler) takes place with two additional parameters: the heating set-point temperatures and the throttling range. The throttling range specifies the range of temperature over which the radiant system throttles from zero heat input to the zone up to the maximum. The heating set-point temperature specifies the control temperature for the radiant system in degrees centigrade and controls the flow rate to the radiant system [Energy+ Engineering Reference, Energy+ Input/ Output Reference]. This set point is different from the thermostatic control set-point for the zone. In our study the heating set point temperature was set to 20 ^{o}C and the throttling range to 1 ^{o}C.

The control for the low temperature radiant system with heat pump takes place with four additional parameters: heating high and low control temperatures and heating high and low water control temperatures, the zone mean air temperature is compared to the high and how control temperatures at any time like it is generally the case in heat pumps. If the mean air temperature is higher than the high temperature, then the system will be turned off and the water mass flow rate will be zero. If the mean air temperature is below the low temperature, then the inlet water temperature is set to the high water temperature. If the mean air temperature is between the high and low value of the control temperature, then the inlet water temperature is linearly interpolated between the low and high water temperature value [Energy+ Input/ Output Reference]. In our study the heating high and low control temperatures were 21 ^{o}C and 18 ^{o}C and the heating high and low water temperatures were 35 ^{o}C and 10 ^{o}C.

Clothing and Metabolic Rate

There were two occupants in the dwelling, a man and a woman. The density (people/m^2) was thus 0.0232. The metabolic rate of the two tenants was chosen to be ''Standing Relaxed'' during the occupancy periods, which corresponds to 126 W/person. Moreover, the metabolic factor accounts for physical size and is 1 for men and 0.85 for women. In our case, the average metabolic factor (0.90) for a man and a woman (which were assumed to be the dwellers of the concept house) was used for the simulations. The clothing factor (clo) was set to 1 for the whole year.

Occupancy

The occupancy schedules vary according to the type of the thermal zone. A half-hour gap in the occupancy of the bedrooms and living room-kitchen can be observed between 7:00 a.m. and 7:30 a.m.; this is because the occupants are assumed to use the bathroom for half an hour in the morning. The bathroom belongs to the non-heated zone.

During occupied periods, the living room and the bedrooms were assumed to have 2 people.

Heat Gains

The internal gains in the dwellings for the base case simulation scenario are due to occupancy (the heat that a person emits while in the room), a refrigerator, a computer a monitor and a wireless router and a television set which are all placed in the living room. lighting is also a major contributor to the internal gains which are set at 5 W/m^2 for the whole house but with different schedules for the operation for every room.

RESULTS

Sensitivity Analysis

This section shows the results for the first day of January. The results for October and April do not lead to different conclusions and the results for July refer to summer conditions where no heating is needed and as such falls outside of the scope of this paper.

General Trends

The results from the sensitivity analysis on the comfort index show (see figures 3 to 12) that in all simulation configurations, the metabolic rate is one of the most important parameters, together with clothing and thermostat level. The impact of metabolic rate was found to be higher in the Class F building that the Class A building.

Ventilation plays the most minor role, and is often insignificant. This is because the air velocity was constant in all cases. Changes in the ventilation flow rate produce changes in the room's humidity and temperature. The temperature is controlled via the heating system, so that every time temperature deviates from the set point the heating system starts working until the room temperature matches the set point temperature. Humidity though, unlike office buildings, is not regulated in residential dwellings and thus ventilation affects the comfort index. Clothing and thermostatic settings alternate between the second and third most influential parameters depending on the configuration. The thermostat is more influential in simulations where the heating system is ideal loads or radiators, which was to be expected because that heating system's controls are more directly connected to the thermostatic use (see previous section). On the contrary, for the floor heating system, thermostat control has no real impact and the only parameters that affect the PMV are metabolic rate and clothing. That is because the internal control of the heat pump takes over the thermostat control.

The proportion of variance that was explained by the four parameters remained above 90% for all the possible configurations that were analysed.

Single Zone, Ideal Loads

Figures 2 and 3 show the results of the sensitivity analysis for the Single Zone configuration with the ideal loads heating system for Class A and Class F.

For the Class A dwelling, the influence of the thermostat follows the heating schedule: after 22:00 the heating stops and the influence of the thermostat decreases constantly until 9:00 and starts increasing again at 10:00 when the heating has already been on for half an hour and until 11:00 when the heating stops again. From 11:00 till 17:00, the impact of the thermostat drops continuously and at 17:00 it starts to increase again until 22:00 when the heating stops again.

An interesting observation is that the impact of the thermostat in Class A never drops below 0.4 (with the only exception is at 9:00 in the morning, when the dwelling has been in the set-back setting for the longest period of the day), even when the heating is off. This is because the simulated dwelling is Class A with very good insulation and heat loss is very small.

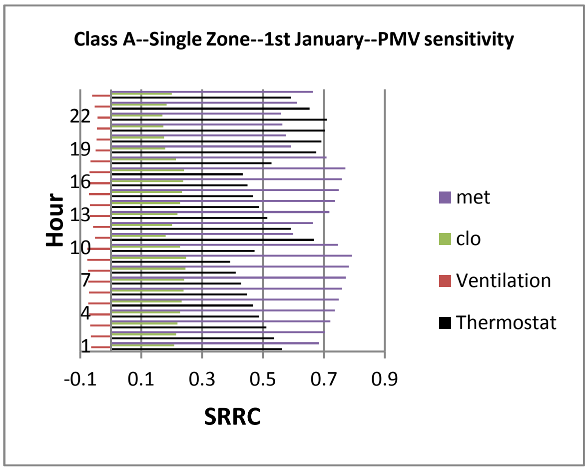

Figure 2: Class A—Single Zone-Ideal Loads—PMV sensitivity per hour for the first day of January

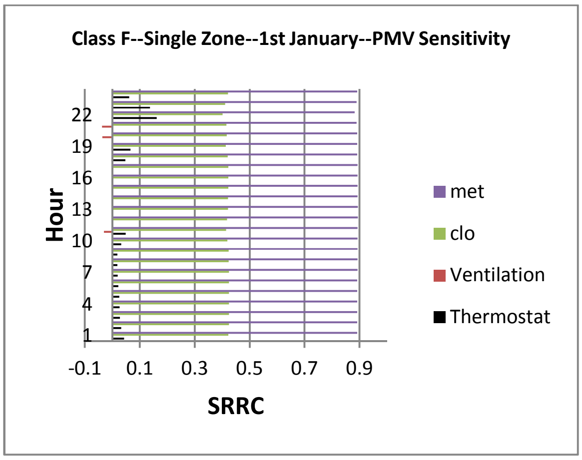

Figure 3: Class F—Single Zone—Ideal Loads—PMV sensitivity per hour for the first day of January

Most of the heat, which is regulated from the thermostat, stays in the dwelling even when the heating is off and thus the influence of the thermostat never drops below 0.4. The factor with the biggest influence in the PMV index is the metabolism which follows the opposite pattern of that of the thermostat. When the heating is off the impact of the metabolism starts to increase, from 23:00 to 9:30, after which it drops for two hours while the heating is on and increases again until 17:00 when the heating starts to operate again; then the impact of metabolism drops until 23:00 when the heating switches off again. The third most influential parameter is clothing which follows the same pattern as metabolism and the opposite to that of the thermostat.

For the Class F dwelling, metabolism and clothing are the most influential parameters, with the thermostat having a very small influence compared to the Class A dwelling. This result was not expected, but can be explained using the comfort theory. The comfort zone depends heavily on the relationship between the radiation temperature (the average of all walls/floor/ceiling temperatures) (Fanger 1970). In a Class A dwelling, the wall temperature is quite high because of the good insulation. Small variations in air temperature +/- 1 ^{o}C (thermostatic level) may then be enough to produce large changes in PMV. In an F-dwelling, the wall temperature will be low because of the lack of insulation and this will dominate the PMV: small variations in air temperature (thermostatic level) will not be able to compensate for the low wall temperature. Clothing has a more significant impact on comfort, almost double during all 24 hours of the day. Metabolic activity also has a bigger impact in Class F dwellings, although not as great as clothing. While in the Class A dwelling the metabolic activity's impact ranges from 0.55 to 0.79, in Class F it is above 0.89 all the time. Ventilation was found to be insignificant for comfort for most of the hours compared to the Class A dwelling.

Figures 4 and 5 display the hourly temperature, humidity and PMV for the 24 hours of the Class A and F simulations. Both the graphs show that the PMV index follows the same pattern as the mean temperature and the opposite of the indoor humidity. It also shows that according to the PMV, all dwellings should be found too cold by occupants (negative PMV). The Class F dwelling is a much colder dwelling; the thermostatic set point temperature of 20 degrees is not enough to condition the space at the desired level. Of course, this is because of the colder temperature of the walls, floor and ceiling due to poor insulation.

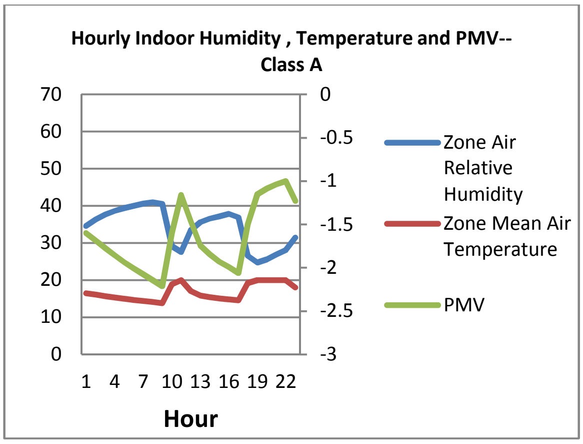

Figure 4: Hourly Indoor Temperature, Humidity and PMV for 1st of January--Class A

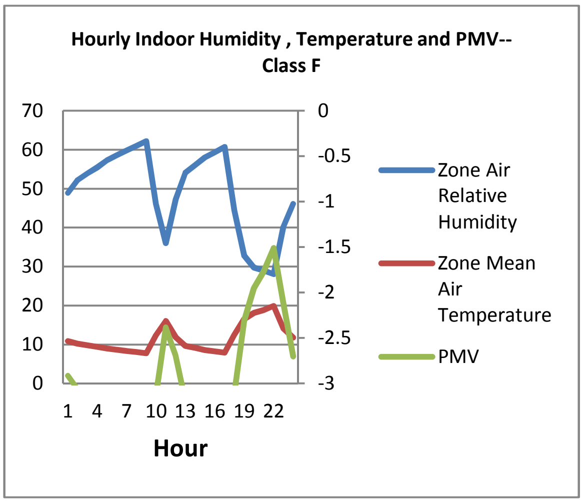

Figure 5: Hourly Indoor Temperature, Humidity and PMV for 1st of January--Class F

Radiator heating system

The multi zone simulations with the boiler/radiator heating system showed that, for the colder month of January and for the Class A building, the thermostat is the most influential parameter for comfort, followed by the metabolic rate. The results are very similar to the results for the ideal load system, which was expected because of the similarity between both control systems. As mentioned already, the radiator system controls, which are immediately connected to the thermostat, and the thermally tight Class A building result in a greater impact on the comfort index from the thermostatic use (figure 6). The results are given for the living room below; The results for the bedroom are similar.

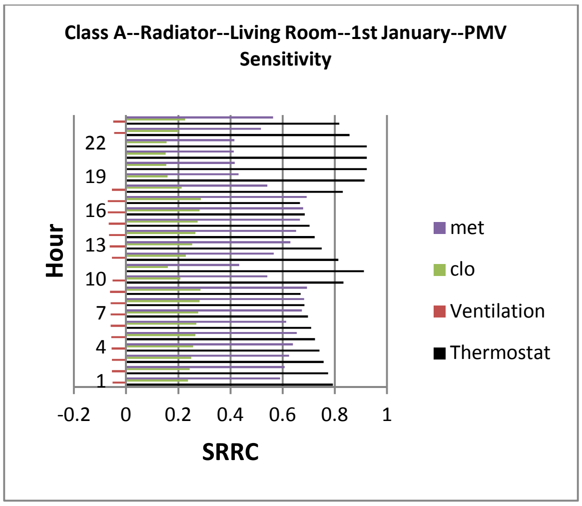

Figure 6: Class A—Radiator—Living Room—PMV sensitivity for January

The results for the Class F dwelling are also in accordance with the findings of the ideal loads system. Metabolic rate and clothing are the most influential parameters for comfort. The thermostat in the cold month of January has no impact on comfort at all in the living room and bedrooms. Small adjustments in the thermostat do not increase the comfort of the occupants due to the bad insulation of the building, results in cold walls. In October and April on the other hand, due to higher ambient temperatures, small adjustments on the thermostat do impact on comfort.

Floor heating system

The results of the sensitivity analyses for the floor heating system were the most straightforward. The thermostat, due to the way in which the system is controlled, does not influence the comfort index at all. The most influential parameter is always metabolic rate, while SRRC is always higher than 0.8, followed by clothing for both the Class A and Class F reference buildings. Figures 7 and 8 show the results for the Class A and Class F reference buildings for the month of January in the living room. The results for the bedroom are similar.

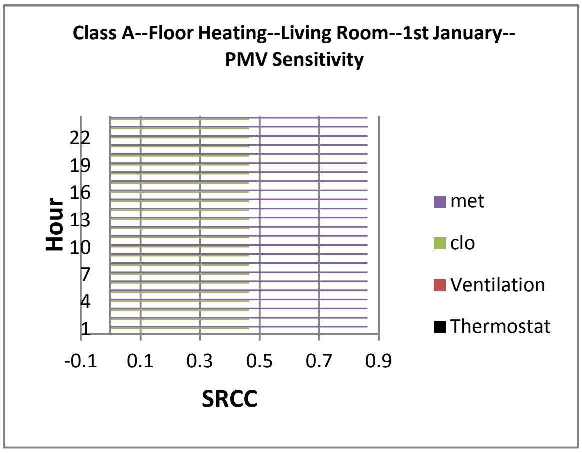

Figure 7: Class A—Floor Heating—Living Room—PMV sensitivity for January

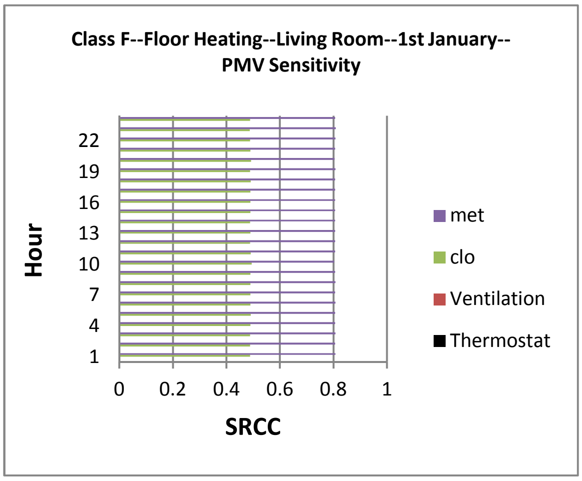

Figure 8: Class F—Floor Heating—Living Room—PMV sensitivity for January

CONCLUSIONS AND DISCUSSION

The most important parameter in determining the PMV during the heating season was, by a long way, metabolic rate (meaning the occupants' level of activity), followed by clothing (clo values). Small variations in the metabolic rate (10% around 100 met, which corresponds to standing relaxed) can explain a very large proportion (up to 95%) of the variance in PMV.

In addition to the metabolic rate, the thermostat setting and clothing were found to be important to a relatively similar extent. However, it is noticeable that the thermostat settings were almost insignificant in the Class F building, which can be explained by the small variations, which could not compensate for the cold walls. For the same reasons as before, the thermostat has no influence on the PMV for the floor heating system.

It was also shown that, according to the simulation results on the PMV index, the reference building was too cold during the heating season, even the well-insulated Class A dwelling. This poses a question about the validity of the PMV index, since the air temperature was 20 ^{o}C, a temperature that is generally accepted as being comfortable in the Netherlands. Even at this temperature, the PMV index did not exceed the threshold of -0.5 at all (the comfort zone according to the PMV theory is between -0.5 and +0.5), but was constantly below -1.

The next step of this research is to gather empirical data on occupant's metabolic activity, clothing patterns, thermostat and ventilation practises, from a large scale measuring campaign in residential dwellings. It seems necessary to gather more empirical information on the comfort perception of occupants in dwellings which may differ from the comfort perception in office buildings. Additionally, the metabolic activity and clothing which were shown to be of great importance, are generally modelled as constant which is not the case in reality. Better predictions could be obtained if we are able to model the actual metabolic rate and clothing of occupants.

ACKNOWLEGEMENTS

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