Comfort Delivery on Demand:
An adaptive approach to comfort systems in dwellings

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ABSTRACT: This paper will explain why it is important to consider a new approach in thermal comfort for dwellings. It presents a literature research that makes clear that because of the nature of mankind we should regard comfort requirements as varying in time due to changes in weather, activity and comfort experience being individual due to different preferences people have. Describing an exploratory simulation the paper makes clear that this adaptive approach, delivering comfort only where and when needed, can lead to energy savings while regarding the individual demand for comfort. The conclusion clarifies what aspects of demand based comfort delivery need to be considered to be able to take full benefit of this new concept.
Keywords: energy, comfort, occupant behaviour

INTRODUCTION
Nowadays newly built homes use all kinds of strategies to save energy. Due to elaborative insulation and heat recovery, the heat loss and thus energy demand for space heating in these dwellings can be minimized drastically. However most of these strategies mainly focus on saving energy by minimizing heat losses and therefore deliver the minimum of comfort for heating and ventilation required by legislation, being universally applied values for indoor temperature and ventilation. The demand for comfort is not static or general, but dynamic in both time and space and above all it is personal. Minimization of the comfort parameters can lead to undesirable and sometimes unhealthy situations which will be corrected by the user if possible, thus leading to more energy use.

Furthermore, looking at the provision of comfort in the heating season, we should also consider summer comfort. There is no use in designing a comfortable winter-home that consumes the least amount of energy in heating, while in summer all the energy saving will be diminished by installing active cooling to prevent from overheating. An adaptive comfort system needs to provide thermal comfort the whole year round.

DIVERSITY IN THERMAL COMFORT
Mankind was raised outdoors [1], being at the mercy of nature's swings. He would cope with the ever changing weather conditions by its adaptive skills and would seek shelter from darkness or the most extreme weather in caves, using the thermal inertia of the earth, or under trees for rainfall and sunlight. Later on in the evolution of mankind he would create his own shelter. However it was merely to mitigate the swings of outdoor conditions. Only recently people started to create their own microclimate. First by heating the occupied space during the winter and even more recently cooling when too hot. By the time of the second half of the 20th century anything was possible and man could bend indoor climate to its will, although at high (energy) cost.

Being able to control indoor climate it became interesting to define optimal climate conditions for certain use of space. In 1970 Fanger published his human heat balance model [2]. He believed that thermal sensation could be predicted by relating the heat generated by the metabolic system of the human body to the heat loss from the body to the environment, with a physical thermodynamic model. This model, based on laboratory experiments in climate chambers in which the thermal environment can be closely managed and monitored, would become the standard for determining design guidelines and even regulations for thermal comfort in buildings all over the world in whatever climate zone or culture. While describing this "ideal" situation to be implemented all over the world without regarding peoples diversity built environments where starting to be actively creating comfort needs instead of meeting pre-existent needs, leading to what Shove calls *social, architectural and environmental convergence* [3], being standards and expectations becoming more and more the same all over the world. Creating this same thermal environment in every climate leads to excessive energy use.

However, like Humphreys and Nicol already stated in 1970 [4], such a universal optimum in climate conditions does not exist. This theoretical “neutral temperature” at which people feel neither cold nor warm varies from person to person and is also dependent on the overall circumstances.

Like we have seen before, mankind is capable of all kinds of adaptive behaviour to cope with its environmental conditions. As can be expected we didn’t lose our adaptive ability in this relatively short period of climate control and as it seems also not our natural need for diversity of environment. People adapt their clothing, activity or posture, as well as their environment by turning down or up the heat, opening a window or turning on fans. Unconsciously they can adapt their physiology, like shivering or adapting metabolism. These reactions highly depend on the individual and the circumstances. Besides physical actions of adaptation, people also have psychological abilities for adaptation, such as expectation (like seasonal or daily variance), habituation (getting accustomed to a certain climate) and tolerance.

This tolerance of the (thermal) environment has proven to increase if people feel in control of their own environment [5, 6]. Everybody knows to some extent the feeling that if a situation has been forced upon you, you want to object to it regardless the situation. This feeling of discomfort increases even if one does not know what or how things are happening, which supports the fact that it is favourable to let the people be in contact with the outdoor climate to see the seasonal and daily changes in climate to be able to anticipate.

PREDICTING THERMAL COMFORT DEMAND

Much research has been done since Fanger to support the idea that thermal comfort experience is not universal nor static, but defined by numerous parameters varying in space and time, not only physiological but also psychological. Fanger’s human heat balance model does take into account parameters such as clothing level and metabolic rate, but considers this as being static. Taking into account mankind’s adaptive skills one could easily conclude that people are tended to take control and adapt their surroundings to seek comfort [7]. This automatically implies that the thermal environment changes (opening a window changes air velocity and more important the air temperature) as are the physiological parameters (like changing metabolic rate). Furthermore as for the physiological parameters, the human body has a certain thermal inertia, which isn’t accounted for in the static models either, nor is psychological adaption.

All of the above mentioned parameters make it very hard to predict the actual neutral comfort parameters. However they also support the fact that there is no need for a very sensitive prediction of the preferred temperature. This means that for thermal comfort, setpoints can be installed with a certain flexibility that can be beneficial for energy savings. For use of controlling thermal environment in offices, many field studies have been performed to model adaptive thermal comfort experience [8-10]. For obvious reasons, the possibilities for people to change their environment to their will are less present than in dwellings. Somebody else (the building operator) has to decide what the thermal environment is supposed to be in order to satisfy as many people as possible, so the settings for thermal comfort in offices is more stringent than in dwellings.

Predicting thermal comfort experience in an adaptive approach is obviously more complex than if it was only depending on physical parameters. Incorporating the means of controlling the environment and the criteria based on which decisions are made by the occupants to adjust their environment makes it even more complex. The determining factors to take action seem to be the combination of the present indoor temperature and the present outdoor temperature where the mean outdoor temperatures of the few days before are influence this threshold. Furthermore sunshine and wind can be triggers to take action or not. Possibilities to cope with discomfort can be opening and closing the drapes, windows or doors, adjusting the thermostat, adjusting clothing or move to another space [7]. Studies to explain and predict this adaptive behaviour patterns are ample and ongoing [11-16]. For this study it is most important to recognise possible behavioural and occupancy patterns and their influence on demand patterns in time and place in a dwelling.

TEMPERATURE LIMITS IN RESIDENTIAL BUILDINGS

For being able to fit installations for residential buildings it is not so important to predict actual comfort temperatures as it is to set lower and upper temperature limits, to be able to provide the instantaneous demand. Also important for adaptive comfort systems, is to know the probability of demand at a certain moment and the frequency of occurrence.

Residents deploy different kind of activities in their home. For various activities there are different temperatures. In their article, Peeters et al. [17] describe three thermal comfort zones in residential buildings; Bathroom, bedrooms and other rooms.

Figures 1-3 are visualisations of the algorithms adapted from Peeters et al. [17] for neutral temperatures and their bandwidth for 10% and 20% PPD in the various zones related to the reference external temperatures, with on the horizontal axis the reference temperature $T_{e,ref}$ and the vertical axis the (indoor) comfort temperature.

The reference external temperatures are calculated according to equation (1), adapted from van der Linden et al. [18], taking into account the adaptation to outdoor climate:

$$T_{e,ref} = \frac{(T_{today} + 0.8T_{today-1} + 0.4T_{today-2} + 0.3T_{today-3})}{2.4} \quad (1)$$

The neutral temperature T_n represents a temperature at which most people feel thermally neutral in the given room type. The T_{upper} and T_{lower} lines represent the values at which 10% respectively 20% PPD is expected. The absolute outer limits of temperature in the rooms are:

1. Bathroom $T \geq 16$ °C
2. Bedrooms 16 °C $\leq T \geq 26$ °C
3. Other Rooms $T \geq 18$ °C

Where in bathrooms the lower temperature limit is most critical, because of the presence of the wet, naked body, in bedrooms the upper limits are more important because of overheating during sleep and the possibility of using sheets and blankets. In the other zones the temperature limits are different because of the clothing being in accordance with the outdoor climate and the activity levels being roughly from 0.7 met for reclining to 2.0 met for cooking, according to the ASHRAE standards [19].

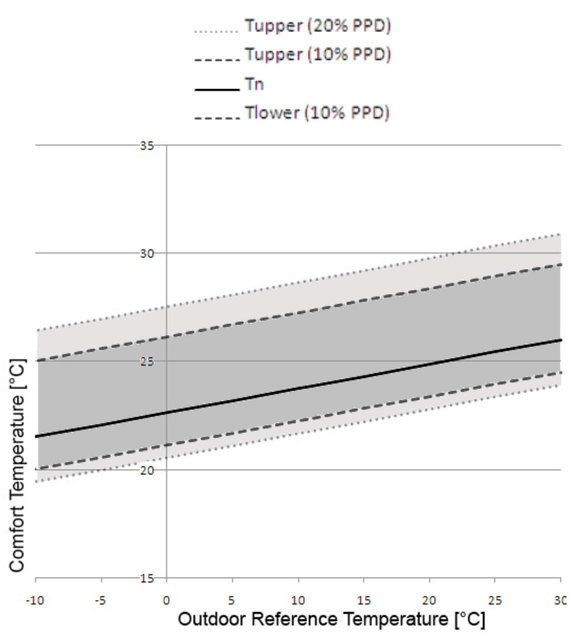

Figure 1: Comfort Temperatures for Bathrooms

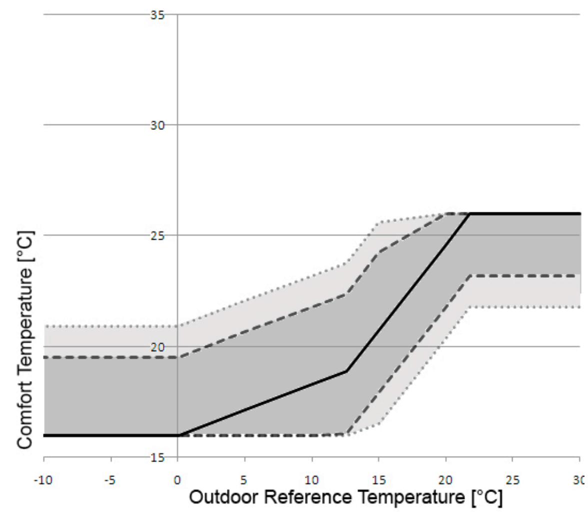

Figure 2: Comfort Temperatures for Bedrooms

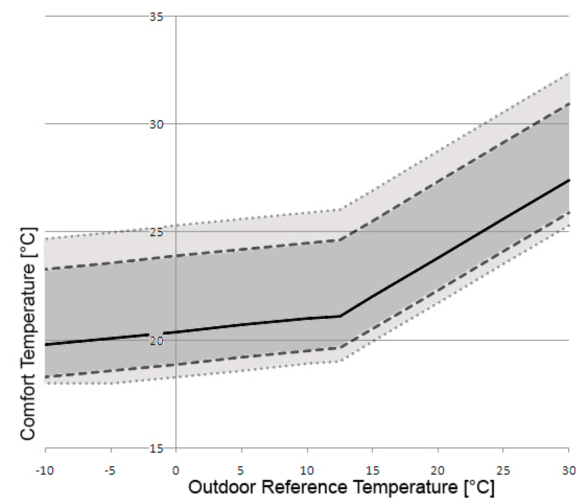

Figure 3: Comfort Temperatures for Other Rooms

In this research not the exact values of these equations can be used. The equations are an example of the range in which the thermal comfort needs to be delivered and the diversity in comfort per room type. They illustrate how the comfort experience can vary with circumstances. More research needs to be carried out to thoroughly define patterns of thermal comfort experience and behaviour of occupants in different rooms and to make clear the possible individual diversity of preferences. This research will be conducted with various scenarios of preferences and occupation patterns to see what influence these time- and place dependent comfort demand patterns will have on the researched system concepts and their comfort delivery and energy consumption to be able to define some optimal preconditions for an adaptive comfort system in a dwelling in terms of comfort delivery, flexibility and minimal fossil fuel use.

SIMULATION OF PRESENCE DEPENDED COMFORT DELIVERY FOR HEATING

For this paper, two simulations were carried out. The program used in TRNSYS, a transient building simulation program for thermal energy. Considered is a two person family, where at least one of the members works at home during the day. The dwelling is a one story, two bedroom apartment. One of the bedrooms is defined as being a study. The simulation time is one whole year, with hourly values. For the weather data the simulation year 1995 for De Bilt in the Netherlands is used in TMY2 format. Figure 4 shows the floor plan of the dwelling used for simulation. Table 1 shows the occupancy patterns of the rooms during the weekdays and Saturday and Sunday per hour of the day.

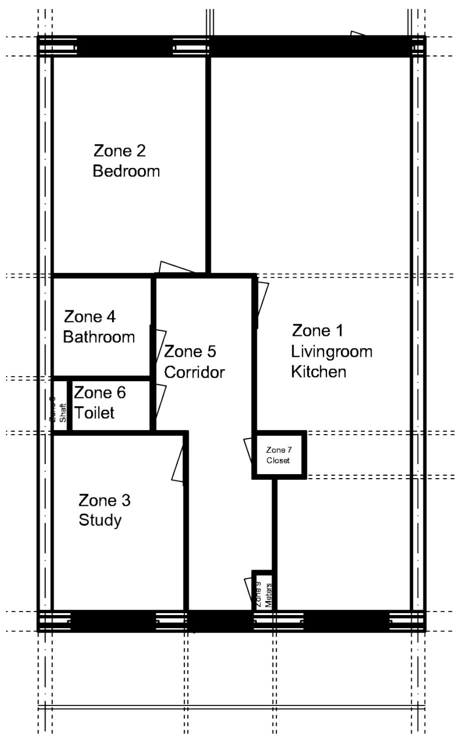

Figure 4: Floor plan of Dwelling used for Simulations

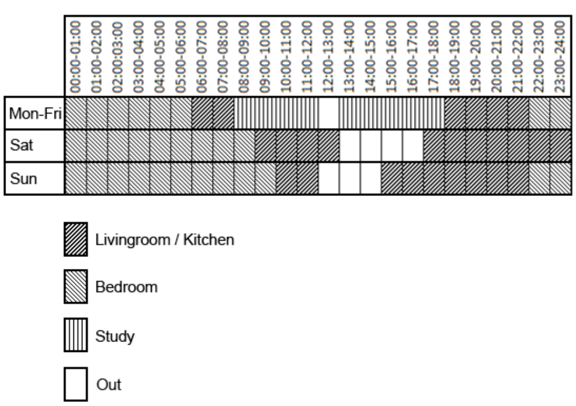

Table 1: Occupancy Schedule

The calculations are made on an hourly basis. Only heating is taken into account and there are no control possibilities like opening a window or adjusting the thermostat when too hot or too cold. The ventilation rate is constant. In these simulations no seasonal or daily variance in comfort temperature is considered. In both simulations, the set point temperature for the living room is 20°C. For the study this is also 20 and for the bedroom this is 18°C for the conventional heating and 17°C for the adaptive comfort simulation.

For the conventional heating method simulation the whole dwelling is heated at the set point Monday to Friday from 6:00 am to 22:00 pm, on Saturday from 9:00 am to 24:00 pm and Sundays from 10:00 am to 22:00 pm. For the remaining hours there is a night time setback of 2°C for the bedroom and 5°C for the other rooms. In this simulation, the heating is considered not to be switched off in the hours that the occupants leave for lunch on weekdays or to recreate on weekends.

In the adaptive comfort simulation, the rooms are only heated to 20°C (17°C for the bedroom) when people are present (Table 1). The bathroom is heated two hours a day, when getting up and when going to bed.

RESULTS AND DISCUSSION

The annual energy consumption of the adaptive dwelling in this study is 14% less than the energy consumption of the conventionally heated dwelling. At most the energy savings are 28% in the first two weeks of the year.

In figures 5 to 8 (Fig. 5-8) the temperatures of the rooms and the energy consumption per room of the second week in January is shown, for both simulations. In this week the ambient temperature drops a few degrees during the weekend. From the graphs you can clearly see the difference in the course of the temperature in figure 5 and 7. In the first graph, for the conventional heating, you can see that all the rooms are heated at the same time, while in figure 7 you can see that the rooms are heated one at a time. Figures 6 and 8 show that the instantaneous energy demand in the case of the adaptive demand is significantly higher than in the case of conventional heating. This is because the rooms have to be heated from a lower temperature which takes more energy than keeping it at a certain temperature level. However the total amount of energy consumption for this week is in fact 28% higher in the conventional heating scenario than in the adaptive heating scenario. This peak demand however in general means a system is needed with a higher capacity. This is something that needs to be considered when dealing with this adaptive approach. It highly depends on the energy resource used and the comfort delivery system.

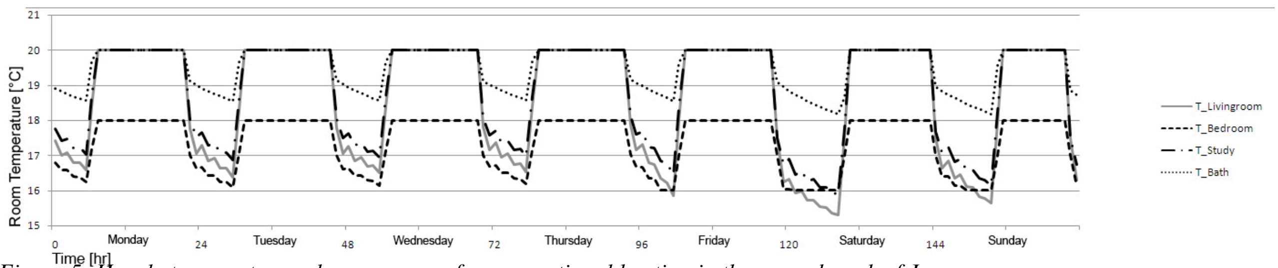

Figure 5: Hourly temperature values per room for conventional heating in the second week of January

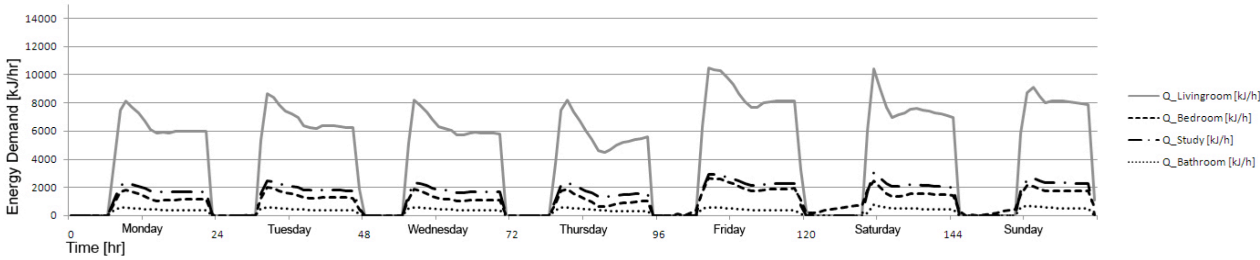

Figure 6: Hourly energy demand values per room for conventional heating in the second week of January

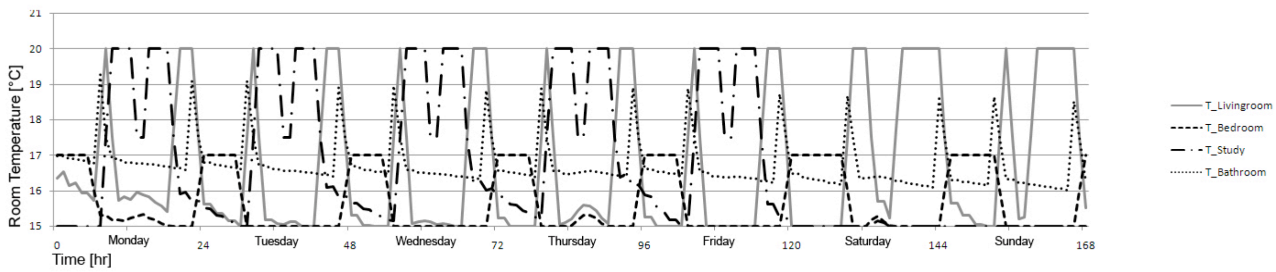

Figure 7: Hourly temperature values per room for adaptive heating in the second week of January

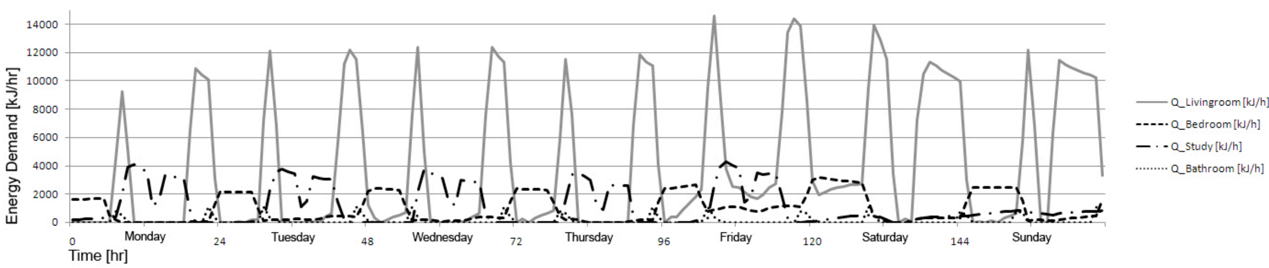

Figure 8: Hourly energy demand values per room for adaptive heating in the second week of January

CONCLUSIONS AND OUTLOOK

The energy consumption can be lowered by using an adaptive approach while delivering the comfort needed by the occupant. The difference in predicted energy consumption of 14% per year in this particular case is based on an adaptive approach in its most simple form, being only heating a room when people are present. The benefits can be even more if the situation is researched into more detail, which will be the next step in the research.

This particular simulation only deals with the heating season. However as stated before also the summer situation and overheating should be regarded.

Considered should be the possible need for systems with a higher capacity for peak demand and how to deal with that in a sustainable way. Is the amount of energy savings enough to make it worthwhile to use a heavier furnace or should we look to other ways in delivering this peak demands?

Furthermore the reaction time of the system should be considered in relation to thermal inertia of the building and the minimum interval considered delivering the comfort.

In the simulations for this paper the means of controlling the environment are not taken into account.

However all actions people take to change their environment, like opening a window will influence both indoor climate as energy consumption. For this it is important to know what the control criteria are and the temperature deadband needed for this.

Wind speed and ventilation are important facets in thermal comfort and energy demand especially when considering varying ventilation rates as a result of operable windows.

Another aspect to be considered is the locality of the comfort delivery. Should the comfort be delivered per room or maybe even per defined zone of a room?

All these aspects need to be optimized to develop preconditions for new concepts for comfort systems in adaptive dwellings.

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