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Making the Difference – Individual Thermal Comfort Demand Profiles for Dwellings

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Abstract
As civilisation is advancing and comfort demand increasing, it is essential to define the circumstances under which people feel comfortable, optimizing conditions for well-being while limiting energy consumption.

In addition to physical parameters, the comfort temperature changes with adaptation: adjustment, acclimatization, habituation and expectation. In dwellings people are considered in charge of their own environment and the comfort system should facilitate the occupant to control their comfort temperature individually around a setpoint. This shifts the question from an actual temperature to a range of comfort temperatures likely to occur and the variability and bandwidth.

To determine this comfort range, this paper describes a method of formulating different realistic occupant profiles for Dutch dwellings, based on statistical analysis of comfort surveys and time use surveys. This research is part of a PhD project about concepts for design of new adaptive and sustainable comfort systems and components for dwellings in the Netherlands.

Keywords: Adaptive Thermal Comfort, Individual Comfort Profiles, Diversity, Adaptive Dwelling, Comfort Systems.

On the origin of thermal comfort

One of the basic necessities of life is shelter from the climate and other possible threats, to be able to develop all kinds of activities supporting life and personal and social development. In former times, man would cope with the ever changing weather conditions by its physiological reactions, like vasoconstriction or vasodilation and adapting activity to change the metabolism. Furthermore, he has adaptive skills; man would use what nature provided to find shelter and the most appropriate environment for its various activities. Later on in evolution of mankind he would create his own shelter, though merely to mitigate the swings of outdoor conditions. This shelter evolved from a mere roof to a complexity of separate spaces like a living room, a space for cooking, a space for sanitation and a space for sleeping. The dwellings, as the shelters are now called, are complemented with all kinds of amenities, like a kitchen, toilet, shower or bath, and (central) heating. The organization of spaces and their amenities co-evolved with the

advancing techniques and culture, making demands and realizations of comfort highly dependent on culture, history, technique, season and climate (Chappells and Shove, 2003).
As civilization was advancing, people invented new techniques and improved the existing ones. By doing so, it became increasingly possible to create a separate and controlled microclimate, first by heating the occupied space during the winter and even more recently cooling when too hot. By the 2nd half of the 20th century man could bend indoor climate to its will, although at high (energy) cost. It was only then when people would talk about comfort in the current meaning, instead of mere shelter from extremes (Baker, 2004; Shove, 2004).

Conflict of comfort and energy

Technically, it is now possible to provide any thermal environment requested. However, the greater the difference between offered outdoor climate and requested indoor climate, the more energy is required to supply and maintain this climate. Partly due to this, mankind is becoming more and more dependent on energy. Most of this energy is generated from fossil fuels. Our increasing consumption of these fossil fuels causes a growing exhaust of greenhouse gases leading to what we call Global Warming, the increase in the average measured temperature of the Earth's near-surface air and oceans since the mid-20th century, and its projected continuation (IPCC, 2007). Global Warming can have some disturbing consequences; from the rising of sea level, leading to floods and more severe storms to more heat deaths a year. Furthermore our dependence on fossil fuels has already led to uncertainties in availability and pricing. While the world is rapidly developing, the worldwide energy supply becomes even more stressed. As a result the international relationships between suppliers and consumers of these primary energy sources are intensifying.

Implications on building practice

Bearing in mind this conflict, it is essential to define the circumstances under which people feel comfortable, optimizing conditions for health and productivity while limiting energy consumption. In their paper for the Environment and Human Behaviour Seminar, Chappells and Shove describe a development of roughly three approaches in regarding thermal comfort (Chappells and Shove, 2003); the physiological approach, the dynamic and adaptive approach and the approach of thermal comfort as a social construct. A combination of these approaches will be the guiding principle for this research.

Physiological approach

Especially in the domain of technicians, it is convenient to describe comfort as a fixed condition, something that exists, can be striven for and ultimately achieved. The first theory on predicting the comfort temperature to be applied globally was Fangers' physiological heat balance model of the human body (Fanger, 1970), which calculates the temperature of thermal equilibrium between body and environment, regarding this to be the same as the comfort temperature. The disadvantage of this approach is the assumption that thermal comfort is uniform, global and static. This leads to unwanted situations, since describing and creating this "ideal" situation to be implemented all over the world, regardless climatic and cultural differences, leads to excessive energy use. Apart from the fact that we cannot continue to condition our indoor space to a universal ideal, 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 not merely determined by physical processes.

Dynamic and Adaptive approach

This approach regards thermal comfort as a result of physical, physiological and psychological aspects, both being dynamic (differing per day), thus rejecting set point standards. The factors beyond fundamental physics can include demographics (gender, age, economic status), context (building design, building function, season, climate, semantics, social conditioning), and cognition (attitude, preference, and expectations). De Dear and Brager (1997) performed extensive field research in 160 offices around the world to find the strongest relation to be between the monthly mean temperature and the comfort temperature. This relation is different in two kinds of buildings, those with natural ventilation and those with centralized HVAC. Besides with physical parameters, the comfort temperature changes with adaptation; adjustment, acclimatization, habituation and expectation. They describe a clear relation between comfort temperature and expectations of the occupant based on past experiences and in addition found different relations per country. Furthermore, in summer people accept higher temperatures in the naturally ventilated buildings than in the buildings with centralized HVAC. Based on that assumption, McCartney and Nicol (2002) developed a basic equation, that relates the comfort temperature (T_c) to a running mean outdoor temperature (T_{rm}); $T_c = a * T_{rm} + b$. They describe equations for average groups in the different countries that were measured. Although dynamic, by its statistical approach the algorithm still regards the user as standardized, disregarding individual differences in preferences and sensitivity and it is only applicable in the office environment. The constants *a* and *b* are also influenced by numerous aspects like gender, individual preferences, culture and behaviour. Theoretically, different values for *a* and *b* can even be found for each individual and by means of statistical regression analysis different average values for a and b can be found for each regarded population.

Comfort as a social construct

This approach considers the notion of comfort as being framed by issues of social convention, symbolism and status and comfort as being culturally relative. Fine and Leopold (1993) find that perception of comfort and the systems through which particular services or resources are produced, delivered, distributed and used mutually influence each other and cannot be explained in terms of consumer demand alone. In this sense it is important to consider how thermal comfort is provided, as habituation of people determines an important part of satisfaction with their environment. For instance, in the Netherlands like in most European countries, it is an established good to have central heating. The Dutch are used to the way the radiators distribute the heat and will consequently organize their interior according to this system, like in former times people would organize their activities around the central fire place. With this habituation comes the demand for the "product" people are used to. Furthermore, one has to acknowledge the capacity of providers to influence the intensity and pattern of consumption. The power of advertising is not to be underestimated. Manufacturers of air-conditioning are of course keen on convincing the consumers how much they need their product for comfort in summer, while if they would not know it existed, might not even have noticed discomfort.

The study of this paper considers a combination between the three approaches in a dynamic way. 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 and unconsciously they can adapt their physiology, like shivering or adapting metabolism, hereby changing their physical interaction with the environment. These actions actively change the heat balance of the human body and its environment (Fanger, 1970). The acceptance of the (thermal) environment has proven to increase if people feel in control of their own environment. Besides physical actions of adaptation, people also have psychological abilities for adaptation, such as expectation (like seasonal or daily variance) and habituation (getting accustomed to a certain climate) (De Dear, Brager et al., 1997; McCartney and Fergus Nicol, 2002). Another strong aspect of expectation is the cultural, and technical context, like the fireplace mentioned in the former paragraph (Chappells and Shove, 2003). Like mentioned, this paper regards all these aspects as being dynamic and personal. Furthermore, a Japanese study points out that the magnitude of comfort expectations to follow the outside climate is mainly dependent on the extent of influence over the indoor environment (both acted by the building as well as the occupant) *expected* by the inhabitant (Chun and Tamura, 1998). Having this in mind, it is crucial for people to roughly understand the thermal behaviour of a building they inhabit and have notion of the outside world. The culture, history, technique, season and climate determine the dynamics of the indoor climate people are used to and relate to.

In this study, a range of possible comfort demand and its variability will be studied for Dutch dwellings, rather than trying to predict thermal comfort, because the essence of a home is a place where one can shape its own (thermal) environment, within certain boundaries determined by expectation. In this respect, the dwelling should be dynamically adaptive to the user as well as the outdoor influences.

The Adaptive Dwelling

An adaptive dwelling with regard to comfort is a dwelling in which the comfort delivery system (whole of passive and active comfort components) adapts its settings to the dynamics of the occupants comfort demands and the weather conditions - seasonal, diurnal and hourly (depending on the aspects adapted), thus providing comfort only where, when and at the level needed by the user, while harvesting the naturally delivered energy when available and storing it when abundant (DEPW, 2006). Components of such an adaptive dwelling can vary from adaptable shading and insulation to a sophisticated demand driven ventilation system. The aim of an adaptive dwelling is to make a comfort system for dwellings that is robust to various weather situations as well as different use patterns.

This paper describes the method of formulating different realistic occupant profiles for Dutch dwellings, based on statistical analysis of demographics and time use surveys, consisting of a description of presence and comfort temperature range, varying over time and place. These profiles will serve to simulate thermal comfort and energy performance of Dutch reference dwellings to determine the possible range of comfort demand. They will be compared with simulations based on average profiles as used in practice, to investigate what quality improvement and energy saving potential this approach can have. In a later stage, different comfort system concepts will be researched on their flexibility in time and place regarding individual comfort demand, changing climate and availability of renewable energy, ultimately leading to concepts for development of new comfort systems and components.
Furthermore, the profiles can be used to asses existing solutions. Most assessment methods used for buildings, like the EPN (The Dutch legislative instrument for assessing building energy performance (Normcommission-351074 Klimatisering van gebouwen, 2009)), assume a

normalized user. As will become clear in this paper, this uniform user profile does not exist and the pattern determines the assessment of the building to a great extent.

Determining the demand

In the office environment where the setpoint temperature is to be controlled centrally, it is sensible to determine average comfort temperatures for the target group, to have the biggest chance of satisfying as many people as possible, optimizing their productivity. However, in dwellings people are considered in charge of their own environment and they can control their setpoint temperature individually. Furthermore, the variety of activities deployed is much bigger. The dwelling and the comfort system should facilitate the occupant to create his own environment fitting to his current activities, within certain bandwidths concerning energy consumption. *This shifts the focus from an actual temperature to a range of temperatures likely to be demanded and their variability and bandwidth.*

As can be seen in figure 1, in the Netherlands, the distribution to household size has the largest percentage of 1 person (36%), second is a household size of 2 people (33%) and the 4 person households (12%) are slightly more than those with 3 people or 5 people and more. Most of the multiple-person households are families with or without children (CBS, 2009).

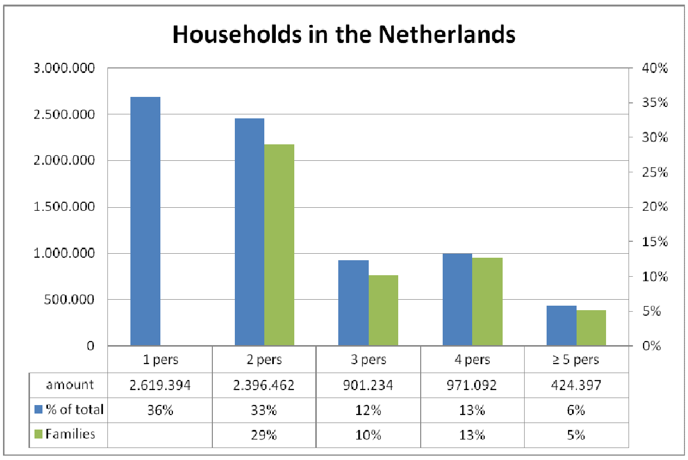

Figure 1: Distribution of the Dutch households in size

To describe the method used in this study, a one person household with a studio apartment (1.studio) is observed, as well as a family with two children under the age of 5 years old (4.small children). The person in the studio apartment is considered to have a day time job, i.e. not being at home during the day. In the family, at least one of the partners is considered to stay at home to take care of the children and do the housekeeping. Determining the schedules for these profiles, data of a Time Use Survey obtained from the CBS is used. The Centraal Bureau voor de Statistiek (CBS) is the Dutch governmental institution that gathers statistical information about the Netherlands. The Time Use Survey was part of a larger survey about social circumstances in the Netherlands (POLS 2000) and was conducted by the Netherlands Institute for Scientific Information Services (NIWI, 2002). For the comparison of the schedules, figure 2 shows the statistics of the two household types. The vertical axis represents the distribution of people being present in the various "activity zones". The activity zones express an indication of presence according to an activity, independent on the layout of the dwelling; e.g. the dining area can be a separate room or an area in a separate kitchen or livingroom. The horizontal axis represents the time of day of the distribution. As can be seen from the figures, significant difference can be seen in daily activities between the groups as well as within the groups between Sundays (weekend) and Mondays (weekdays) and the different members of the family.

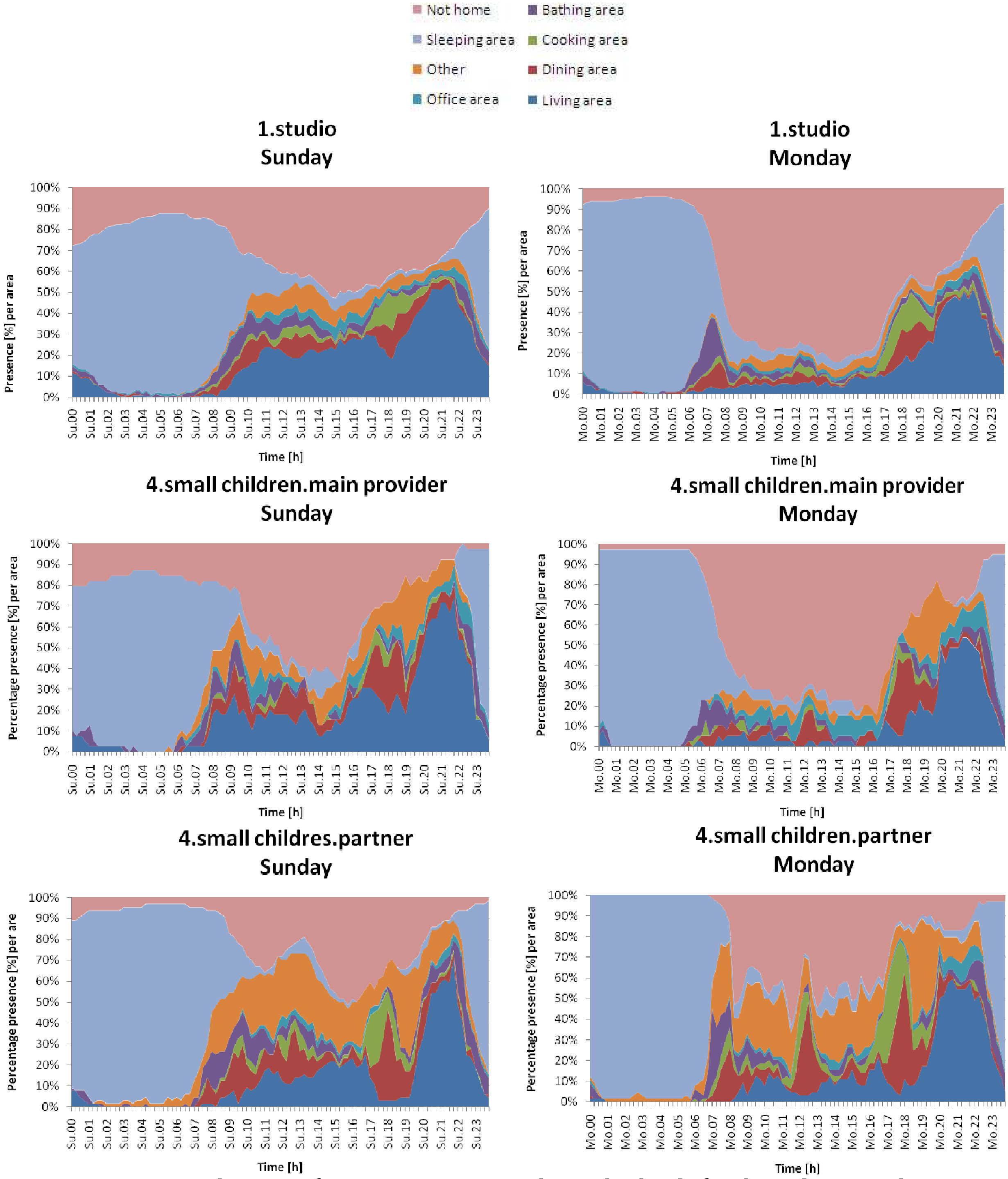

Figure 2: Visualization of Time Use Survey in the Netherlands for three demographic groups, indication presence in the dwelling in various activity areas.

Peeters and de Dear (2008) developed Adaptive Temperature Limit algorithms for three zone types in Belgian homes. For the example of the studio, the two zone-types of the livingroom and the bedroom are applied in one room, to illustrate the possible variability in demand and the bandwidth. It should be noted that these algorithms are used as example for explaining the method, since they are based on the Belgian population. For cultural reasons this data cannot be translated directly for the Dutch situation as explained in the first part of the paper. However, such data is not available for Dutch dwellings and the Belgian climate is very similar to the Dutch so it gives a good image of the dynamics of thermal comfort and the difference for different activities. The method is fit to incorporate any algorithm relating outdoor climate and comfort with regard to the different activities deployed.

The schedules made for this paper are monthly mean schedules, based on monthly mean temperatures and average occupancy of this particular group. Table 1 indicates the monthly mean temperatures of the past 30 years in the Netherlands, based on data obtained from the website of the Dutch meteorological institute, KNMI (2009).

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
T_{Mean}	3,11	3,43	6,11	9,13	13,18	15,59	17,79	17,51	14,51	10,69	6,70	3,82

Table 1: Average monthly mean temperatures in De Bilt, Netherlands (1980-2009).

The algorithms for the Adaptive Temperature Limits adopted from Peeters (Peeters, Dear et al., 2008) are as follows;

Sleeping area

$T_n = 16$ for $T_{e,ref} < 0$ °C

$T_n = 16 + 0{,}23 \cdot T_{e,ref}$ for 0 °C $\leq T_{e,ref} < 12{,}6$ °C

$T_n = 9{,}18 + 0{,}77 \cdot T_{e,ref}$ for $12{,}6$ °C $\leq T_{e,ref} < 21{,}8$ °C

$T_n = 26$ for $T_{e,ref} \geq 21{,}8$ °C

Bandwidth

$T_{upper} = \min(26, T_n + w \cdot \alpha)$

$T_{lower} = \max(16, T_n - (1 - w) \cdot \alpha)$

Living area (reclining activity)

$T_n = 20{,}4 + 0{,}06 \cdot T_{e,ref}$ for $T_{e,ref} < 12{,}5$ °C

$T_n = 16{,}63 + 0{,}36 \cdot T_{e,ref}$ for $T_{e,ref} \geq 12{,}5$ °C

Bandwidth

$T_{upper} = T_n + w \cdot \alpha$

$T_{lower} = \max(18, T_n - w(1 - \alpha))$

10% PPD: $w = 5$; $\alpha = 0{,}7$

20% PPD: $w = 7$; $\alpha = 0{,}7$

Correction factor for living area light household work

$\Delta T_n = -8 \cdot (M - 1{,}4)$

With:

T_n [°C] = Statistical neutral temperature, in this work considered as comfort temperature.
$T_{e,ref}$ [°C] = Outdoor reference temperature (regarded as the monthly mean temperature.)
T_{upper} [°C] = Upper temperature limit
T_{lower} [°C] = Lower temperature limit
w [°C] = Width of the comfort band
α = Statistical constant
M [met] = Metabolic rate

The bandwidths Peeters uses, are those of the 10% and 20% percentage dissatisfied, according to Fangers PPD scale. In this study, the bandwidth is not considered as such, but as a spread in desired comfort temperature. In this respect, a bandwidth equivalent to 20% PPD is chosen, since it can represent a larger diversity in population. However, it could well be that the bandwidth is bigger. This needs to be researched via comfort surveys conducted in the Netherlands, before one could truly decide on that. For adjustment for increased metabolic rate during light household work, a correction factor is used according to ISSO 74 (Reference).

Some studies indicate that a rise (and fall) of temperature of approximately 1,5 °C per hour will not be noticed by the occupants (Baker and Standeven, 1996; Brager, Paliaga et al., 2004). Furthermore, a Japanese study found that rising the indoor temperature by 3 °C in the afternoon is beneficial for alertness and can decrease stress levels. In addition, in medical science it is acknowledged that regular strain benefits the cardiovascular health. Like the thermoregulation system, the cardiovascular system is regulated by the sympathetic nervous system. These two systems are related. There are indications that stimulation of the thermoregulation has a beneficial effect on the health system as well (Stoops, 2004). These studies imply that certain variability and thus a widening of the bandwidth during the day is possible or even preferable. Although in this study this is not included, it opens up possibilities for even more adaptive and sustainable solutions in comfort systems. The method to define occupant demand profiles described in this paper can easily fit in new ways of calculating thermal comfort, by adjusting the algorithms. The chosen algorithms illustrate the way it works.

Combining the data of occupancy, activity and daily average temperature leads to comfort temperature ranges in the schedules in figure 3, for the studio apartment in January and July, respectively the coldest and the warmest month of the year. The horizontal axis represents the time of day. The vertical axis shows the comfort temperature (based on average weather circumstances) and the range below and above this temperature. The lines for the comfort temperature in the figure represent the neutral temperature of one activity, to illustrate the difference between two different activities in the same room. It should be noted that according to studies mentioned above, these comfort temperatures can vary over the day, even within the same activity level. In this paper this is not considered. However, in the course of this research, this will be accounted for. As can be seen in figure 3, during the winter the comfort temperature for the sleeping activity and the day activities are very different, while in summer these two are almost the same. The difference in setpoint range and ambient temperature is significantly less than it would be if the house would be heated all day according to the 21 °C standard. Figure 3 shows that there are only two or three hours per day at which this temperature would be required and to cut energy use it can easily be a few degrees lower, without compromising comfort.

Furthermore, the ventilation during absence can be very low. If the dwelling is well insulated, the temperature drop during absence will be low as well.

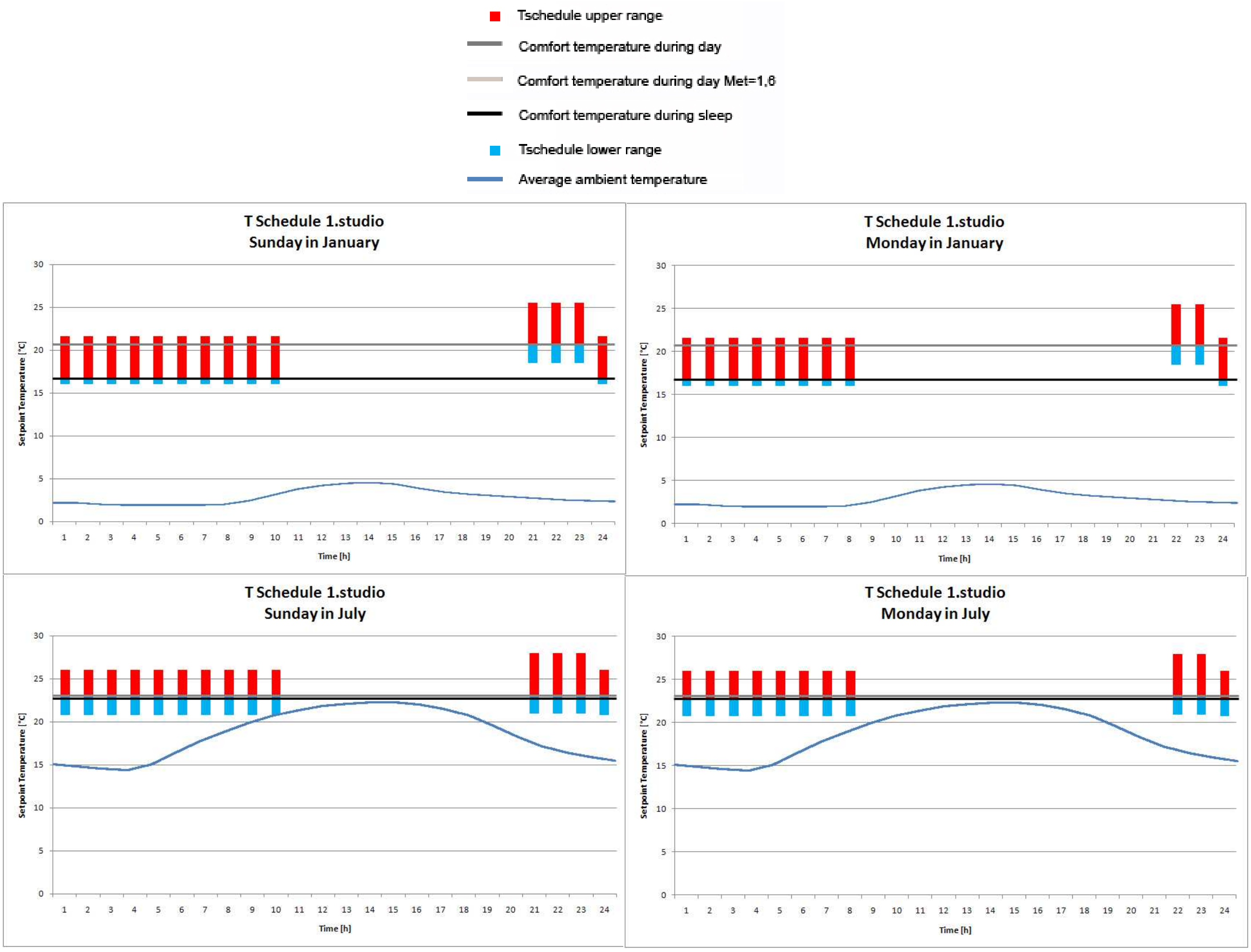

Figure 3: Schedules of comfort temperature and bandwidth according to occupancy schedules of a one person household in a studio apartment, in average weather circumstances.

Figure 4 shows the schedules for the living room and the master bedroom of the family home. Because this dwelling has more than one room, a schedule can be made for each room. In this paper, only the living room and master bedroom are shown and only Mondays to compare schedules with the studio apartment. Although there is a slight variance in comfort temperature within the living room area due to a change in activity level (reclining activity and light household work), it is less than in the studio room. The overall schedule per room is more constant and there are more hours of occupancy. As there is a comfort demand during the day, more use can be made of potential direct solar gain.

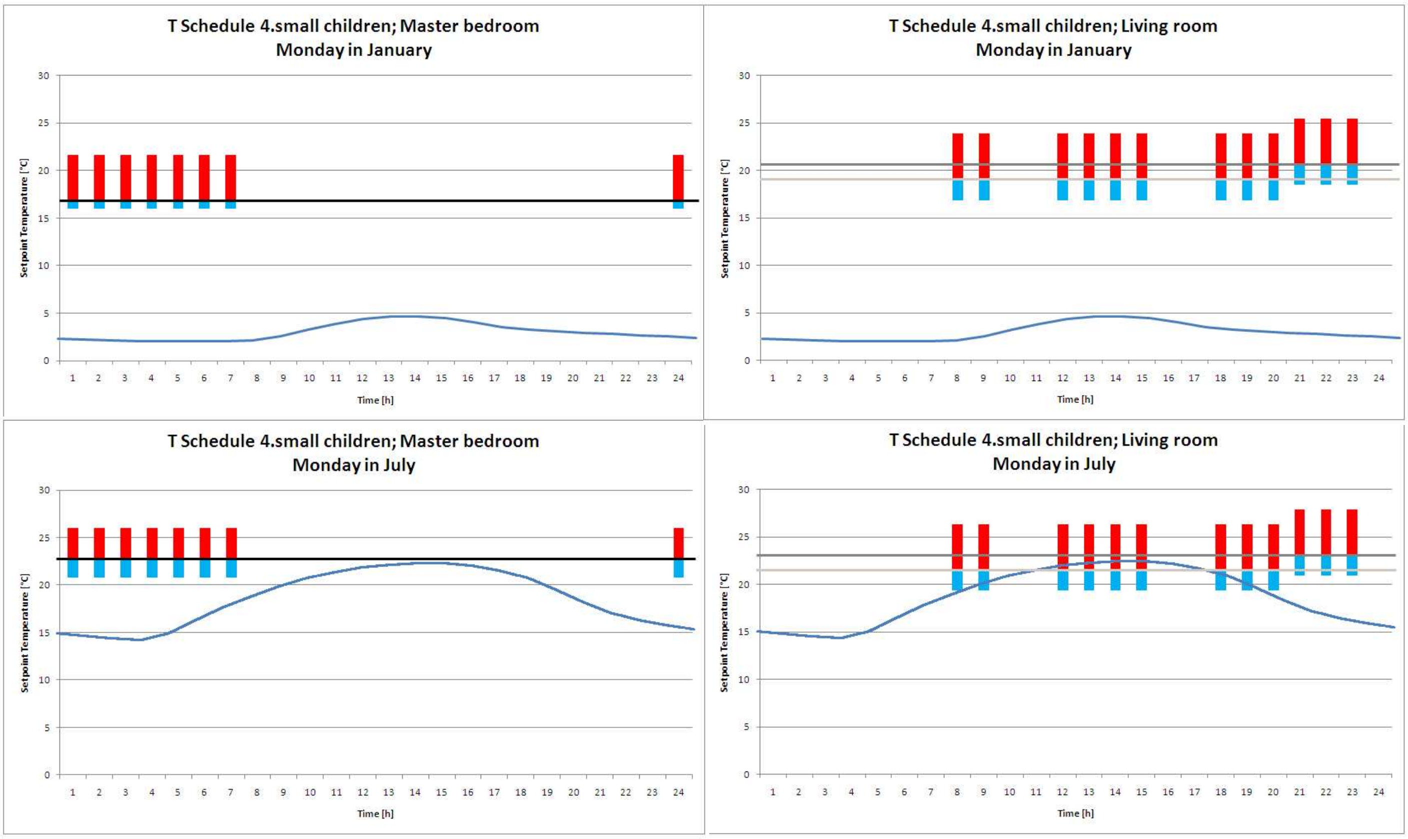

Figure 4: Schedules of comfort temperature and bandwidth according to occupancy schedules of a family with two small children.

Conclusions outlook

Comparing the two different situations one can conclude that an optimal comfort system for a studio apartment is not necessarily optimal for a family house. In addition, it can be seen that the performance of traditional comfort systems is highly dependent on use patterns. For instance, a home with an occupancy pattern like 1.studio could do with high insulation, variable ventilation and lower thermal mass, because the latter creates stability in temperature. Low thermal mass enables the operative temperature to drop when the occupant is going to bed, by means of increasing ventilation. In the case of the schedule of 4.small children, per room the desired temperatures are fairly constant because the comfort temperatures of the two different activities deployed in this room are closer (grey lines), so high thermal mass could be a good solution to stabilize the temperature per room.

Because the occupancy hours of the schedules are different, the demand for ventilation is also different. During absence the ventilation level can be minimized, minimizing the heat loss due to infiltration. This makes it useful to look at whether or not heat recovery will be profitable. According to the profile of domestic hot water use, one can decide to use the recovered heat for space heating or domestic hot water.

For space heating, to match both profiles it could be a good option to have basic heating at the level of 16 °C (the lowest comfort temperature) with additional heating when and where needed. The basic heating of 16 °C could be supplied by a slow system like floor heating, while the auxiliary heating could be supplied by a fast system like radiators or even electric wall heating. In the latter option, the air temperature could be maintained at a lower level, compensated by a higher radiative temperature on a big surface, making thermal mass applicable stabilizing the lower basic temperatures.

It is the aim of the PhD project, of which this paper is a part, to design robust solutions like mentioned above, that facilitate various use patterns and to unexpected weather circumstances while still having good energy efficiency. Building simulations will be made of different comfort system concept with various occupancy profiles and weather scenarios. With these simulations, considered will be the fact that the comfort system, one way or another, “knows” when the occupant is present and what comfort level is required as well as the expected weather conditions (to one or two days ahead). In real life, this knowledge can be obtained from sensors and human interfaces like buttons and sliders. The exact interface between occupant and system (buttons, sensors etc.) is outside the scope of this study; however, recommendations and preconditions for development will be given as well as energy saving potentials. The weather scenarios will be composed according to analysis of weather data of past years, in order to determine average patterns and variance, like was done with the user profiles. In this way, the system could anticipate the desired settings to secure comfort requirements are met at lowest fossil fuel use (adaptive dwelling).
Overall, this paper makes clear the aspects to be considered to assure occupant satisfaction and health concerning the thermal environment in dwelling as well as the energy saving potential of its approach not considering them to be opponent. Furthermore, it makes clear why an assessment method based on non-normalized user profiles would give a better image of the actual performance of a building in terms of thermal comfort and energy performance.

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