# Adaptive Principles for Thermal Comfort in Dwellings

## From Comfort Temperatures to Avoiding Discomfort

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*ABSTRACT: Many theories on thermal comfort exist and there are many ways to deliver this in an energy efficient way. Both aspects are often studied in a static way and most of these studies only regard one of the aspects, seldom investigating what influence the way of delivering thermal comfort has on the actual perceived thermal comfort. This paper analyses the knowledge of the different disciplines and integrates it to get a holistic image of comfort and its delivery systems as well as opportunities in energy saving and enhanced thermal comfort. Furthermore, it aims to understand the dynamics of weather, thermal comfort and occupancy in dwellings, finding the opportunities for quality improvement and energy saving. The paper explains the framework considered for further development of new concepts for comfort delivery and an analytical method for optimizing dynamic building characteristics. This research is part of a PhD project at the Delft University of Technology.*

*Keywords: thermal comfort, dynamic analysis, energy, adaptive dwelling*

## 1. INTRODUCTION

As civilization is advancing, the demand for thermal comfort is increasing, as is the case for all kinds of comfort. With regard to the design of thermal comfort amenities for homes, new concepts for dwellings should be developed to meet the development in increase of comfort demand. Specifically the need for flexibility and adaptivity of the dwelling and its comfort system are eminent in the following shifts of focus in the Netherlands [1]:

- More varying use of the home and individual spaces.
- Individual differences in (thermal) comfort experience get more pronounced and important to account for.
- Increasing differences in health sensitivity.
- Individualisation increases the need for prevention of internal nuisance.
- Increasing need for adaptability to future climate chance.

Technically, it is possible to provide any thermal environment requested and so is the provision of diversity in thermal environment. However, various studies point out that it is not only the physical thermal environment that determines thermal comfort [2-4] and that over-conditioning leads to more health problems and general complaints [5]. Furthermore, the greater the difference between outdoor climate and requested indoor climate, the more energy is required to supply and maintain this indoor climate. Therefore, it is essential to define the *range of environmental conditions* under which people feel comfortable, optimizing circumstances for health and productivity while limiting energy consumption. Besides the physiological parameters, other conditions should be considered as well, like the possibilities for influencing the environment and the context of thermal perception as this greatly enhances the acceptance of the thermal environment and thus the range of accepted temperatures.

In the office environment where the setpoint temperature often is to be controlled centrally it is still useful to determine average comfort temperatures for the target group. In this way it is likely that, statistically, as many people as possible are satisfied, optimizing their productivity. However, in dwellings people are considered in charge of their own environment and they should be able to control their setpoint temperature individually. The dwelling and the comfort system should facilitate the occupant to create their own environment. Furthermore, various studies point out that thermal comfort is not related to only one fixed temperature or temperature range [6-8]. It is also not possible to calculate thermal comfort with a formula of only physical variables, like the ASHRAE definition already implicates: "thermal comfort is a state of satisfaction on the thermal environment". The main conclusions are that thermal comfort, like the demand for other types of comfort, is very personal and relative to time, place and situation. These aspects shift the question from an actual comfort temperature to a range of temperatures that should be avoided to ensure absence of discomfort likely to occur due to the thermal environment and the variability of this range as well as the constraints for other aspects that influence the perception of thermal comfort. The main question becomes;

*What is the range and diversity of thermal comfort demand that can be expected and what are the most appropriate ways of delivering this thermal comfort in an energy efficient way without compromising the feeling of homeliness?*

Because there are so many factors that determine whether there is a demand for influencing the thermal environment for comfort and at which level, answering this question requires a multi-disciplinary approach. Not only the physiological and quantitative approach should be considered, but also sociological and cultural as well as the technical approach are necessary to be able to meet these various demands in an energy efficient way. Furthermore this paper aims to clarify the non-quantifiable qualities that homes should have in order to propagate the wellbeing of its occupants. After all, a home is a place to feel at home. Above all it should offer protection and comfort in a wider sense.

## 2. COMFORT AS A SUBJECTIVE AND DYNAMIC CONCEPT

When talking about comfort, the people that design and produce the systems to deliver it, quantify the concept of comfort by introducing standard calculation models, calculating the thermal neutral temperature using physical parameters as input. It takes the temperature of thermal neutrality as exact thermal comfort temperature, standardizing all people in one model. This approach is often applied as it is a clear method for assessing quality and predicting cost. These calculations by comfort models, like the heat balance model of Fanger [9], appear more scientific, because exact and finite. However, the requirements calculated from them are only reliably obtained by mechanical means, on which they are based. In this way, air conditioning created its own market and necessity because natural means cannot deliver these exact values [3]. However, quantifying this based on merely physical values leaves out important factors in perceived comfort. Without doubt, there is a thermal niche [10], defined by the range between a critical lower temperature and a critical upper temperature, outside which people would not survive for long. Inside this thermal niche there is also a general neutral zone, defined by a lower comfort limit and an upper comfort limit, within which there will be minimum effort to keep the heat balance between the body and the environment. However, the thermal neutral temperature isn't necessarily the same as the thermal comfort temperature. When the thermoregulatory system is balanced there are many other factors that determine one's comfort. If you are bothered by one aspect you are more likely to be uncomfortable by other things; so within the thermal niche, negative factors decrease tolerance for the thermal environment and cause to narrow the bandwidth in which people feel comfortable. Therefore, great care should be taken to how the comfort is delivered and the quality of the system, avoiding discomfort that can frustrate the feeling of comfort. Not only should the physical properties of thermal comfort be assessed, but also the non-quantifiable assets. Furthermore it deserves attention that people enjoy the action of alleviating discomfort rather than being comfortable all the time [11, 12].

The level of comfort is neither a static nor a global phenomenon. Neither is the occupancy or the activity in the house. The dynamics of stimuli experienced by the occupant, both thermal and non-thermal, bring about a perception of the thermal environment by the occupant. Depending on the thermal state moments before, but also the more distant past experience are important, as well as the state and personality of the occupant and the context of the thermal environment. The adaptive opportunities are of great influence as well, regardless of the actual physical change they cause. The perception of one and the same set of thermal conditions can be different almost any time. Therefore it should not be globally defined by standards and rigid numbers. In the end this can lead to expectations of homogenous thermal environments all over the world, which does not only have a negative effect on health and comfort, but can lead to excessive energy consumption, trying to fit all the indoor environments to that one rigid standard [2, 13]. Furthermore, people prefer diversity in their environment over a homogenous one, both in time as in locality [11, 14, 15]. In this way they are able to experience the thermal environment and enjoy it, which stimulates the feeling of homeliness.

To determine a range of the comfort demand that could occur, this research uses existing comfort models. However, the way it deals with these models is different, because it regards the models as probabilistic information rather than deterministic as well as taking into account the dynamics of comfort perception and taking into account more aspects than just the physical aspects.

In general, from the thermal comfort models developed from the 1930s, the adaptive comfort models (for example, ASHRAE 55 [16] or EN15251 [17]) best describe the situation in homes [18]. Because all of these standards were developed for offices, the following aspects need to be taken into account. The approach is evident in the following; this approach can be used as an opportunity to better provide the comfort demand and to achieve energy savings:

Thermal sensitivity of people varies with the context and expectation. This means that per individual, thermal sensation and comfort experience may vary, at constant thermal environmental factors. These can be both physiological (body weight, vaso-motion) and mental (expectation, habituation). In addition, people's thermal sensitivity may vary from person to person. Older people for instance are more sensitive to discomfort and hypothermia or overheating due to reduced thermal perception and reduced physiological adaptation [19, 20].

This means there is no fixed optimal temperature at which least people experience discomfort in a given situation. In this study, the comfort temperatures are not regarded as a precision. Because in the home, there is a small population which can control their own environment, these bandwidths are regarded as a probability distribution of increasing improbability of occurrence. This statistical dispersion of comfort temperatures will be greater in homes than in offices, because the sample is larger, with more individual differences, and the setpoint temperature can consequently differ significantly per household.

In homes the adaptive capabilities are typically greater than in offices by the possibility of customized clothing, activity, location and opening of windows and doors. This leads to greater acceptance of the climatic conditions and thus a broadening of the bandwidth of accepted temperatures.

Within the broad temperature limits that need to be secured, the controllability of the temperature and the thermal environment are almost as important as the temperature range itself. This means that the setpoint temperature is not a single value (like stated above) but a temperature range which can be easily adapted by the user within the given bandwidth and possibly even outside this bandwidth.

Adaptive Comfort Models focus more on a steady state situation, with one comfort temperature per day. However, the activities change throughout the day and so is the assessment of the comfort. This is partly due to the expectation that the temperature on the day varies by the natural course of the outdoor temperature and the response of the dwelling and its comfort system.

Different comfort bandwidths will be regarded for different functions because of the difference in activity levels, clothing insulation, expectations and adaptive opportunities. These algorithms are used as an example. Actual data for the Dutch situation is no available and the questions and data are mainly based on studies in offices, where the activities and overall circumstances are different than in dwellings. However, these algorithms are used as an example, to clarify the method. More data can later be implemented. The bandwidths for the living area are adopted from the SCATS project [7]. The bandwidths used for bedrooms and bathrooms are adopted from a Belgian research by Leen Peeters [21].

Figure 1 depicts boundaries for heating and (passively) cooling indoor spaces. The bandwidths are defined by the following boundaries; for heating, there is a minimum, given by the temperature above which most people feel comfortable and a predefined system boundary, above which more people will feel uncomfortable and therefore above which it would be inefficient to heat. Likewise, for cooling there is a minimum and a maximum of cooling for energy efficiency and thermal comfort. Even the width of the bandwidth can vary from person to person and even situation, according to the thermal sensitivity of people.

The following constraints must be bared in mind too:

For children the indoor climate is controlled by the parents. It is assumed that in general they have larger physiological adaptation, but because they have fewer behavioural adaptive capabilities it will comfort area within the same limits.

Adaptive comfort models can not directly be translated to use for actively cooled residences. This project will attempt to provide comfort without active cooling (use of (additive) energy for the generation of cold).

Combining the detailed weather data with detailed occupancy profiles can create detailed comfort demand profiles that inform about patterns in the required indoor environment. In this research, different occupancy patterns are compiled, for the most common household compositions and for comparison, some less expected patterns.

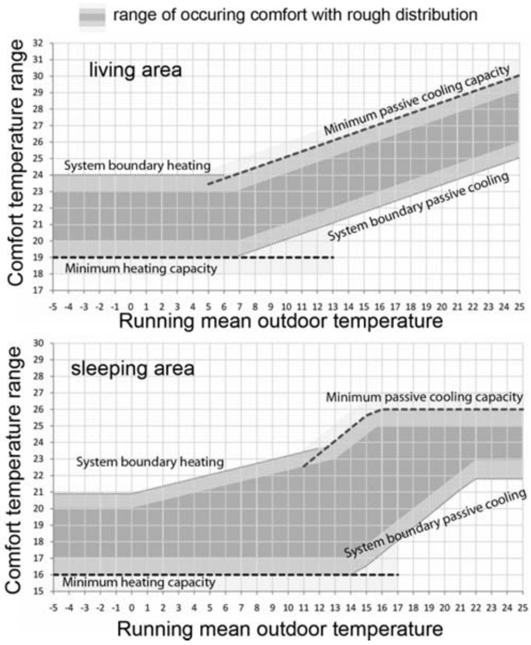


*Figure 1: Example of adaptive bandwidths for space temperatures for living areas and bedrooms as a function of the prevailing outdoor temperature (Running mean outdoor temperature).*

## 3. DYNAMICS OF WEATHER

To make the system able to seize upon every conceivable situation, an analysis of variance should be made, in order to know what kind of combinations of factors are most likely to occur and which situations are so rare that they could be omitted. A combination of frequency distribution, weekly occupancy profiles, simulation and load duration curves will be used in this study. The following weather variables are most influential on the indoor climate and will be compiled into frequency tables for the past 30 years in weather station de Bilt (the Netherlands):

- Ambient temperatures
- Solar irradiation (total on surface) (during day)
- Daily and hourly temperature fluctuations
- (Wind speed and direction)

The coincidence of some weather variables can pose extra constraints on the indoor climate and comfort. These will be compiled in cross frequency distributions, to see where highest demand will occur, for example:

- High ambient temperature + high solar radiation
- Low ambient temperature + high wind speed especially coming from North

## 4. DESIGN OF ADAPTIVE DWELLINGS AND COMFORT SYSTEMS

Most buildings are designed for average weather circumstances and the dynamic behaviour of the building is seldom regarded. However, if you look at the dynamic behaviour of weather and the occupant, the dynamic thermal behaviour of a building is crucial. Because of the diversity in perception and demand, the system should be flexible to be sufficient in all conceivable scenarios and adaptive to the changing user needs and be energy efficient in just delivering these fluctuations of need. A dwelling and its comfort system can be designed to benefit from the prevailing *dynamics* of weather and occupancy, adjusting various settings, like insolation, insulation and ventilation, according to these dynamic demands and outdoor climate.

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T outdoor within comfort bandwidth

*Figure 2: Frequency table depicting differences between outdoor temperature and demanded temperature bandwidth for a living room in July in 'de Bilt' (the Netherlands), with occupancy hours and bandwidth of comfort temperatures.*

With the frequency tables per hour of the day (possibly compared to average daily course per month) together with occupancy profiles per room, an estimate can be made of variance of occurring demand and possible solutions. In figure 2 an example is given with the comfort bandwidth (2K above and below the average comfort temperature) and an example of occupancy hours.

The dynamic thermal behaviour of a building can be outlined by a number of specific properties. The properties of delay and damping the indoor temperature fluctuation relative to the behaviour of the outdoor temperature are most important. These influences can be calculated in an analytical way by an estimation model. In this model the settings of the building (e.g. high or low insulation / shading on or off) can be calculated, per hour or per day, depending on the techniques used. The following parameters are considered dynamic:

Instantaneous (independent variables)

$T_i^*$ = required indoor temperature [°C]
$T_e$ = outdoor temperature [°C]
$q_{sol}$ = solar incidence [W/m2]
$W_{int}$ = internal heat gain [W]

Instantaneous (control variable)

$H_{vent}$= characteristic heat loss coefficient by ventilation [W/K]

Per day or season (control variables)

$H_{trans}$= characteristic heat loss coefficient by transmission [W/K] (e.g. thermal shutters)
g = ratio of admitted solar incidence through a transparent surface [W/K]
M = accessible thermal mass [J/K]

Instantaneous (Dependent variable)

$W_{inst}$= heating or cooling power applied [W]

The independent variables are $q_{sol}$, $T_e$, and $W_{int}$. The dependent variables are $T_i$ and $W_{inst}$; $T_i$ should remain in the $T_c$ range (thermal comfort bandwidth) and $W_{inst}$ should be minimized. All other variables can be considered control variables, that are adjustable within certain ranges and with a certain rate, depending on the variable and techniques used. With these equations, the optimal settings for these variables can be calculated per hour or per day and possibly per season. These settings could then be depicted in similar frequency distributions as for the weather and thus determine the required physical behaviour of adaptive comfort systems for dwellings and their components.

Numerous Climate Responsive Building Elements and installation techniques are already available or being developed which can fulfil these required physical behaviours and this research can give an impulse for others to be developed.

## 5. ADAPTIVE HEATING AND PASSIVE COOLING

The now remaining energy demand for comfort ($W_{heat}$) should be delivered in an energy efficient and flexible way with a high degree of user control.

In the summer season the aim is to avoid all active cooling by preventively flushing excess heat to ensure that the upper limit of the comfort temperature is not achieved (not even during absence). However, these passive measures are slow and cannot prevent that the temperature still rises at the time of activation of the measures. Because these measures are far less energy demanding than active cooling, they can be used as a preventive measure, when the temperature has not yet reached the upper limit and also during absence. The Dutch climate is suitable to provide for the required indoor climate in this way for the major part of the year. If the dynamic behaviour of the home has been determined, the threshold temperature for preventive passive cooling can be specified as well.

In winter, if passive measures are not sufficient, heating is required. However, the patterns of presence can be unpredictable and the general and average schedules programmed in the usual clock thermostat for heating can cause the heating system to be operational even if people are absent, or the need to adjust the thermostat when present unexpectedly. This almost always leads to unnecessary and unwanted energy use because the thermostat is not turned off automatically at times of unscheduled absence and people will take a margin leaving the heating on, in case they would be home unexpectedly. Furthermore, normally the thermostat only controls the sensor in the living room, thus heating the entire dwelling at the same time. To account for this lack of predictability of the comfort demand, it is useful to operate the heating on momentary presence per room or zone. With an eye on comfort and energy saving, the heating preferably only switches on at presence. This means that the heat up time must be limited. There are various measures to ensure fast heating up: for instance enough capacity, low thermal mass or a certain lower limit for the temperature at absence. The behaviour of the total system, the passive and active components of the house, defines these parameters. During this heat-up-time the basic temperature should be reached and subsequently the temperature can be adjusted according to the preferences of the user.

Basically, the heating can be turned off immediately when leaving the room. The temperature will not quickly drop in a well-insulated house.

The building elements should be flexible and responsive to the dynamic circumstances of weather and user demand (operable shutters, blinds, windows etc). The ranges of flexibility of the different elements, like range of U-value for the windows or range of ventilation capacity, can be determined by the use of the estimation model mentioned in paragraph 4.

Provided the temperature behaviour is predictable and there is a possibility to correct the temperature within the given comfort area, the temperature may fluctuate at a speed of 2 K/h maximally. This fluctuation is hardly noticed and has no negative impact on comfort [19]. With simulations, the outcomes will be validated.

## 6. FURTHER CONSIDERATIONS; USER ACCEPTANCE

Like all (new) technologies, in order for people to accept them and to propagate the desired behaviour to make the system efficient, a number of factors need to be considered first before designing and being able to pronounce in the end on energy saving or quality of the building. The two most important factors are Perceived Usefulness and Ease of Use, like described in the Technology Acceptance Model (TAM) used in sociology and information management [22]:

- Perceived Usefulness:
  *The degree to which a person believes that using a particular system would enhance his or her daily life.*

- Ease of Use:
  *The degree to which a person believes that using a particular system would be free of effort.*

To ensure a high degree of Perceived usefulness and ease of use, the following aspects need to be considered

Motivation: The occupant needs to know why an amenity is there. For heating or cooling this is evident, but for ventilation this is not always the case, let alone if the ventilation system is combined with the heating or cooling system. In the case of energy saving it is even more difficult. Saving costs in energy is usually not so obvious. The energy bill is only presented in the end of the year and mostly people don’t know exactly how and where energy is saved.

Transparency in operation: The occupant needs to experience in one way or another, why the system is doing what it’s doing. If there are too many things going on of which the occupant doesn’t know what the purpose is, this can lead to stress, discomfort and counteractions to alleviate this discomfort. However, the counteractions can be irrational if the occupant doesn’t understand the systems action, which can lead to more energy consumption, system failure and even more discomfort. This is especially important for systems that operate things that concern our health, like ventilation and to a lesser degree heating and cooling.

Flexibility: The settings should be flexible to be sufficient in all conceivable scenarios.

Control: It is important that occupants have as much control as is practically possible. Various studies point out that when occupants can control their (thermal) environment, the tolerance for inconveniences increases. These controls should be, like the system itself, perceivably useful [12, 23, 24].

In their report on controls for end users, Leaman and Bordass discuss the requirements for good controls [23]. The main aspects are listed here:

Intuitive: To increase the ease of use for most occupants, the controls need to be intuitive as there is no possibility for training, other than a written guide.

Feedback of control: If the control is used, there should be an immediate feedback that shows the system status. This could be a tangible feedback like a click, or an indicator light indicating the system had “read” the control input.

Feedback of effect: The intended effect of the control should be noticeable. This could be the heating of the radiators that shows the furnace is on.

## 7. DISCUSSIONS AND CONCLUSIONS

Contrary to what the thermal comfort legislation and standards claim, there is no need for precise comfort temperature prediction or measuring in dwellings. Regarding the diverse and dynamic character, together with the adaptive possibilities in a dwelling, make it feasible to assess the thermal comfort quality of a dwelling by its amenities, flexibility and control possibilities. Furthermore, to be able to design a flexible dwelling and comfort system, a method is proposed to analyse the dynamics of both the outdoor climate and the occupancy and comfort preferences, on which future comfort systems for dwellings can be based.

The method can also provide more insight, besides simulations used for legislation purposes, to analyse the response of the building to the outside world (climate) and the possibilities of occupant's interaction with the system and adjustment of the system to their needs. In that way a risk analyses can be made as to which extreme situations can be tolerated as rarely occurring and which situations need to be avoided and at which cost to prevent unnecessary excessive energy consumption.

The remaining work for the PhD will be the development of concepts for comfort systems that can provide the required flexibility and comfort quality in an energy efficient way. The concrete results of the PhD will be guidelines for designing a flexible and adaptive dwelling with an integrated comfort system.

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