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The potential of the adaptive thermal comfort concept in long-term actively conditioned buildings for improved energy performance and user wellbeing

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Abstract. Technological progress in conditioning practice combined with prevailing thermal comfort criteria, created stable, tightly controlled indoor temperature bands. Research shows indoor temperatures to be increasing in the heating period, leading to higher building energy use than planned. Field studies provide proof that occupants not in control of their indoor climate are more dissatisfied and report problems in wellbeing. Widening temperature bands could be an effective measure leading to energy conservation, increasing satisfaction and, as shown recently, helping to mitigate health problems related to our way of life. The adaptive approach to thermal comfort postulates that people's thermal comfort perception adapts to the indoor and outdoor climatic conditions they normally experience. However, according to standards, the adaptive model is applicable only to passively conditioned (free-running) buildings, even though the adaptive principles may well apply also to actively conditioned buildings. Our review found studies demonstrating positive health effects and energy conservation potential in permanently or seasonally conditioned buildings. On this basis, the potential of the adaptive approach and translations into concrete design or operation solutions for actively conditioned buildings are discussed in this paper. We conclude that the adaptive concept offers a potential for indoor climate control in actively conditioned buildings in the temperate and cold climates.

1. Introduction

In current developed societies people spend most of their lives indoors and the environmental conditions they experience affect their health, comfort and wellbeing. Over the last six decades there has been a trend towards creating stable indoor climates, where temperatures remain with low variance throughout the year. A number of developments contributed to this: (i) the large uptake of central heating, air conditioning and ventilation systems with heat recovery, (ii) the increasingly high standards of building insulation and airtightness, and (iii) thermal comfort criteria developed 50 years ago that have been interpreted to promote indoor temperature stability. Low variance temperature ranges have become the norm and people consider it to be the ideal conditions, even though there is strong indication that it has an impact on wellbeing, apart from being energy-intensive.

In terms of thermal comfort, field studies have shown that people's thermal preference ('comfort climate') adapts to the indoor and outdoor climatic conditions they normally experience [1]. This means that indoor temperature can follow a climate-adaptive variation throughout the year, which can lead to reduced energy for heating and cooling and clipping of peak loads by 'relaxing' the current common static temperature set-points, whilst still providing comfort. Unlike static temperature set-points commonly used for controlling indoor environments, adaptive temperature ranges can provide a healthy seasonality in indoor climate, leading to more tolerant and proactive occupants. However, until now adaptive models have been developed and included in international standards only for naturally ventilated (free-running) buildings in summer based on results under these conditions [2, 3], even though the adaptive principles may still well apply to air-conditioned buildings [4]. Translating the adaptive comfort principle for buildings with the necessity of long-term active conditioning would lead to user-centred, more effective and energy-efficient indoor climate control. This approach, amongst others, is addressed in guidelines developed within Annex 69: "Strategy and practice of adaptive thermal comfort in low energy buildings", on how to use the adaptive comfort concept for lowering the energy use in buildings, including the usage of personal thermal comfort systems [5, 6].

The objectives of this paper are: i) to review and summarize evidence on the benefits of adaptive comfort for wellbeing (health and comfort), ii) to demonstrate the potential energy savings from applying the adaptive comfort concept to actively conditioned buildings and iii) to discuss how the concept of adaptive thermal comfort can offer solutions through a new interpretation and transformation of the adaptive principles to actively conditioned buildings. Insofar we mainly address the United Nations sustainable development goals a) good health and well-being for a better life (SDG03), b) sustainable cities and communities (SDG11) as well as c) responsible consumption.

2. Method

We base our analysis on: the "Framework for adopting adaptive thermal comfort principles in design and operation of buildings" developed in the IEA-EBC's Annex 69 [5]; a literature review; information and insights from building practice. We discuss the findings from literature and interpret them with regard to their potential for future solutions for actively conditioned buildings.

3. Increasing and stabilising indoor temperatures

The history of indoor temperature development in temperate and cold climates shows that technological development, wealth and availability of energy have contributed to a changed heating and conditioning practice of using buildings but also of designing buildings [7]. In the early 20th century rooms had a heating device (furnace) but bedrooms and side rooms were normally not heated. In 1935, the German Health Authority recommended winter temperatures between 17.5 and 18.5°C for decentralised or centralised heating, stating a room temperature above 21°C is regarded as being "overheated" [8]. Temperature measurements in first German demonstration projects of energy efficient buildings in the 80ies ("Solarhäuser Landstuhl") showed a temperature practice between 17 to 23°C in the living rooms and 16°C to 21°C in the bedrooms [9]. When upgrading buildings' heating systems from decentralised heating devices (furnace) to a central heating system, the energy use in these buildings increases by 20%, as the mean temperature of the non-renovated buildings is typically 16-17°C [10]. With changed conditioning practice the expectations of what a comfortable temperature is, have changed. Mean temperatures in a German passive house project were measured in 50 apartments to 22.4°C (range 20-24.5°C) with a standard deviation of 1 K [11]. In Sweden, Teli et al. [12] reported daily mean temperatures of 22°C with about 80% of all values above 20 and below 25 °C. At the same time they found a very low standard deviation of 0.7 K. In some dwellings and houses the standard deviation was as low as 0.1 K. Mean temperatures in other regions, as reported in [13, summarised in table 3 in 12], give lower temperatures in UK: 19.0°C+/- 2.5 K, Tokyo, Japan: 19.6+/-2.8 K, Harbin, China: 20.1+/-2.4 K, and Beijing/Shanghai, China: 21.4+/- 2.7 K.

Design temperatures for different levels of expectations and rooms of different usage are given in ISO Standard 17772-1:2017 [3], ranging from 18/21°C for living rooms/ bedrooms to corridors with

14/18°C or 19/21°C for offices. Having in mind these design temperatures are given for the design of heating systems under extreme outdoor conditions, the temperatures measured in everyday practice seem, at least for countries with traditionally cold winters like e.g. Sweden, Denmark or Germany, to lay systematically above these temperatures. Variation of the temperatures *between* different spaces might be lower than what the design temperatures imply.

Factors like ownership [14], or whether heating costs are paid by a lump-sum instead of equivalent to use [15], and the level of energy efficiency of houses may impact the temperatures found in practice. Teli et al. [15] report on the adaptation of occupants of UK social housing blocks to high indoor temperatures (23.8+/-1.3 K). Users of Danish energy-efficient houses tend to have higher indoor temperatures compared with users of less energy-efficient houses [16].

4. Health and comfort impacts of stable indoor temperatures

There is increasing evidence that tight temperature ranges impact on wellbeing. Stable indoor conditions work at odds with human biology [17] and the adaptive nature of human behaviour [18], while geophysical cycles, such as climate variation, are interlinked to numerous biological processes and therefore isolation from them may contribute to the decline in 'human seasonality' [19] or adaptability. Evidence from scientific research focuses on two areas, i.e. the health impacts from living in rather stable, thermoneutral environments and the effects of transient thermal environments on comfort and health.

Studies have found that people in air-conditioned offices are more sensitive to temperature drifts than those in naturally ventilated buildings [20] and to have weaker thermoregulation [21]. The health impacts of constantly experiencing low-variance thermoneutral conditions are mainly associated with diseases related to: obesity, diabetes and cardiovascular diseases [22]. Stable indoor temperatures within a tight comfort zone have been highlighted over recent years as a potential contributing factor to body weight gain and obesity [23-25]. More importantly, excursions outside thermal neutrality can have positive health effects, e.g. an improved health status of patients with type 2 diabetes [26, 27]. For example, exposure to 19°C, which is considered a mild but tolerable cool temperature, results in a significant increase in energy expenditure [28]. The most likely responsible parameter for this is brown adipose tissue (brown fat), which produces more heat than any other body tissue when activated by cold [22]. Furthermore, as demonstrated in thermal comfort research, thermal exposures outside thermal neutrality lead to a wider range of accepted temperatures [1].

Wang et al. [29] found that the occupants in residential buildings in the North of China adapted to a warm heated environment gradually during the whole winter represented by a higher indoor temperature at the end of the winter compared to the start of the heating season. Occupants living in the unheated thermal environments in the South-East China zones are more adaptive and tolerant to cooler winter indoor conditions than those living in the North part of China where central heating systems are in use [30].

Whereas thermal comfort is mostly an unconscious perception, as the body does not receive any signals of a disturbing stimulus from the thermal environment, positive feelings (pleasure) will occur when slight discomfort perception was successfully mitigated, often through behaviour of the person; a phenomenon called "alliesthesia" [31, 32, 33]. Whether a behavioural adjustment was successful in restoring comfort is a psycho-physiological feedback signal [34], which comes from the skin when a change of the skin temperature in the desired direction is perceived [35]. From surveys among passive house occupants it is reported that temperature variation is preferred, especially for bedrooms [36]. Evidence from laboratory studies shows pleasure perception in a temperature zone with reverse trend than the previously experienced temperature [37].

5. Discussion: Energy saving potentials in conditioned buildings' operation

The potential occupant-related reasons contributing to the energy performance gap in buildings have been previously summarised as follows [38]: i) changed temperature regime (set-points), ii) changed conditioning schedules (intermittent/night set-back or shut-off vs permanent), iii) changed spatial conditioning (extended availability of conditioning systems to more rooms), and iv) changed occupant behaviours e.g. clothing habits. Energy savings can therefore be realised through addressing these items.

Changed temperature regime (set-points): Energy demands for heating and cooling are determined by the temperature that HVAC systems are set to achieve. As reported in section 3 exemplarily for residential buildings, there is evidence that winter temperatures indoors have been increasing. Raised temperature set-points can lead to increased use of energy of 5 to 15% per 1 K increase - depending on the climate. It is normally expected that with better insulation this influence decreases. Surprisingly, Stein and Müller [39] reported on an increased energy use of 15% with every degree higher indoor temperature and typical user behaviour. This is supported by reported energy use in extremely low energy buildings from Germany [11] and Denmark [40] which show about 25 to 40% more energy use than calculated.

The typical temperature dead band (i.e. range) in air-conditioned office buildings is 22-24°C [41]. Widening this temperature band, hence i) reducing the indoor-outdoor temperature difference, meaning conditioning at lower temperature in winter and higher in summer, ii) implementing a long as possible period in which a building is neither heated nor cooled, is a very effective energy reduction strategy, while being low cost, technically easy to implement and has been vigorously investigated in research studies. Savings in a modelled office building in the USA have been estimated at 32%–73% of HVAC energy consumption depending on the climate [42], while indoor temperature reduction to 20°C in the Swedish residential housing stock would achieve the second greatest energy savings of 14% amongst a set of 12 measures, including several costly technical solutions [43]. In a recent study, a multi-objective optimization of HVAC set-points resulted in up to 60% energy savings without compromising comfort, using the PMV model in the optimization process [44]. The above savings are based on widening the static set-points.

A further development of this idea is the implementation of advanced control algorithms. This can be reached through ICT technologies (integrated building automation with communication) as proposed in EN 15232 and leading to energy savings in the range of 10 to 30% compared to standard thermostat use [45]. The premise of adaptive comfort is that people adapt to and can accept a wide range of temperatures. The ability to adapt to variable temperatures means that cooling and heating may not be required at all (free running mode) or may be required at certain times (mixed/hybrid mode), depending on outdoor climate. In this respect, energy savings are achieved by reducing the heating/cooling hours. In air-conditioned buildings savings can be achieved through the use of adaptive set-points, i.e. temperature set-points based on adaptive thermal comfort models [2, 3, 46]. Unlike the static set-point widening described above, the adaptive set-points follow the weather variability.

This approach is not currently supported by the international standards ASHRAE-55 [2] and ISO 17772-1 [3] which include adaptive comfort models only for buildings without mechanically conditioning. There is indeed an inherent limitation in using the existing adaptive comfort models in mechanically conditioned spaces, since the models were derived from data collected in buildings without mechanical cooling. An exception is the Indian Model for Adaptive Comfort (IMAC) [47], which includes a separate model for mixed mode buildings based on relevant data. The model has been included in the Indian National Building Code 2017, the Energy Conservation Building Code 2017 and building certification schemes.

One of the first estimations on the energy savings from using adaptive set-points was based on an initial version of the adaptive model from the SCATs project [48], which formed the basis for the model included in the European Standard EN15251 [46], now [3]. An air-conditioned building in the UK was used as a case study, which was using a rather conservative cooling set-point of 22°C [48]. Savings of 30% were achieved by using the adaptive comfort set-point instead, without compromising occupants' thermal comfort. In another study, based on 13,523 individual comfort votes from AC buildings, an adaptive model was developed which confirmed the dependence of occupants' comfort temperature on the outdoor climate, even when they experience tightly controlled thermal environments [4]. An approximate estimation of the cooling energy savings from using the AC adaptive model instead of the previous fixed temperature set-point of 23°C gave on average 22%. The advantage of such approaches is, that they rely on the recent history of thermal experiences of people outdoors, i.e. taking into consideration whether the recent development of the outdoor weather showed an upwards or a downwards trend. Typically, and driven by adaptation delay, the comfort expectation has a delay of about one week [48] expressed with the prevailing mean outdoor temperature [3]. For the building design phase, optimal building thermal mass control [49] might be a suitable strategy to extend the time a building can be operated in a free running mode.

Changed conditioning schedules: Saving potential might also be found in within-day temperature variation. In residential buildings, different user types were identified. Gruber et al. [9] identified energy saving user behaviour which includes: night set-back, applied by energy-efficient users and normal users. High energy consuming users do not apply night set-back. Huebner et al [50] for the UK and Teli et al. [12] for Sweden report similar patterns for the building stock. In highly energy-efficient houses, night set-back strategies would cause only slight changes because of their rather high thermal inertia due to high insulation levels.

Changed spatial conditioning: Temperature variation in space has been requested by occupants in low energy buildings, especially in bedrooms [36]. A longitudinal survey among passive house users in Germany shows a tendency towards adaptation to new conditions [39]. Whereas 50 to 68% perceive the bedroom temperature as too warm in the first survey after moving in, after living for a time in the new indoor environment they get used to the new conditions, resulting in now 45% (after 6 month) or 35% (after 3 years) of the occupants still perceiving the bedroom temperature being too warm. Georges et al. [51] investigate how a zoning could be realised in passive houses with mechanical ventilation with heat recovery. In their pilot study they show the impact of the thermal properties of the separating walls and a changed ventilation control strategy. Because of the widespread design of central mechanical ventilation systems with heat recovery, these systems contribute to a more even distribution of recovered heat in the building and reduce the necessity of additional heat supply – hereby also reducing the opportunity to maintain lower temperatures than average in certain rooms. Another aspect is the availability of elements separating rooms, e.g. doors – elements not necessarily to be found in more contemporary floor plan layouts. Spatial variation in conditioning in office buildings has been investigated recently for the cooling case and has been identified as offering benefits for thermal comfort perception and for energy conservation [37, 52].

Changed occupant behaviour: An underestimated effect is the behavioural adaptation by adjustment of clothing. Although standards [53] show that clothing adjustment can compensate for differences in temperatures of 1 to 2 K, this opportunity is seldom used or promoted. In 2005, Japan introduced the CoolBiz campaign in order to cut the peak power demand for cooling in summer. The cooling set-points were raised to 28°C and the government set an example with relaxed summer adjusted dress code.

Individualised conditioning practice: Instead of conditioning whole spaces with comfortable temperatures, personalised comfort systems follow the idea of an increased personal control through providing locally additional heat or cooling [54]. With this approach, the difference between outdoor temperature and indoor temperature can be reduced, called corrective power [55], ranging from 1-6 K for cooling and 2-10 K for heating. Local fan use can relax the indoor temperature requirements through enhanced heat dissipation from the body by about 2-3 K [2].

6. Conclusion

People adapt to the environment they are regularly exposed to. The increasing temperatures we reported on in section 3, support an interpretation that occupants get adapted to the indoor environments with slightly increasing temperatures over time. First, tight indoor climate control isolates us from annual and seasonal rhythms, which could have significant implications for our health and wellbeing, such as body weight gain and increased sensitivity to temperature variations. The latter is important considering the climate change projections for more variable and extreme weather events in the future. Secondly, maintaining stable indoor temperatures in climates with variability requires the use of large amounts of energy. Are we wasting energy and money to create conditions that make us more vulnerable?

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Evidence shown in this paper (especially section 4 and 5) suggests that transitioning from stable, energy-intensive indoor temperatures to climate-adaptive temperatures based on occupants' thermal response would yield significant benefits. The way such adaptive temperatures are applied should be adjusted to the type, use and particularities of each building, i.e. residential, educational, etc. In the face of reports that e.g. newly built energy efficient houses cause difficulties for some people to adapt because they provide *too high* temperatures in winter and *urge* them to adapt, we may discuss whether our new building practices enhance a development which counteracts our long-lasting efforts to reduce the energy use in buildings. The widely accepted assumption that stable, uniform indoor temperatures throughout the year would be the ideal situation needs to be revisited.

From our discussion in section 5 it follows, that if people in current indoor environments do not get exposed to temperatures outside the comfort range and therefore adapt to the specific indoor temperature they experience, future indoor environment design should consider planned exposure to indoor temperatures slightly outside the comfort range in order to minimise such adaptation. This would then be followed by positive health effects and improved thermal comfort perception and energy conservation. There are several strategies available to further develop energy efficient buildings without negating what we are doing already. Temperature zoning, night set-backs, promotion of seasonally adjusted clothing would certainly contribute to reversing this overall trend. However, more intense research is required in order to derive concrete design recommendations. We are reliant on mechanical conditioning parts of the years in many climates. Therefore, we should direct our efforts towards minimising the period of active conditioning in order to contribute 1) to energy conservation, 2) to prepare people for climate change through supporting their adaptability and at the same time 3) to contribute to their health and wellbeing indoors. Promoting and applying design practices and behaviours that follow an adaptive thermal comfort concept have the potential for this transition.

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