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Mitigating climate change through healthy discomfort

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Abstract. Amid the climate change and the worldwide catastrophes, witnessed on a daily, we find ourselves in a time in which we need to start justifying any recourse and energy consumption, at least of which is not truly renewable. While the outside temperatures become more extreme, the inside environment becomes more relevant. The way we design and operate our buildings is directly influenced by current building standards and as we spend almost all our time indoors, our comfort, wellbeing and health are crucially affected by such. The last five decades have seen many approaches in establishing guidelines for a comfortable indoor environment. But while current standards favor the narrow temperature ranges of static homogeneous environments, they have been criticized for their high energy consumption and long-term health implications. The paper compares a typical office space with mechanical cooling with that of a passive strategy, by evaluating the energy consumption and health over comfort. The results show a 64% cooling potential within the mechanically cooled scenario as well as the passive strategy complying to standard without any cooling energy.

Keywords: Thermal comfort, health, mechanical ventilation

1.　Introduction

According to the German government, the building sector is one of the main emitters, accounting for 14% of the total CO_2 emissions in Germany. If emissions from the production of electricity and district heating as well as building materials are included, this figure doubles to 28%. On the other hand, the necessary reduction of greenhouse gas emission according to the Paris agreement assumes 66 - 67% until 2030, compared to the values of 1990. [1] An essential part of this target lies in the responsibility of the energetic building renovation and more concretely in the reduction of the mechanical cooling and heating energy. The required energy demand for indoor cooling is gradually rising at an average pace of 4%/year since 2000 and makes up roughly 16% of the total building sectors energy consumption worldwide. This has led to a doubling of the respective CO_2 emissions between 1990 and 2020. [2] With the advancing climate change and most recent predictions of a warming of 1.5°C in the next 20 years compared to 1990 [3], indoor cooling has become a focus of necessary adaptation [4-6]. Air conditioning, being one of the most common strategies of indoor cooling, is therefore expected to grow by 40% more units worldwide until 2030. [2] This trending development of mechanically regulating the indoor temperature poses real challenges to the energy sector and its necessary reduction of greenhouse gas emissions.

2.   Problem Statement and Hypothesis

One, often-overlooked reason for the high energy consumption of Air Conditioners (AC) is the usage according to the current building standards of indoor environments. The thermal indoor environment is evaluated by comfort and addressed by standards like the ASHRAE 55 [7] in the USA, the DIN EN 16798-1:2021-04 [8] in Germany, or the International Organization for Standardization (ISO) 7730 [9]. The standards thereby define the acceptable temperature range of indoor environments to meet the average comfort perception of users. Most standards accept temperature ranges between 2 – 9°C, depending on typology and season. While maintaining a relatively tight range of acceptable indoor temperature demands a relatively high energy consumption, accepting a wider range does the opposite. Besides saving resources when allowing for larger variation in indoor temperature, it might also benefit our health and wellbeing. Recent studies show a significant correlation between a uniform thermal exposure and cardiovascular diseases [10] as well as type 2 diabetes [11]. When evaluating the energy efficiency within the building sector we must therefore address the question why we are heating and cooling buildings as strictly as we do.

The paper is made up of two parts. The first reviews how we evaluate indoor environments nowadays and briefly summarizes more recent findings towards the negative impacts of current standards on our health and wellbeing. The second part evaluates the potentials towards energy-efficiency and health when rethinking the current standards, with a simple simulation of five scenarios. The hypothesis of the paper is that future climate mitigation can be achieved through passive strategies that allow for wider temperature ranges within indoor environments, therefore reducing the energy demand and leading to healthier indoor environments.

3.   Part I – Literature review

3.1. Evaluating Comfort

Many human responses are coherently related to environmental stimuli, so that increasing exposure to light or noise, for example, elicits a similar positive or negative response. The louder the environment, the more unpleasant. The same is true for the lack of light in any given environment. This relationship between stimulus and response does not apply to temperature, where a linear increase in temperature leads to an inverted U-curve in comfort. [12] While a moderate thermal environment is considered comfortable by most people, the extremes of a cold or hot environment lead to dissatisfaction and, in the worst cases, extreme physical reactions like hypothermia or hyperthermia [13]. This sensitivity towards small variations in body temperature can offer insight into the state of human well-being, health, stress, and productivity [14].

It has long been known that weather can have a major impact on our behavior and psychological wellbeing. But more recent literature shows that this influence on humans, can be observed not only in outdoor weather, but also in indoor climate. [15] The fact that humans spend more than 90% of their time indoors [16] makes it essential to study the possibilities and limitations of thermoregulation and possible adaptation. Many indexes have been proposed to quantify and predict indoor thermal comfort. As the PMV/PPD and later the adaptive comfort theory have found their way into current standards, norms and recommendations, they will briefly be introduced in the following.

The Predicted Mean Vote (PMV) was first introduced by Ole Fanger in 1970, when evaluating data from field studies as well as laboratory studies done by himself [17]. He concluded the magnitude of discomfort as the function of the six parameters: Air temperature (Ta), Radiant temperature (Tr), Relative Humidity (rH), Air velocity (v), Clothing factor (clo) and metabolic rate (MET). With this Fanger went on predicting the thermal perception of hypothetical subjects in any evaluated environment on a scale from Hot + 3 to Cold − 3; 0 being without any discomfort. Furthermore, he constructed the Predicted Percentage Dissatisfied (PPD), as the relation between the mean vote and the people uncomfortable with the environment [18], as seen in **Figure 1** [7].

The adaptive comfort theory was introduced in 1976 by Humphreys and Nicol explaining a shift of people's indoor comfort temperature preference according to the outside climate, allowing not only for seasonal shifts of preference within one location but also shedding light on differences dependent on climate zones. [19] The adaptive comfort, as used for passive buildings (buildings without mechanical cooling) by almost all standards nowadays, relates the comfort indoor temperature to the outdoor temperature by exponential averaging of the running mean outside temperature.
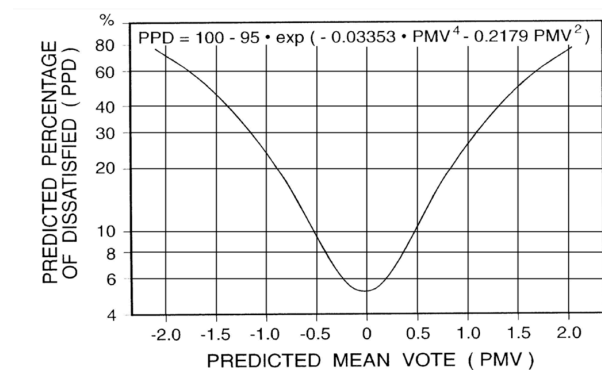
**Figure 1.** PMV-PPD relation according to Fanger as seen in [7]

Standards like the DIN EN 16798-1 in Germany take both indexes into account when evaluating the indoor environment. While the acceptable indoor temperature range for passive buildings adjusts according to the outdoor temperature as established by the adaptive theory, the range for mechanically ventilated buildings is defined by four categories according to the PMV/PPD as seen in **Figure 2**. [8]

I	< 6	$-0,2 < PMV < +0,2$
II	< 10	$-0,5 < PMV < +0,5$
III	< 15	$-0,7 < PMV < +0,7$
IV	< 25	$-1,0 < PMV < +1,0$

Figure 2. Acceptable PMV/PPD for indoor mechanically ventilated environments according to DIN EN 16798-1:2021-04. From left to right: Category, PPD and PMV [8]

Following the concept of the PMV/PPD the standard assesses an indoor environment close to PMV=0 as most desirable and therefore encourages narrow temperature variations, with the maximum indoor operative temperature to be ≤ 25,5°C (Category I), ≤ 26°C (Category II), ≤ 27°C (Category III), ≤ 28°C (Category IV) during the cooling period. [8]

Passive buildings (without mechanical cooling) are assessed only through the adaptive comfort theory by relating the indoor operative temperature to the moving average value of the outdoor air temperature. It thereby also differentiates between three categories (I,II,III) with varying temperature ranges (5°C, 7°C, 9°C), that are shifted asymmetrically as seen in **Figure 3**. While the assessment of passive buildings allows for overall wider temperature ranges, compared to that of active buildings, it also favors the tightest temperature ranges.
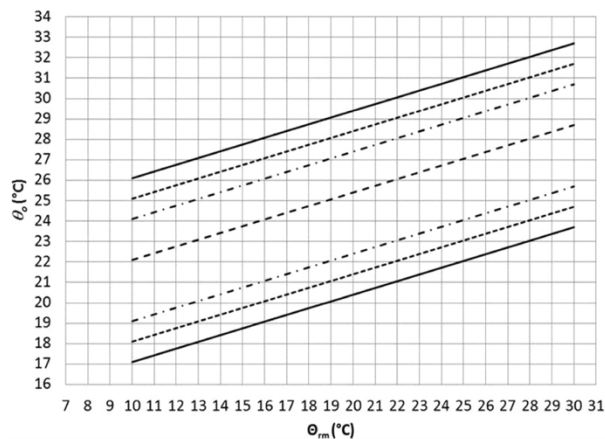
Figure 3. Adaptive comfort range for passive indoor environments according to DIN 16798-1 with the X-axis describing the outdoor mean running temperature and the Y-axis describing the indoor operative temperature [8]. From outermost lines inwards: Category III, Category II, Category I and optimum indoor operative temperature.

3.2. Evaluating Health

When addressing the indoor thermal environment, standards as shown focus on the terminology of comfort and discomfort. Comfort thereby describes the feedback of how people feel within a certain static environment or as described by ASHRAE 55 [20] as "the condition of mind that expresses satisfaction with the (thermal) environment and is assessed by subjective evaluation." The underlying studies represent an individual's perception of a time and place, that are then scaled and averaged to fit all people's needs. This subjective feedback of a homogeneous sample, represent only a small percentage of the worldwide population with comparable preference. The PMV/PPD for example shows big variation in accuracy when comparing different ages [11], sex [21] or climate zones [22]. This is further critical as this narrow range is becoming even more homogeneous on a global scale and throughout seasonal weather shifts. [23] One reason may be the worldwide growing use of Air Conditioners that allow for consistent indoor environments independent from the outside. [24] Furthermore, there is strong evidence, that perceived thermal comfort has little to do with what are healthy conditions for the human body. Studies done by Yao, et al. (2007) conclude the subjective vote of the PMV to be correlated closely to the skin temperature and more specifically to single regions of the body. Therefore "the overall thermal comfort will closely follow the parts of the body that feel the most uncomfortable in a cool or warm environment." [25]

More recent technical advances enable literature to focus on analyzing stress. From a physiological standpoint stress can be defined as a reaction to various environmental stressors triggering alarm, resistance and exhaustion. Stressors are thereby defined as „exogenous or endogenous stimuli, events or conditions that are able to elicit the stress response." [26] All mammals contain biologic systems like the nervous system, cardiovascular system, musculoskeletal system, or the immune system, that are in constant communication with themselves or their environment through changes in electrical activity, pressure, chemical concentration, temperature and more. [27] The human peripheral nervous system consists of the somatic (conscious) and the autonomic (unconscious) system (ANS). During stressful periods the body utilizes more sympathetic activity, that derives from the ANS, produces stress hormones, increases the heartrate and forces an increase in heart contractions. While eustress describes the human body successfully coping with these reactions and returning to a decreased level of activity, distress, occurs in situations where the body can't recover from this increase in neuroendocrine reaction and sympathetic dominance of the ANS function. [28] While it is nearly impossible to quantify thermal comfort as it is an abstract concept of various parameters, it is possible to objectively measure and compare the ANS responses to environmental stressors. [29] As stress is a measure of how much the body is working it can also indicate its long-term wear and tear effects on the persons health. [30] While

the relation between stress and health has been ongoing research for many decades in the fields of medicine, neurology, physiology, psychology, etc. [31] it is more recently occurring within the building industry, which has led to new insight into the health implications of thermal environments.

Current studies show that the energy expenditure, brown fat activity and obesity, skeletal muscle metabolism, insulin sensitivity, blood pressure cardiac output and the immune system of humans are all linked to the influence of our individual temperature profile. Metabolic syndrome is thereby amongst the most researched and widespread health issue around the world. It accounts for obesity as well as type 2 diabetes, cardiovascular disease and certain types of cancer. [23] While a positive energy balance is necessary to counteract obesity, most recent research assumes that long exposure to thermal neutral environments, does the exact opposite. [23, 24, 32-34] Several studies were able to show that cold and warmth both effect the metabolic health and mild colds to positively increase the energy metabolism without shivering. This non-shivering thermogenesis (NST) increases energy expenditure in temperatures between 14 – 16°C for lightly clothed, lean adult, and in temperatures as high as 19°C and regular exposure for two hours per day for six weeks to 17°C, as shown in a study done by Yoneshiro, according to Lichtenbelt, et al. (2017) [23]. Not only did the temporary exposure to cold conclude a health benefit but an increasing capacity for NST in all age and health groups examined. The same temporary exposure profiles also demonstrated an increase in insulin sensitivity and improvement in cardiovascular stability. Even more surprising the studies showed not only the necessity of thermal fluctuation as a health benefit but a change in comfort perception as well. Van Marken Lichtenbelt, et al. (2017) state that "with respect to thermal (dis)comfort, it was shown that during the experiments involving 10 days of cold acclimation, thermal comfort changes from uncomfortable to just comfortable." [23]

Another study done by Ivanova, et al. (2021) was able to show higher energy expenditure and activity levels when the participants were exposed to a drifting temperature of +2.58°C/h in the morning and –2.58°C/h in the afternoon and overall range between 17–25°C, in alliance to the maximum fluctuation of ISO 7730. Within the study, the PMV vote drifts accordingly from slightly under -1 to slightly above +1 in the morning and from slightly under +1 to slightly under -1 in the afternoon, indicating little correlation between perceived comfort and health. The authors furthermore refer to similar result in increased energy expenditure in a study with a higher temperature range of 22-27°C. [34]

All studies to the knowledge of this research, conclude that a temporary exposure to heat and cold outside of the comfort zone (PMV= 0) can benefit our metabolic health, insulin sensitivity, cardiovascular and immune system, while trends in the last decade show an increasing homogeneity in indoor temperatures throughout the year. [23] While it's crucial for the body to maintain a stable core temperature, literature suggests a constant indoor temperature to be counterproductive. Or in other words, while too much stress is not so good for our health, neither is too much comfort. As this seems to be closely related to the temporal dimension of thermal stress, the physiological reaction of the body depends highly on the time of exposure as well as the time of the day [29]. As the human body follows a circadian rhythm, it will tend to react more strongly to heat in the afternoon as it will in the morning. [29, 35, 36] Even though there is more research needed to understand the boundary conditions of such healthy temperature fluctuations, it is vital to address the accompanying standards. Kramer et al. (2016) were able to calculate a 63% reduction of a museum's total energy demand with an increase of ± 1°C temperature fluctuation compared to the current uniform conditioning. As this still complies to the ASHRAE standard it exemplifies the enormous saving potential of indoor conditioning. [37]

While comfort and wellbeing are often subject of evaluation, it may be more appropriate to evaluate the inflicted health implications. Considering the current necessity to sustainably minimize recourse consumption as well as the new gained knowledge of possible health implications by the strictly uniform climatization of the indoor environment, subjective comfort perception can no longer be justified as the main evaluation metric. Comfort has always been a luxury that we can no longer, and may have never been able to, afford.

4.   Part II – Simulation

Rather than aiming for PMV= 0 (Category I), as shown in the standard DIN EN 16798-1, the accompanying simulation explores the possibility of focusing on the cooling energy saving potential within the absolute necessary comfort range (Category IV). Subject of the simulation is an office space with common usage boundary conditions defined in several European standards.

4.1. Boundary Conditions

The simulation consists of five scenarios; the four categories of PMV/PPD as described in the standard (**Figure 2**), represented by actively cooling the operative room temperature to the respective upper temperature limits, and one passive scenario without any active cooling but elevated air speed (ceiling fan) instead.

The simulation uses the predicted weather data for Mannheim as the most extreme summer temperature scenario within Germany. The weather data, obtained from the German Weather Service (DWD, dt.: Deutscher Wetterdienst), is provided in form of a test reference year (TRY), representing averaged but typical meteorological conditions [38]. These can either reflect past measurements as well as climate forecasts of the year 2045, showing higher summer temperatures, due to the current and predicted climate change. As the simulation aims to analyze the limitations of the energy saving potential and thermal comfort range the most extreme weather situation was chosen. The simulation therefore depicts the week with the highest 24h-mean ambient temperature within the TRY2045 summer scenario. The simulated office space is 6.5 m wide, 5 m deep and 2.75 m high. The south facing façade has a window-to-wall ratio of 60 %. These geometrical assumptions are based on [39]. The heat capacity of the room's components are assumed according to DIN 4108-2 and DIN EN ISO 13786 as a "medium-weight construction". The insulation quality of the outside wall (U-value of 0.19 W/(m²*K)) represents current German standards [40]. Assumptions regarding internal gains, such as people, equipment and light, as well as necessary air change rates and other usage-related inputs are based on Swiss standard SIA 2024:2015 and German standard DIN V 18599-10. Specific measures for all scenarios include external sun protection (radiation-controlled) and nighttime ventilation to reduce the operative temperature effectively during user absence.

The investigated office space represents a common building standard, incorporating already effective measures for reducing extreme heat stress in summer. The scenarios only distinction lies in the upper temperature limit allowed to be experienced by the user according to DIN 16798-1. Scenarios 1 to 4 are limited to 25.5, 26, 27 and 28 °C operative temperature respectively through active cooling. The passive scenario 5 does not provide any mechanical cooling.

Detailed information about the simulation model can be obtained from the authors of this study.

4.2. Results
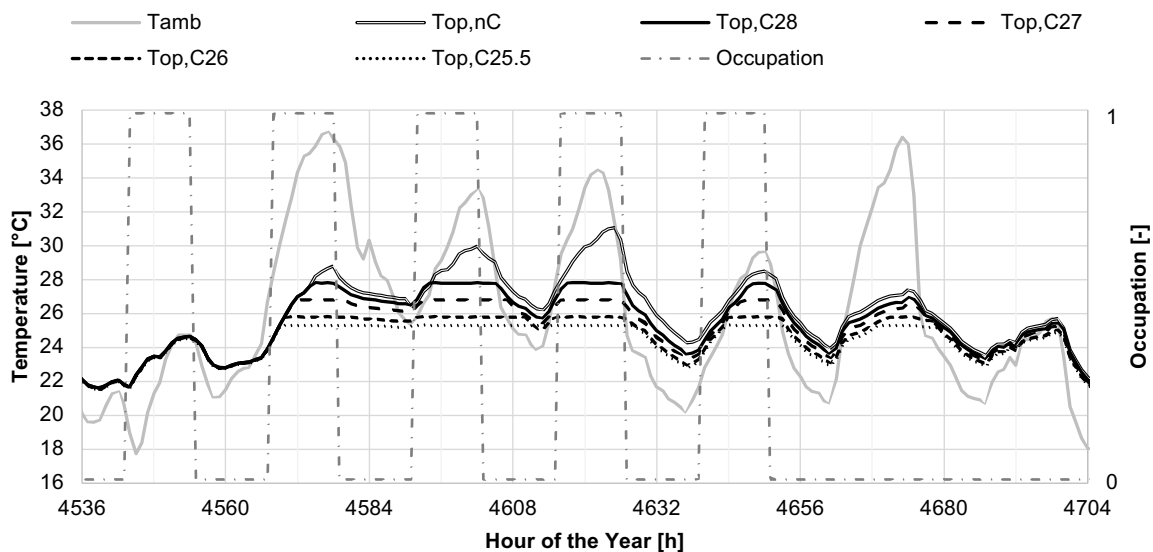
Figure 4. Temperature Profile of the five scenarios for the warmest week of the TRY2045 data prediction.

Figure 4 depicts the temperature profile of the ambient outside temperature (Tamb) and the operative indoor temperature (Top) of the five scenarios as well as the occupation periods with 1 being occupied and 0 not occupied. Due to effective nighttime ventilation, external shading and decent thermal mass, even operative temperatures in scenario 5 stay below outside temperatures for most of the occupied time. The highest indoor temperatures and therefore also highest cooling loads occur after two nights of ambient nighttime temperatures never dropping below 24 °C (between hour 4584 and 4632).
Scenario 1 (C25.5) – 4 (C28) depict the necessary temperature cap through mechanical cooling according to the categories I – IV of DIN 16798-1 respectively. Scenario 5 (nC) doesn't use any mechanical cooling, with the Top ranging between 22 – 31°C (acceptable after Category II), with a maximum range of 5°C per occupation and day.

The temperature profiles manifest themselves in the cooling energy demand for the investigated summer week, as seen in **Figure 5**. An increased upper temperature limit can therefore reduce cooling demand within periods of extreme heat significantly. Limiting the allowed operative temperature to 28 instead of 25.5 °C therefore reduces the energy demand by 64%, while still complying to the standards Category IV maximum operative indoor temperature. This suggested maximum temperature range within mechanically ventilated buildings, that are simulated as the scenarios, rely on the assumed PMV/PPD range as seen in **Figure 2**. The passive scenario also aligns to the necessary requirements utilizing no cooling energy at all.
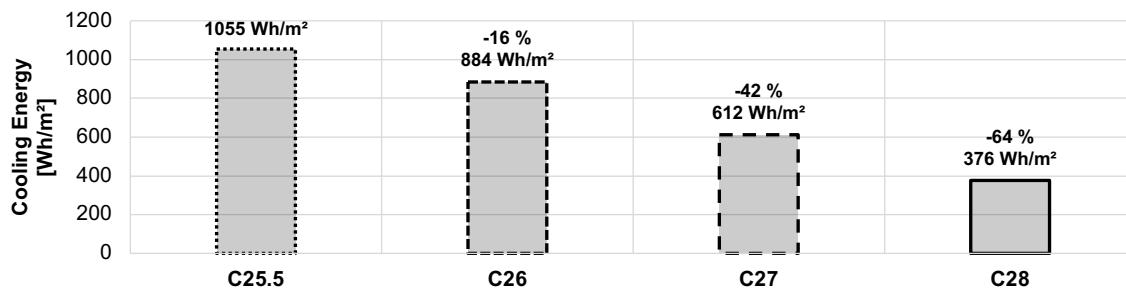
Figure 5. Cooling energy demand of scenarios 1-4, with mechanical cooling.
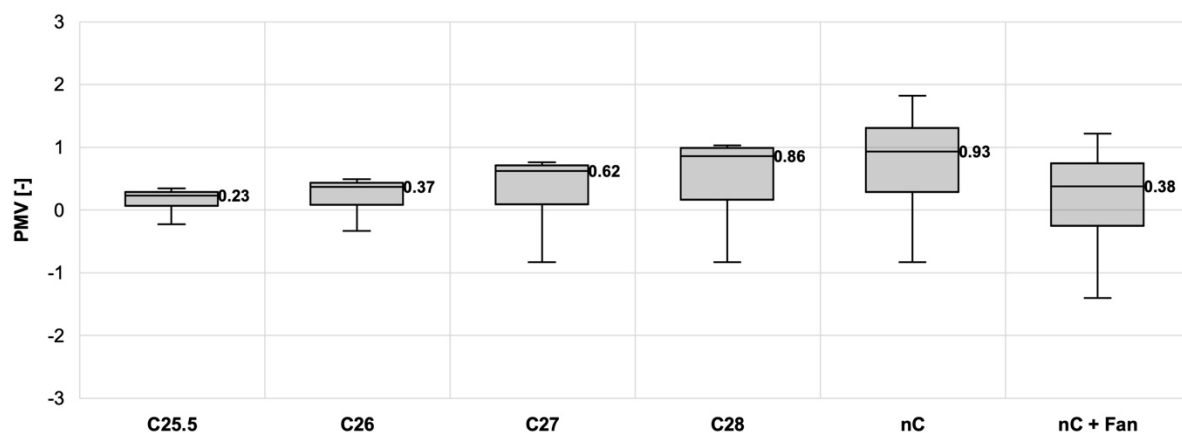
Figure 6. PMV values of the scenarios 1-5 and scenario 5 (nC) + Ceiling Fan with v= 0.25 ms-1.

Figure 6 comprises the range of all hourly PMV values during occupation throughout the simulated week. Next to the five known scenarios, a sixth scenario (nC + Fan) depicts the PMV range of scenario 5, when equipped with a ceiling fan that provides 0.25 ms-1 elevated air speed (v) at all times of occupation. The boxplot indicates the PMV range by depicting the upper and lower quartile (boundary of the grey box), extremes (top and bottom horizontal line) and median value (shown also as number). While scenarios 1 – 4 show most values in the positive (warm) range of the PMV they seem to be fairly in line to the respective categories I – IV of the DIN 16798-1.

Even though the passive scenario 5 (nC) depicts rather high perceived discomfort, when including a light air breeze through a fan, into the PMV calculation, the median value shifts by -0.55 as seen in scenario 6 (nC + Fan). This comes to show that even though the Top of the scenario without mechanical cooling ranges beyond the acceptable ranges set for active buildings, the underlaying limits of PMV can still be complied with, even in the passive scenario. When introduced to even higher air speeds this range keeps shifting further to the negative spectrum of the PMV range, even though it should be noted that air speeds over 0.8 ms^{-1} start to become a problem within office environments, as these speeds can blow away loose paper.

While energy intensive adaptation like change of temperature is often used to assess the *right* thermal environment, this simulation raises the question if passive adaptation could be an equally successful way of climate mitigation. Even though the DIN 16798-1 offers a compensation of increased air temperatures through air velocity [8], this may also be relevant to other behavioral adaptions like change in clothing or accounting for the overall exposure time. While not surprising, the passive scenario 5 (nC) in Figure 4 shows that the highest temperatures occur at the end of the workday between 4 and 6 p.m., due to the accumulated solar gains throughout the day. While these temperatures might cause thermal stress to the body, it is important to assess this as not being a constant but rather a temporary exposure,

shortly before the occupants leave the building. This aspect of exposure time must therefore be more closely evaluated, as mentioned in *3.2.   Evaluating Health*.

5.   Conclusion / further research

Current norms focus on the air and operative temperatures as the main indication of the thermal environments effect on human comfort and as a justification for a uniform steady environment to be a healthy and satisfying indoor environment, whilst accepting enormous energy consumptions. By contrast recent literature shows this goal of achieving a uniform optimum temperature to be counterproductive to our health and wellbeing. The simple simulation depicts the energy saving potential of an office room by allowing for passive temperature fluctuation and adaptation through air velocity, while still following the maximum acceptable range of standard and achieving similar PMV values. Following research by the authors will focus on recreating this as well as other passive adaptation strategies (i.e., clothing factor) in real laboratory experiments, to understand the thermal stress and overall physiological processes during different environmental conditions within similar PMV ranges.

Achieving energy efficient systems and at the same time embracing healthy environments by changing the operation of the buildings HVAC- systems provides a fast and cheap opportunity for climate mitigation in the building sector. It is vital to address the PMV/PPD and adaptive comfort theory as a momentary subjective response to a thermal environment that includes many biases and can't indicate healthy environments. More research is needed to understand the upper temperature exposure limit to an individual's health, considering the time of exposure as well as the age, sex and overall health conditions. Achieving better insight into the medical consequences of thermal exposure, can help us design solutions where we embrace thermal fluctuations of passive environments by having the indoor environment work with the human body instead of against it. Gaining more knowledge in the relation of individual physiological processes, adaptive behavior and our indoor environment is a crucial research foundation for the needed design solution of our time and that to come.

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