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Comparative Evaluation of Natural Ventilated and Mechanical Cooled Non-Residential Buildings in Germany: Thermal Comfort in Summer

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Abstract

This paper presents a detailed analysis of thermal comfort in summer for 19 low-energy non-residential buildings in Germany, applying the comfort standard EN 15251:2007-08. The study aims to propose (1) a methodology for the evaluation of thermal comfort, (2) to discuss redefined constraints for the thermal comfort standard EN 15251:2007-08, (3) to analyze the thermal comfort, and (4) to assign the buildings studied to three comfort classes I, II and III.

In summer, eight buildings employ a nighttime ventilation concept in order to condition the building. The other 10 buildings use geothermal energy (ground and ground water) as environmental heat sinks to cool the buildings via thermo-active building systems (TABS). For comparison, one building is air-conditioned.

A method is proposed to determine and evaluate thermal comfort in a building. It is suggested, to present the time of occupancy, where 84 % of the building area complies with comfort class I, II, and III. Therefore, each building with its energy concept for heating, cooling, and ventilation gets its individual *thermal comfort footprint.*

Keywords: building monitoring, thermal comfort, thermo-active building systems,

EN 15251:2007-08, PMV-PPD, low-energy cooling

1 Introduction

This paper presents a detailed analysis of thermal comfort in summer for 19 low-energy non-residential buildings in Germany, applying the comfort standard EN 15251:2007-08. Although different architectural approaches and designs were applied, the objective for all buildings studied was to reduce the primary energy consumption significantly with carefully coordinated measures (Table 2).

An extensive long-term monitoring of the building and plant performance was carried out over two to five years. The monitoring data consist of hourly measurements of the room temperature, the cooling energy supplied to the building, the auxiliary energy use required for harvesting the cooling energy from environmental heat sinks, the auxiliary energy use necessary for distributing the cooling energy through the building, and local weather conditions. Thermal comfort assessments of the buildings in summer are determined according to the adaptive and PMV-PPD comfort approach of the European standard EN 15251:2007-08, using the number of hours during occupancy when the operative room temperatures exceed the defined comfort classes.

2 Thermal Comfort – objectives and methodology applied for the evaluation

Current national and international regulations draw on diverse results from thermal comfort studies carried out in laboratories or in the field. There are two main models to determine human thermal comfort and to predict the occupant's satisfaction with the interior conditions: (i) the PMV-PPD approach defined in the standard EN ISO 7730:2005 and (ii) an adaptive approach described in the standards EN 15251:2007-08, ASHRAE55:2004, and the Dutch Guideline ISO 74:2005 [van der Linden et al. 2006]. Hellwig et al. (2008), Voss et al. (2006) and Olesen et al. (2002) have presented an overview of the current national and international thermal comfort standards and regulations.

PMV-PPD approach to thermal comfort EN ISO 7730:2005

The PMV-PPD approach [EN ISO 7730:2005] is derived from the physics of heat transfer and is combined with an empirical fit to sensation (predicted mean vote, PMV and predicted percentage of dissatisfaction, PPD) [Fanger 1970]. The required four environmental input variables are air and mean radiant temperature, air speed, and humidity. The two personal variables are clothing and metabolic heat production. Therefore, the person is a passive recipient of thermal stimuli since the occupants' response to the thermal environment is expressed in involuntary actions such as shivering or sweating [Kwok et al. 2009].

Adaptive approach to thermal comfort EN 15251:2007-08 and ASHRAE55

Since the publication of the PMV equation in the 1970s, there have been many studies on thermal comfort in buildings under operation. Some of these studies have given support to PMV while others have found discrepancies, and it has become apparent that no individual field study can adequately validate PMV for everyday use in buildings [Humphreys et al. 2002]. EN 15251:2007-08 and ASHRAE55 describe the adaptive approach that includes the variations in the outdoor climate and the person's control over interior conditions to determine thermal preferences [van der Linden et al. 2006], [Olesen 2007]. It is based on findings of surveys on thermal comfort conducted in the field.

Therefore, standards for thermal comfort in summer differentiate buildings according to the HVAC systems installed [ASHRAE 55:2004, EN 15251:2007-08] into (i) "mechanically cooled buildings" which must guarantee the very stringent comfort conditions specified by EN ISO 7730:2005, and (ii) "non-mechanically conditioned buildings", which allow the application of the adaptive comfort model.

The challenge for a sustainable building design will be to comply with state-of-the-art standards for thermal comfort by featuring energy-efficient systems for cooling and heating [Roulet et al. 2006a and 2006b], [de Dear and Brager 2001]. The authors believe that the variety of heating and cooling concepts of the building stock and new constructions cannot be covered by just two categories in the current European standard EN 15251:2007-08, i.e., mechanically cooled and non-mechanically cooled buildings. On that account, it is necessary to differentiate between more categories of building types and HVAC systems. Table 1 proposes five building categories: (1) air-conditioned buildings, (2) mixed-mode air-conditioned buildings, (3) low-energy buildings with mechanical cooling, (4) low-energy buildings with passive cooling, and (5) buildings without cooling.

Unfortunately, the national and international denotation of energy concepts of buildings is ambiguous. In the U.S., mixed-mode buildings are understood as buildings that are mainly air-conditioned but use free ventilation of the office area during periods with favorable ambient conditions. The European understanding differs from that definition insofar mixed-mode buildings employ cooling technologies with a limited power (e.g., use of environmental heat sinks), but abstain from full air-conditioning.

2.1 Objectives

The study presents a comparative evaluation of thermal comfort according to the European standard EN 15251:2007-08 in the 19 non-residential buildings. The allocation of the buildings to comfort classes is based entirely on long-term measurements. It is not the intention to correlate measurements of operative room temperature with occupant satisfaction derived from post-occupancy evaluation. Furthermore, it is not discussed whether current comfort standards adequately represent occupant satisfaction with the thermal environment of the workplace. For that reason, user behavior (in terms of opening windows and using solar shading) was not observed.

The objectives are to:

(1) to propose a methodology for the evaluation and the presentation of comfort ratings

(2) to discuss redefined constraints for the thermal comfort standard EN 15251:2007-08,

(3) to analyze thermal comfort, and

(4) to assign the buildings to the comfort classes I, II and III.

Table 1 Proposal for a categorization of building types for the evaluation of thermal comfort.

building	heating/cooling concept	ventilation concept	occupant	comfort approach
I: AIR-CONDITIONED (AC) BUILDING				
(usually) sealed building envelope	heating and cooling by air only	de-/humidifying air	no influence (closed windows, no solar shading), no adjustment of temperature set point for heating/cooling, dress code	static approach with constant set points independent from outdoor conditions according to ISO 7730:2005
II: MIXED-MODE (AC) BUILDING				
standard quality building envelope, use of few passive heating and cooling technologies [1]	heating and cooling by air only	de-/humidifying air and additionally natural ventilation through open windows	operation of windows and solar shading, no adjustment of temperature set point for heating/cooling, dress code	static approach with constant set points independent from outdoor conditions, during periods with natural ventilation more frequent exceedance of comfort boundaries is allowed
III.1: LOW-ENERGY BUILDING WITH WATER-BASED MECHANICAL COOLING				
high quality building envelope, use of passive heating and cooling technologies [1]	*heating*: fossil fuels, environmental energy sources, biomass, co-generation, heat pump and TABS *cooling*: environmental heat sinks and TABS	hybrid ventilation² for hygienic fresh air (30 – 40 m³/h and person) if, necessary de/-humidifying of air	high user influence (operation of windows, doors, solar shading system), no or minor influence of influence of occupant to adjust temperature set point for heating/cooling, no dress code	adaptive approach according to EN 15251:207-08, but with more stringent comfort boundaries, e.g., definition of maximum indoor temperature allowed
III.2: LOW-ENERGY BUILDING WITH AIR-BASED MECHANICAL, COOLING				
high quality building envelope, use of passive heating and cooling technologies	*heating*: fossil fuels, environmental energy sources, biomass, co-generation, heat pump and TABS *cooling*: mechanical night ventilation	hybrid ventilation	high user influence (operation on windows, doors, solar shading system), no adjustment of temperature set point for heating/cooling, no dress code	adaptive approach according to EN 15251:2007-08 in dependence on the running mean ambient air temperature
IV: LOW-ENERGY BUILDING WITH PASSIVE COOLING				
high quality building envelope, use of passive heating and cooling technologies	*heating*: fossil fuels, environmental energy sources, biomass, co-generation, heat pump and TABS *cooling*: passive night ventilation through inlet vents, windows	natural ventilation	high user influence (operation on windows, doors, solar shading system), no adjustment of temperature set point for heating/cooling, no dress code	adaptive approach according to EN 15251:2007-08 in dependence on the running mean ambient air temperature
V: BUILDING WITHOUT COOLING				

[1] *passive heating/cooling technologies*: high-quality building envelope, passive use of solar heating gains, day-lighting concept, sun-protection glazing, static solar shading devices, heavy-weight building construction, moderate ratio of glass-to-façade
[2] *hybrid ventilation*: natural ventilation through windows and inlet vents and mechanical ventilation (supply and exhaust air system)
[3] The term *mechanical cooling* does not encompass full air-conditioning (heating, cooling, de-/ humidifying of air)

2.2 Methodology

The proposed methodology for the evaluation of thermal comfort in non-residential buildings varies from EN 15251:2007-08. The alterations derive from comprehensive investigations of thermal comfort in buildings by means of measurements. Thermal comfort in all buildings was analyzed for the following varying constrains:

(i) *Reference temperature for ambient air*: Three variables were examined to define summer and winter season: (i) daily mean ambient air temperature, (ii) running mean ambient air temperature and (iii) daily maximum ambient air temperature.

(ii) *Building space*: Thermal comfort ratings were analyzed considering 95, 84, 75 and 68 % of the building.

(iii) *Exceedance of comfort classes*: Thermal comfort ratings were discussed considering an acceptable exceedance on a weekly, monthly, and annual basis.

(iv) *Acceptable deviation in time*: Thermal comfort ratings were discussed considering a tolerance range of 3 and 5 % of the working hours.

(v) *Occupancy*: Thermal comfort was evaluated with and without the consideration of holidays.

(vi) *Quantitative and qualitative evaluation*: Comfort ratings were analyzed qualitatively in hours of exceedance and quantitatively in Kelvin-hours of exceedance.

Besides, as well-founded research results concerning the thermal comfort in low-energy buildings are missing, the recommendations for re-defined comfort standards are motivated by experience from day-to-day practice, as well.

Building category: In this study, the buildings belong to the category of 'air-conditioned buildings' and of 'low-energy buildings with air-based and water-based mechanical cooling'.

Thermal comfort approach: For the buildings presented, the authors propose the following three categories for the evaluation of thermal comfort in summer:

(1) *PMV-PPD comfort approach for 'buildings with air-conditioning'*: Air-conditioned buildings provide a stable indoor environment. Therefore, user expectations concerning the indoor climate and, especially, the room temperature are high. The user hardly influences the indoor climate.

(2) *Adaptive comfort approach for low-energy buildings with air-based mechanical cooling:* Mechanical nighttime ventilation is used to precool the building structure. Auxiliary energy is used in order to operate the fans of the ventilation system. Further, passive cooling techniques are employed to prevent and modulate heat gains, including the use of natural ventilation. Heat gain modulation is achieved by proper use of the building's thermal inertia mass. The level of adaptation and expectation is related strongly to outdoor climatic conditions in these buildings.

(3) *Adaptive comfort approach for low-energy buildings with water-based mechanical cooling:* Environmental heat sinks such as the ground and ground water are used to cool the buildings via thermo-active building systems. A cooling concept employing environmental energy and TABS cannot guarantee a stringent comfort boundary because of the limited cooling potential of the heat sink, the limited cooling power of the TABS, and the reduced control of TABS systems. Besides, satisfaction with the thermal conditions correlates strongly with both the possibility and the effectiveness of the occupants' interactions with their surroundings [Wagner et al. 2007]. The buildings investigated provide the occupants opportunities to control the surrounding conditions by operating windows, doors and solar shading system. However, the TABS systems do not provide individual room control, i.e., the occupant cannot individually adjust the heating and cooling set point. However, Nicol and McCartney (2002b) showed that the mere existence of a control did not mean that it was used, and that merely adding up the number of controls does therefore not give a good measure of the success of a building or its adaptive community. It would seem that as well as the existence of a control a judgment is needed as to whether it is useful in particular circumstances.

Measurements: Various scientific teams carried out an extensive long-term monitoring in fine time resolution of the building and plant performance for two to five years. The monitoring data consist of minute-by-minute and hourly measurements of temperature sensors and energy meters or manual heat meter readings, if not stated otherwise. In general, data accumulation is associated with erroneous data due to the malfunctioning of sensors and outages. Raw data are processed before data evaluation using a sophisticated method to remove erroneous values and outliers from the database. Data were recorded by building automation systems or by a stand-alone acquisition system. Thermal comfort is quantified by measurements of operative room temperatures and local meteorological conditions. The number of representative, monitored offices/rooms in a building is given in Table 2.

Thermal comfort assessments are determined separately for the summer and winter season according to the comfort approaches of the European standards EN 15251:2007-08. Evaluated are the numbers of hours during occupancy when the operative room temperatures exceed the defined upper and lower comfort limits I, II and III. Comfort ratings are analyzed in hours of exceedance.

Time of occupancy: With the exception of the ISE building, the daily presence of the occupants at their workplace is not recorded. Obviously, the buildings tend to be less routinely occupied, with out-of-hours use, and flexible working hours, and contain an increasingly wide range of activities and equipment [Bordass 2001], [Gossauer 2008]. In this investigation, however, the occupancy period is defined to be 7 a.m. to 7 p.m. (12 hours per weekday), for all buildings to facilitate direct comparison between them. Statutory holidays (e.g., Christmas, Easter, etc) are considered, but not summer/winter vacation periods. Excluding weekends, the working hours amount to approximately 2,952 per year (246 per year).

Acceptable deviations in time (tolerance range): As recommended by EN 15251:2007-08, measured values of the operative room temperature are allowed to be outside the defined comfort boundaries during 5 % of working hours. EN 15251:2007-08 determines acceptable deviations on an annual, monthly, weekly, and even daily basis. However, findings of previous investigations [Kalz et. al 2009] suggest that a specification based on a monthly and weekly maximum of exceedance is not a promising approach, since it is too sensitive to malfunction of the plant, improper operation, and inappropriate user behavior. The exceedance of thermal comfort limits during moderate ambient conditions, e.g. periods during spring and autumn, is exclusively attributable to the occupant behavior. The user has the opportunity to counteract the increasing operative room temperatures effectively by operating sun-shading devices or opening windows. With respect to these results, it is proposed to determine thermal comfort ratings on the basis on the entire summer season, and that the comfort class be allocated accordingly. For example, considering 1358 working hours during summer, the number of tolerated working hours, which exceed the comfort limits would be about 40 to 67 hours per season.

Summer and winter evaluation: The comfort standard EN 15251:2007-08 is not consistent in the definition of summer and winter period, i.e., the distinction of the upper comfort boundaries according to the seasons differs for the adaptive and the PMV comfort approach. Fanger's thermal comfort model (PMV comfort approach) requires the input variables metabolic rate and the insulation level of clothing (winter period 1.0 clo and summer period 0.5 clo). The prevailing ambient conditions are not considered in the model. Therefore, it is not explicit, when Fanger's model refers to summer or winter conditions. The adaptive comfort approach defines upper comfort boundaries for a running mean ambient air temperature from 10 to 30 °C and lower comfort boundaries for a temperature range of 15 to 30 °C.

Haldi et al. (2008) concludes from field studies that clothing level can be reliably modeled by outdoor conditions, using for example regressions on running mean ambient air temperature. As a result, clothing adaptation tends to be more a predictive strategy – the level being set at the beginning of the day, based on prior experience of thermal outdoor conditions. This relationship is expressed by a linear regression by [Haldi et al. 2008]) with good agreement (R^2 0.97). Therefore, a running mean ambient air temperature of 15 °C would result in a clo factor of 0.7 and a running mean ambient air temperature of 22 °C in a clo factor of 0.5, which is the criterion for the summer period according to ISO 7730:2005.

Though different studies on people's clothing behavior come to slightly different conclusions on the dependency between clo-value and outdoor temperature, all studies show that the clo-value converge to 1 for low (1 to 2 °C) and to 0.5 for high (22 to 27 °C) daily mean temperatures or running mean temperature, respectively. These studies show that the clo-value is 0.7 at approximately 15 °C outdoor temperature. Consequently, a reasonable "switching temperature" from winter to summer is an outdoor running mean temperature of 15 °C since a clo-value 0.7 is typical office clothing with long-sleeved shirt but without jacket.

The recommendation is to use a clear temperature reference for both the PMV and the adaptive comfort approach. Heating mode and winter season is below an outdoor running mean temperature 15°C. Cooling mode and summer season is above an outdoor running mean temperature 15°C. The real cooling or heating time (energy [kWh]) may differ from the perceived summer or winter season (adaptation [clo]).

Acceptable deviations in location (tolerance range): Operative room temperatures and, finally, thermal comfort ratings are evaluated separately for each room monitored in the building for the summer and winter season. Obviously, the recorded temperatures vary significantly throughout the day within a building due to different user behavior, room orientation, and presence of occupants [Kalz et al. 2009]. EN 15251:2007-08 requires that the building meets the criteria of a specific [thermal comfort] category if the rooms representing 95% building volume meet the criteria of the selected category". The authors do not believe that considering 95 % of the building for the evaluation of monitored data is a promising approach since outliers dominate the evaluation procedure. These data do not characterize the entire building. There are certain rooms within a building that can be treated as outliers due to a wide range of reasons: occupant prefers higher operative room temperature, no use of solar shading since the occupant prefer to have a view outside, occupants are not present, rooms are heavily equipped with office equipment, room has two external walls, rooms are occupied denser that assumed during the design stage, etc [Kalz et al. 2009].

In real buildings, and especially in passively cooled and mixed-mode buildings, the exceedance of the comfort limits at a given outdoor temperature is a distribution rather than a single value. Provided that the exceedance of the upper and lower comfort limits is a Gaussian variable, the standard deviation σ might be a good scale unit. For design purpose, the recommendation is to use the established 95%-criterion, required by the current standard EN 15251:2007-08. In order to preclude overestimation of extremely high or low temperatures in monitoring campaigns, however, the recommendation is to use the floor area weighted average for 84 % (standard deviation σ) of the building spaces.

Building classification: In accordance with the comfort criteria, the buildings are assigned to a comfort class I, II or III, indicating the percentage of satisfied occupants. The requirement for a certain comfort class is fulfilled when at least 84 % of the recorded, hourly temperature measurements remain within the defined comfort limit and its equivalent tolerance range. This approach considers that extremely high room temperatures are temporarily caused by users, e.g. closed windows, open blinds, and cooling switched off.

Thermal comfort footprint: It is suggested, to present the time of occupancy, where 84 % of the building area is in compliance with comfort class I, II,III and IV. Therefore, each building with its energy concept for heating, cooling, and ventilation gets its individual *thermal comfort* *footprint.* The period is given as percentage of the total occupancy during summer and winter. Depending on the project status, the annual energy demand / consumption for heating and cooling can be directly compared with the simulated / monitored thermal comfort. Accordingly, a room air quality “footprint” can be compared with the annual energy demand / consumption for ventilation from the Energy Performance Certificate. Note: Thermal comfort footprints are presented for the winter and summer season, however, the discussion of the comfort evaluation focuses on the summer season only.

Presentation of thermal comfort results: As the “footprint” characterizes the building in a general matter, clients may not be able to understand the conclusion, especially the relevance of room temperatures exceeding the upper comfort limit in winter and the lower limit in summer. Therefore, we recommend to clearly state that the comfort diagram should be shown in addition to the footprint. Despite the building categorization, the results of the thermal comfort assessment should be presented for both the adaptive and the PMV comfort approach. This will provide the client with data for the expected performance of the entire building concept.

3 Description of the investigated buildings

The 19 buildings are categorized according to the cooling concept employed into: (i) air-based mechanical cooling (8 buildings), (ii) water-based mechanical cooling (10 buildings) and (iii) air-conditioned buildings (1 building) (detailed description in in [EnOB 2009, EnSan 2009, Voss et al. 2006b, 2007].

In spite of different approaches for architecture and design, all of the buildings in this study strive for a significantly reduced primary energy use with carefully coordinated measures (Table 2, Figure 1). Except for the air-conditioned building, all buildings allow the user to influence the indoor environment with devices as operable windows and sun shading controls. The buildings have a net floor area of 290 to 21,500 m² and are located in three different German climate zones, defined as summer-hot, moderate and summer-cool, respectively [DIN 4108-2:2003]. Figure 1 describes the measured operative room temperatures of the buildings in summer by means of box plots (i.e., median, 25^{th} and 75^{th} percentile, outliers are not portrayed).

Table 2 Building key information.

build-ing	net floor area [m²]	orien-tation	floor	moni-tored rooms	TABS area [m²]	occupancy [-] [b]	occupants [f]	U-value ext.walls [W/(m²K)]	U-value window [W/(m²K)]	surface area-volume [m^{-1}]	window to façade ratio [%]	solar shading [a]	primary energy for HVAC [k]
air-based mechanical cooling concept													
DBH	5,974	S	5	9	-	9 - 18	100	0.3	1.6	0.27	28 - 64	exterior	118.5
ISE-A	288	E	3	5	-	7 - 20	48	0.2	1.4	0.31	25 - 50	exterior	85.9
ISE-C	288	S	3	16	-	7 - 20	48	0.2	1.4	0.31	25 - 50	exterior	85.9
KFW	8,585	S	5	20	-	8 - 18	300	0.24	1.4	0.25	41	exterior	125.0
LAM	1,000	N+S	2	2	-	7 - 18	35	0.2	1.1	0.40	22 - 46	exterior	46.5
POL	3,510	S	3	1	-	7 - 18	100	0.2	1.4	0.32	31 - 51	exterior	62.1
SIC	13,822	all	6	42	-	6 - 20	400	0.19	1.3	0.29	33 - 49	exterior	67.1
SOL	8.120	S	2	7	-	7 - 18	150	0.2	1.1	0.36	32 - 43	exterior	85.0
SUR	4.423	E	3	6	-	7 - 18	50	0.22	0.85	0.25	13 - 55	non [d]	147.0
water-based mechanical cooling concept													
BOB	2,076	N+S	4	9	2,000	7 - 18	90	0.17	0.8	0.37	34 - 47	non [d]	77.2
DVZ	4,878	all	4	11	- [h]	7 - 18	550	0.20	1.0/1.4	0.30	48	exterior	-
EBD [e]	950	W	2	3	258/237	7 - 18	30	0.30	1.4	0.27	7 - 87	exterior	218.7
EFB	20,693	all	8	52	4,012	7 - 19	800	0.21	1.3	0.15	35 - 64	inte-	92.3
EGU	6,911	all	5	20	5,000	7 - 19	420	0.13	0.84	0.22	36 - 48	inte-	69.8
GMS	10,650	all	3	2	10,000	7 - 18	1,500	0.20	1.3	0.30	47 - 53	exterior	70.7
LHL	4,623	N+S	2	3	3,252	7 - 18	240	0.18	0.7	0.39	20 - 70	exterior	100.5
SOB	63	S	1	3	23	7 - 18	4	0.18	1.13	- [g]	62	exterior	-
TMZ	8,976	S+E	4	46	4,500	8 - 18	60	0.26	1.5	0.38	28 - 91	inte-	-
ZUB	1,347	S	3	21	873	8 - 17	20	0.11	0.8	0.34	15 - 85	exterior	32.8
air-conditioning													
PFI	6,880	N+S	4	87	6,500	7 - 17	280	0.25	1.3	0.29	- [i]	exterior	225.0

[a] solar shading: exterior and interior solar shading device (exterior, interior), glazing-integrated solar shading device (integrated) | [b] general time of occupancy, but often flexible office hours | [c] 16 office in on wing of the building | [d] no exterior solar shading, but interior blinds | [e] 258 m² TABS in first floor (grid conditioning) and 237 m² ceiling suspended cooling panels in second floor | [f] occupants per building | [g] three office rooms within the building SIC | [h] no information on the area of TABS | [i] no information | monitored primary energy use for heating, cooling, ventilation and lighting [$kWh_{prim}/m^2_{net}a$]. The following primary energy factors are used: electricity 2.6 $MWh_{prim}/MWh_{en}d$, biomass 0.2 MWh_{prim}/MWh_{end}, and fossil fuels 1.1 MWh_{prim}/MWh_{end}.

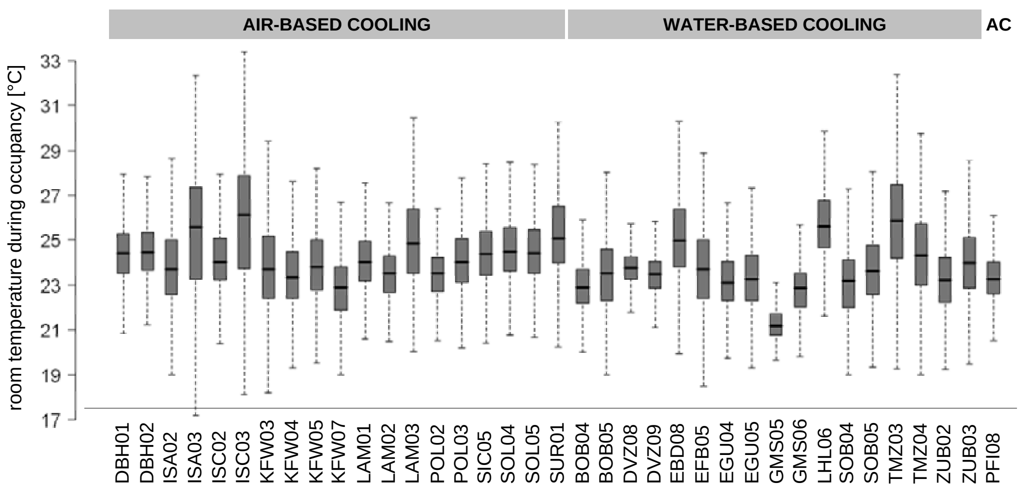


Figure 1 Summer season: Box plot of the recorded, hourly operative room temperatures [°C] during occupancy (7 a.m. to 7 p.m., excluding weekends and holidays) in all investigated rooms in the buildings with maximum and minimum values. Outliers are not portrayed. Buildings are grouped according to the cooling concept employed. A summer day is defined by a running mean ambient air temperature above 15 °C.

4 Comparative evaluation of thermal comfort in summer

The following chapter presents the evaluation of thermal comfort during summer, i.e., during the period with a running mean ambient air temperature greater than 15 °C. Again, a building is allocated to the particular comfort class when the room temperatures of 84 % of the building space remain within the defined comfort boundaries, i.e., do not exceed the upper and the lower comfort boundaries.

Exceedance of upper and lower comfort boundaries

The classification I, II, III, and IV of all buildings in terms of thermal comfort corresponding to the PMV-PPD and adaptive comfort approach is given in Table 5, considering separately the exceedance of the upper and the lower comfort boundaries. In conclusion, all buildings (except the buildings that tend to be too warm during summer: ISA and ISC in 2003, SUR in 2001, and EBD in 2008) reveal a more frequent exceedance of the lower than the upper comfort boundaries. In general, the rating of thermal comfort is one class better considering the exceedance of the upper than the lower boundaries. This result applies in particular to mechanically cooled buildings (Figure 4), which have a lower increase of operative room temperatures even during periods with higher ambient air temperature.

In detail, the evaluation of the monitored thermal comfort according to the adaptive approach of EN 15251:2007-08 is illustrated in Figure 2 for the naturally ventilated SIC building (upper left, 52 monitored rooms) and the mechanical cooled EGU building (upper right, 20 monitored rooms). Maximum (84th percentile) and minimum (25th percentile) operative room temperatures for all monitored offices (gray symbols) and the mean temperature of all rooms in the building (black symbols) are shown during the time of occupancy. Obviously, the operative room temperature varies distinctly between the monitored offices. Some monitored rooms do not violate the comfort boundaries at all, whereas others reveal a significant exceedance. This discrepancy within a building might be mainly affected by the orientation of the rooms, the presence of the occupants and the occupants' behavior in terms of opening windows and using solar shading, which is not monitored in this investigation.

An unexpected result is the different frequency of exceeding the upper and the lower comfort boundaries, respectively, as is given in Figure 2. Taking the SIC buildings as an example (lower left), just few offices exceed the comfort boundary for class I, however, mostly during less than 5 % of the occupancy. On the contrary, in many office rooms the operative room temperatures fall significantly below the lower comfort boundary of class I, even at higher ambient air temperatures. As can be seen in Figure 2, 60 % of the monitored building space exceeds the lower comfort boundary during eight to even 40 % of the occupancy. Considering the exceedance of the upper comfort boundaries only, the SIC building could be assigned to class I. Considering the frequent exceedance of the lower limits, however, the SIC building comply with class II only (Table 5).

Similar results are obtained for the mechanically cooled EGU building (Figure 2, lower right). Considering again the exceedance of the upper limits only, the building reveals excellent thermal comfort conditions since just one office room violates the comfort boundaries. Exactly the opposite is true for the violation of the lower comfort boundaries. None of the 21 monitored office rooms provides thermal comfort in compliance with the lower comfort requirements. Some offices exceed considerably the limit for class I during 20 to even 80 % of the occupancy. As presented in Table 5, the EGU building can be allocated to class I considering the exceedance of the upper boundaries only, but to class II considering the exceedance of the lower boundaries.

Table 3 **Thermal comfort in summer**: Classification I, II, III, and IV of all buildings in terms of thermal comfort corresponding to the PMV-PPD and adaptive comfort approach. Buildings are assigned to the corresponding thermal comfort class when 84 % of the recorded, hourly operative room temperature measurements remain within the defined comfort limit and its tolerance range of 5 %. Class IV indicates that the comfort criteria are not satisfied for any class. The classification is presented separately for exceedance of the upper and the lower comfort limits as well as for the total exceedance. Note: The comfort evaluation is given for a chosen monitoring year of the particular building.

BUILDING	**DBH**	**ISA**	**ISC**	**KFW**	**LAM**	**POL**	**SIC**	**SOL**	**SUR**	**BOB**	**DVZ**	**EBD**	**EFB**	**EGU**	**GMS**	**LHL**	**SOB**	**TMZ**	**ZUB**	**PFI**
YEAR	01	03	03	07	03	03	05	05	01	04	09	08	05	05	06	06	05	04	03	08
SUMMER: EXCEEDANCE OF UPPER COMFORT CLASS																				
PMV	IV	IV	IV	II	IV	III	IV	IV	IV	I	I	IV	IV	II	I	IV	IV	IV	IV	I
adaptive	I	II	III	I	I	I	I	II	III	I	I	III	II	I	I	III	II	III	I	I
SUMMER: EXCEEDANCE OF LOWER COMFORT CLASS																				
PMV	III	IV	IV	IV	IV	IV	IV	III	III	IV	III	IV	IV	IV	IV	III	IV	IV	IV	IV
adaptive	I	III	II	IV	III	III	II	II	II	IV	III	II	IV	III	IV	I	IV	IV	III	IV
SUMMER: TOTAL EXCEEDANCE OF UPPER AND LOWER COMFORT CLASS																				
PMV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV
adaptive	I	III	III	IV	II	III	III	III	III	IV	III	III	IV	III	IV	III	IV	IV	III	IV

Allocation of buildings to a thermal comfort class

Considering the total exceedance of the upper and lower comfort boundaries, none of the monitored buildings complies with the comfort classes of the PMV approach. Surprisingly, this is mainly attributes to violation of the lower comfort boundaries. Considering the adaptive comfort approach, all naturally ventilated buildings can be allocated to comfort class III (except KFW due to the frequent exceedance of the lower boundaries). As for the mechanical cooling concept, just five buildings comply with class III, the other five buildings do not fulfill the comfort requirements. Unexpectedly, the results do not vary much taken different building spaces into consideration, i.e., 95, 84, 75, or 68 % of the building space.

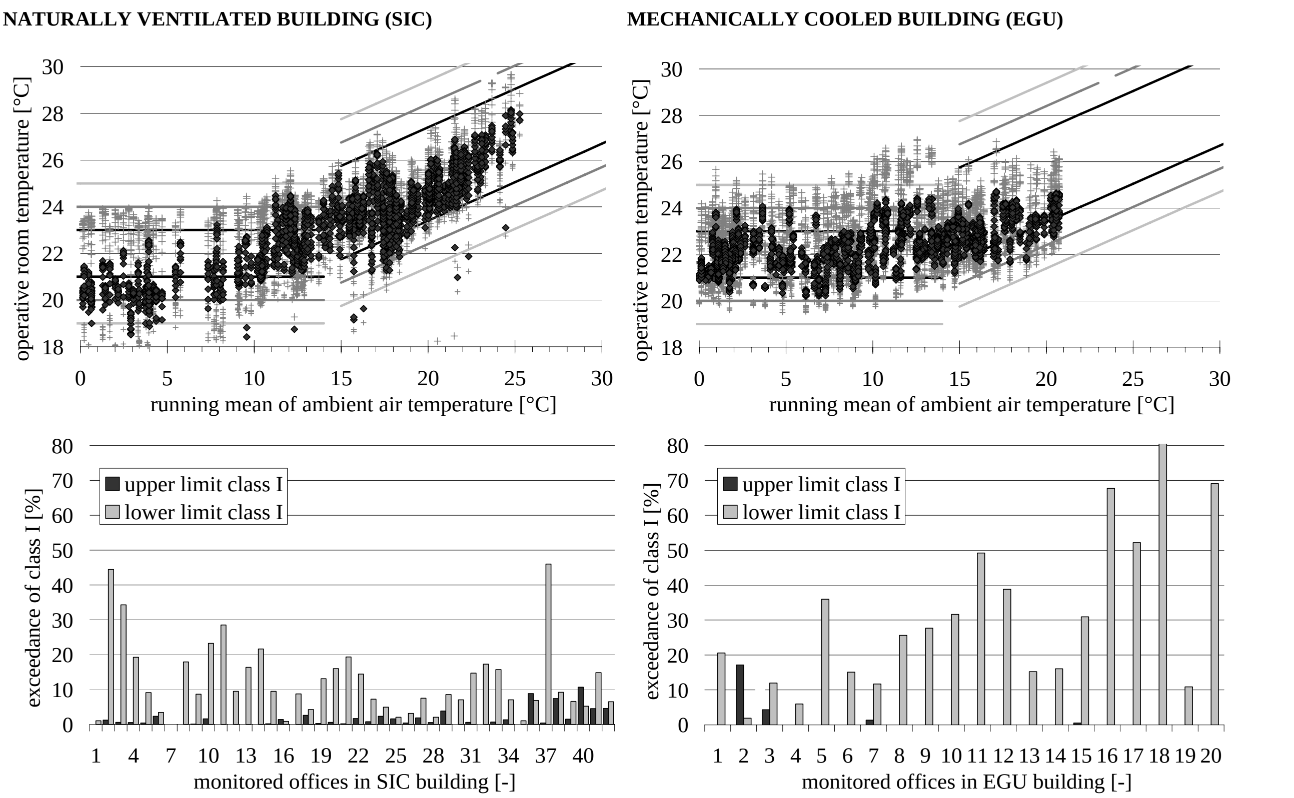


Figure 2 **TOP**: Thermal comfort evaluation during summer: (left) naturally ventilated building SIC and (right) mechanically cooled building EGU. Evaluation of hourly measured operative temperatures of the building during occupancy [°C], that is the **median** (black) as well as the **84th** and the **16th quartile** (grey) of temperature records of all rooms. The 84th quartile represents the warmest room and the 16th quartile represents the coolest room. Temperature records presented for the time occupancy from 7 a.m. to 7 p.m. according to adaptive comfort approach. The lines indicate the temperature range for comfort classes I, II and III.
BOTTOM: Exceedance of the upper (black) and lower (grey) comfort limit for **class I** for all rooms monitored in the buildings.

5 Results and conclusions

Thermal comfort is presented for the time of occupancy, where 84 % of the building area is in compliance with comfort class I, II, III and IV. Results are given as thermal comfort diagram (Figure 3) and comfort footprint (Figure 4).

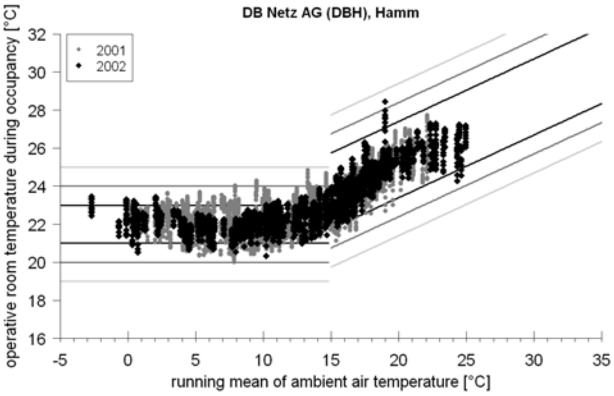
The allocation of the building to the comfort classes reveals the following findings:

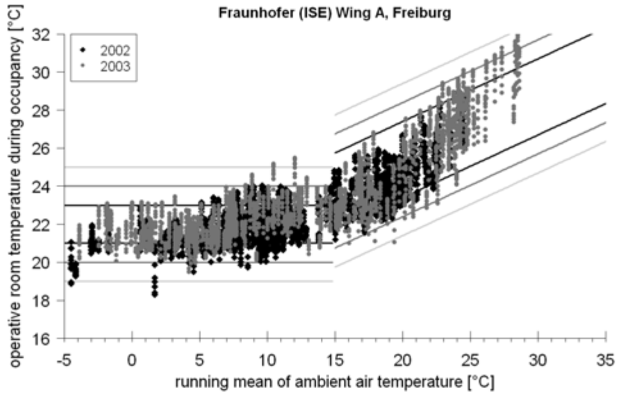
- The proposed methodology proves to be applicable and reasonable for the evaluation of thermal comfort. Results of the comfort assessment meet the authors' expectations from the day-to-day practice and reflect the satisfaction of the occupants.
- The buildings with air-based mechanical cooling comply during 80 to 95 % of the occupancy with comfort class II considering the adaptive approach.
- Applying the adaptive comfort approach, most buildings meet the upper comfort requirements of class II and III. An unexpected finding is the frequent violation of the lower

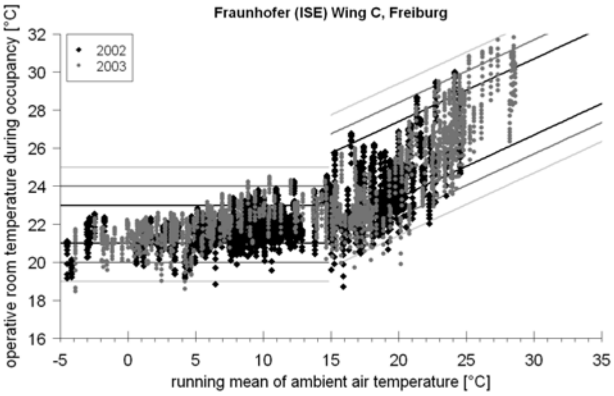
comfort boundaries II and III. Therefore, most of the buildings have to be assigned to the overall comfort class III. This conclusion cannot be supported by the authors' experiences with the performance of low-energy buildings and the user satisfaction.

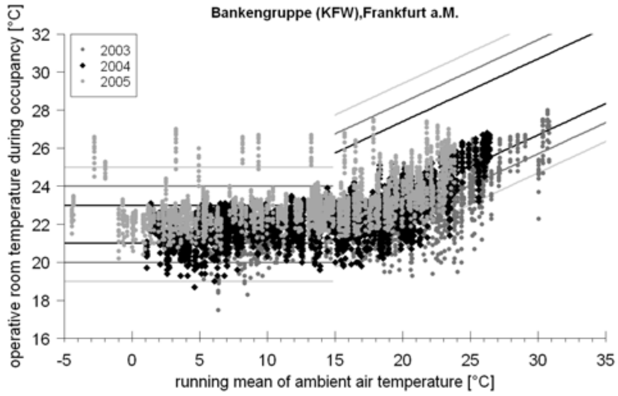
- Obviously, buildings with water-based cooling system reveal a less frequent exceedance of the upper than the lower comfort boundaries. Considering the adaptive approach, the buildings meet the comfort requirements of class II during 55 to 95 % of the occupancy during summer. This means, the comfort ratings are equal or even worse than those from natural ventilated buildings. These results question the applied adaptive comfort approach. The supply of cooling energy by use of environmental heat sinks and therefore the prevention of elevated room temperatures might be rated more favourable than the respect of the upper and the lower comfort boundaries.
- Consequently, further research is necessary in order to verify and adjust, if required, the upper and lower comfort boundaries for low-energy buildings that employ cooling systems with a limited cooling power such as thermo-active building systems. Measurements of long-term monitoring of building and plant performance as well as thermal comfort have to be related to comprehensive post-occupancy investigations. As a result, current approaches and guidelines for the evaluation of thermal and overall interior comfort need to be verified, perhaps revised and redefined for particular building categories. It might be necessary to adjust the slope of the lower comfort limit allowing greater temperature amplitudes between the lower and the upper limits, as for example suggested by the Dutch Guideline NPR-CR 1752 [van der Linden et al. 2006].
- All buildings investigated prove to be energy efficient. The total primary energy consumption for heating, cooling, ventilation and lighting ranges between 32 and 218 $kWh_{prim}/(m^2_{net}a)$. The night-time ventilation concept provides useful cooling energy in the range of 5 to 18 $kWh_{therm}/(m^2_{net}a)$. Is an earth-to-air heat exchanger employed, the cooling energy is supplied with an energy efficiency of SPF 20 kWh_{therm}/kWh_{prim} (related to primary energy). The mechanical ventilation systems provide cooling energy with an efficiency of SPF 0.5 to 6 kWh_{therm}/kWh_{prim} (again related to primary energy). The environmental cooling systems provide useful cooling energy in the range of 5 to 44 $kWh_{therm}/(m^2_{net}a)$, which is provided with an efficiency of SPF 1.3 to 3.5 kWh_{therm}/kWh_{end} (related to the primary energy).

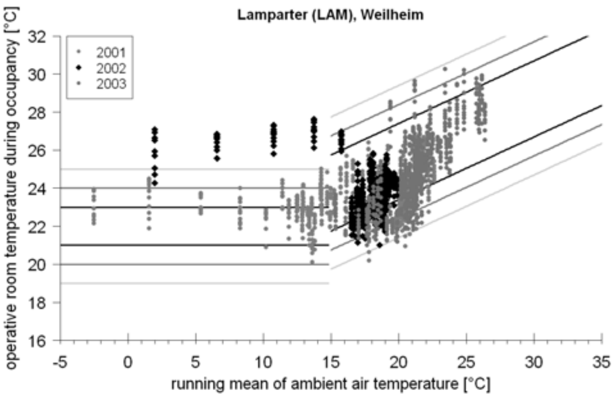
AIR-BASED MECHANICAL COOLING

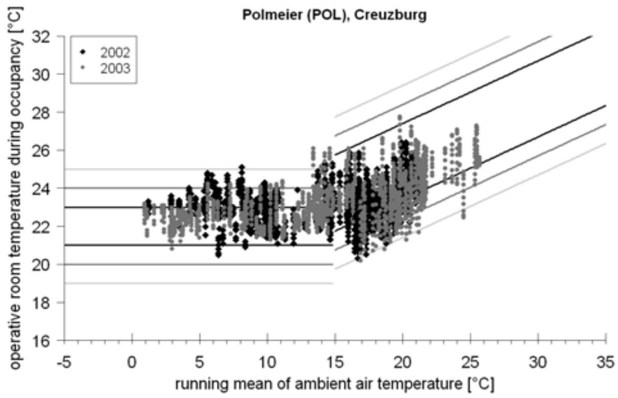


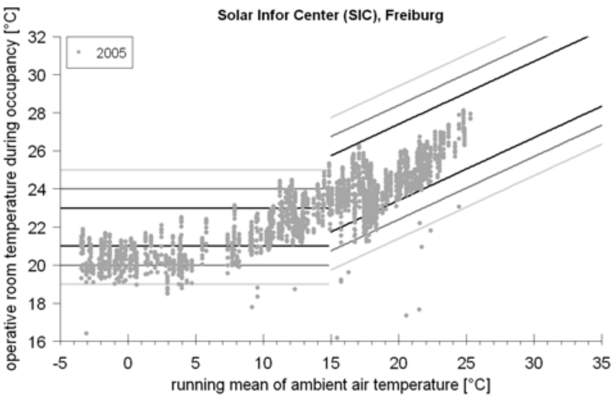


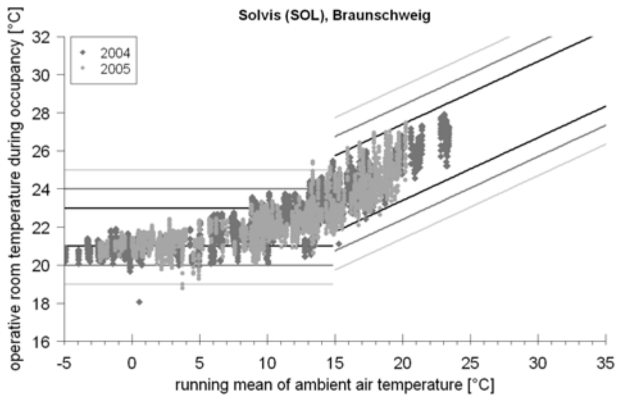


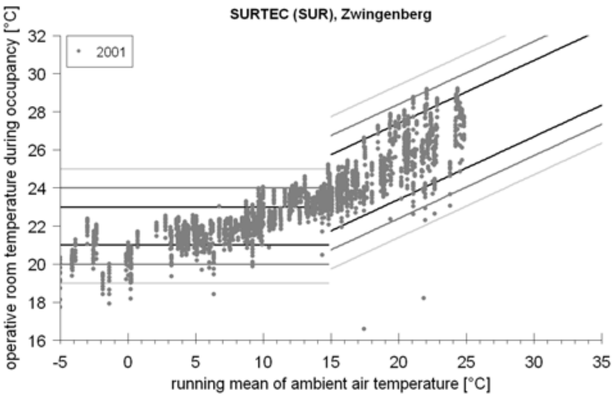


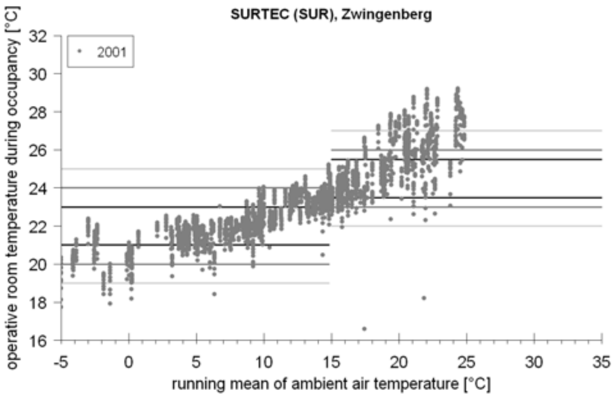




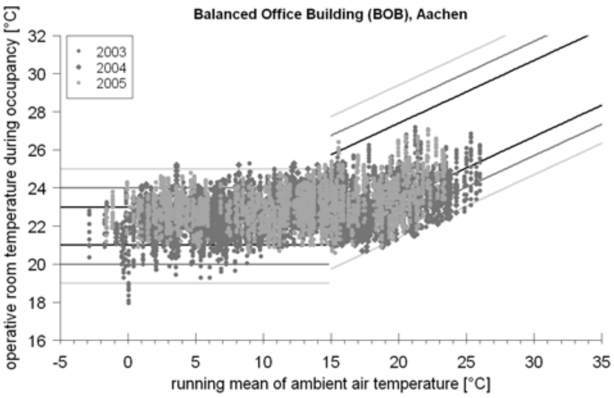


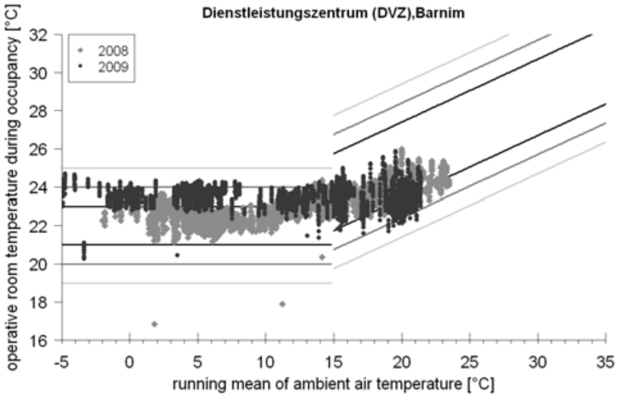


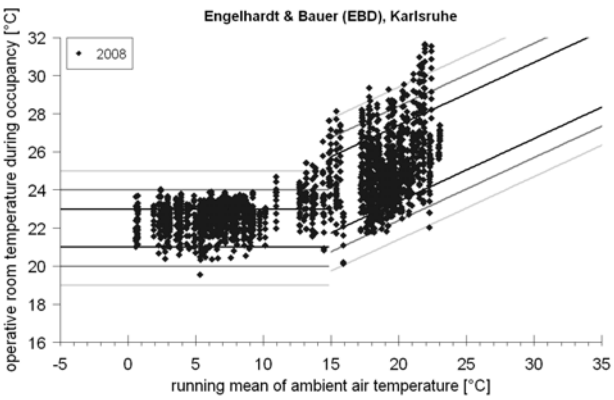


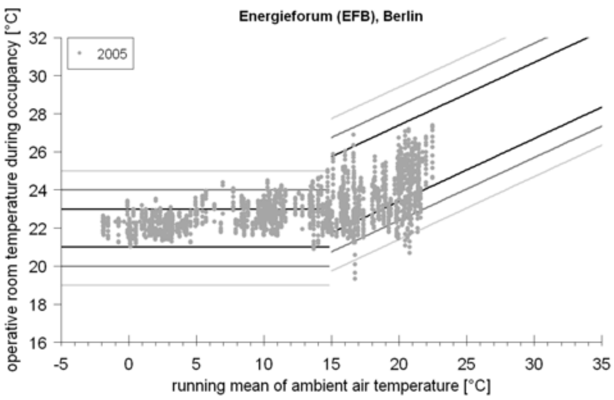


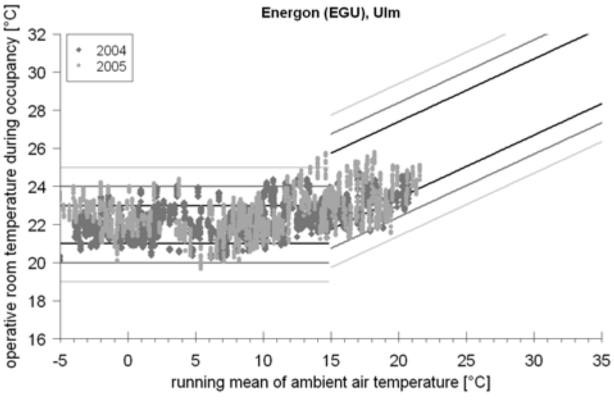
WATER-BASED MECHANICAL COOLING

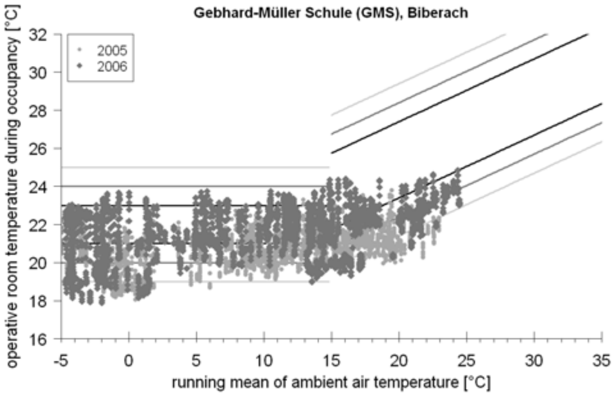


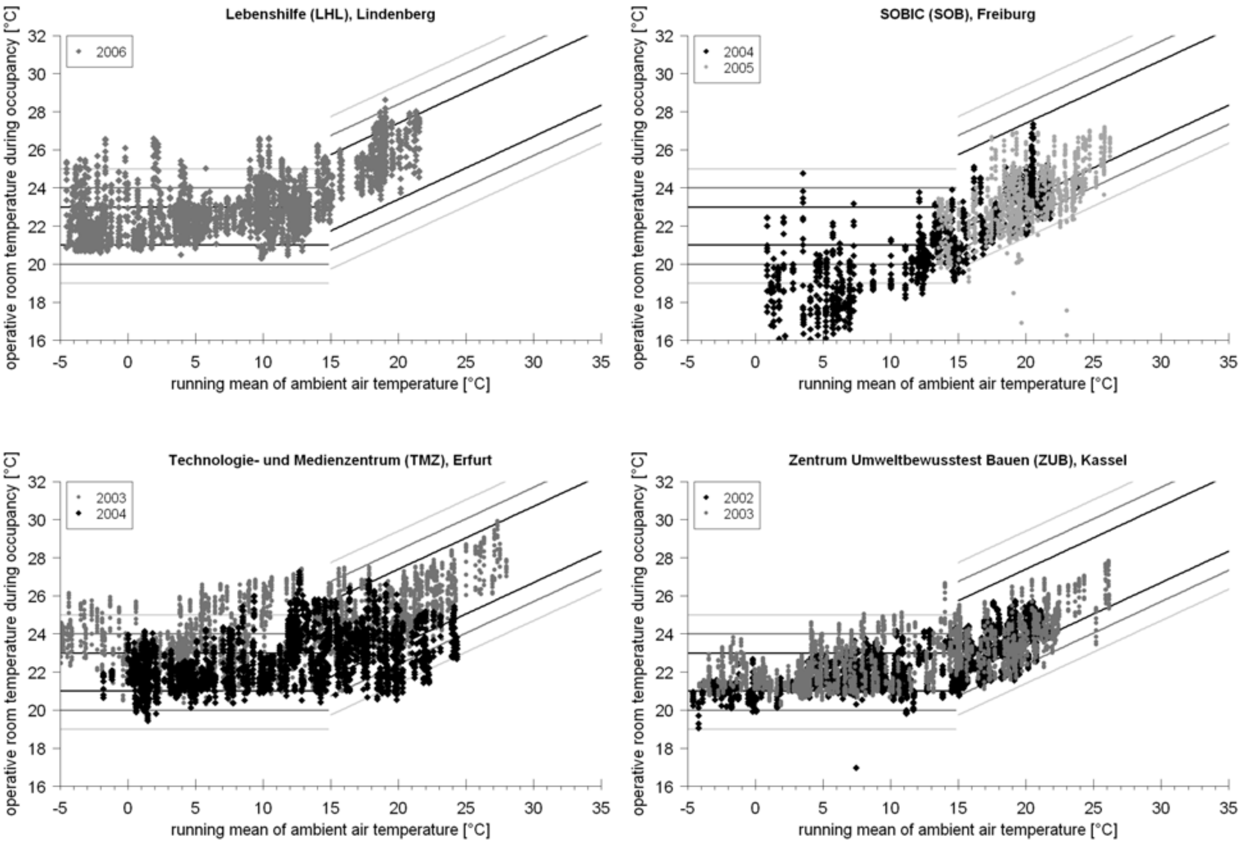












AIR-CONDITIONING

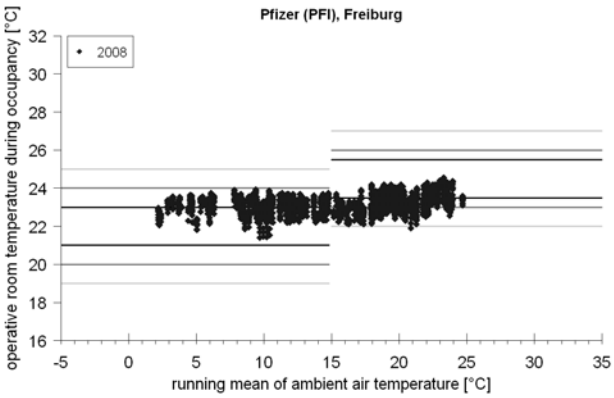
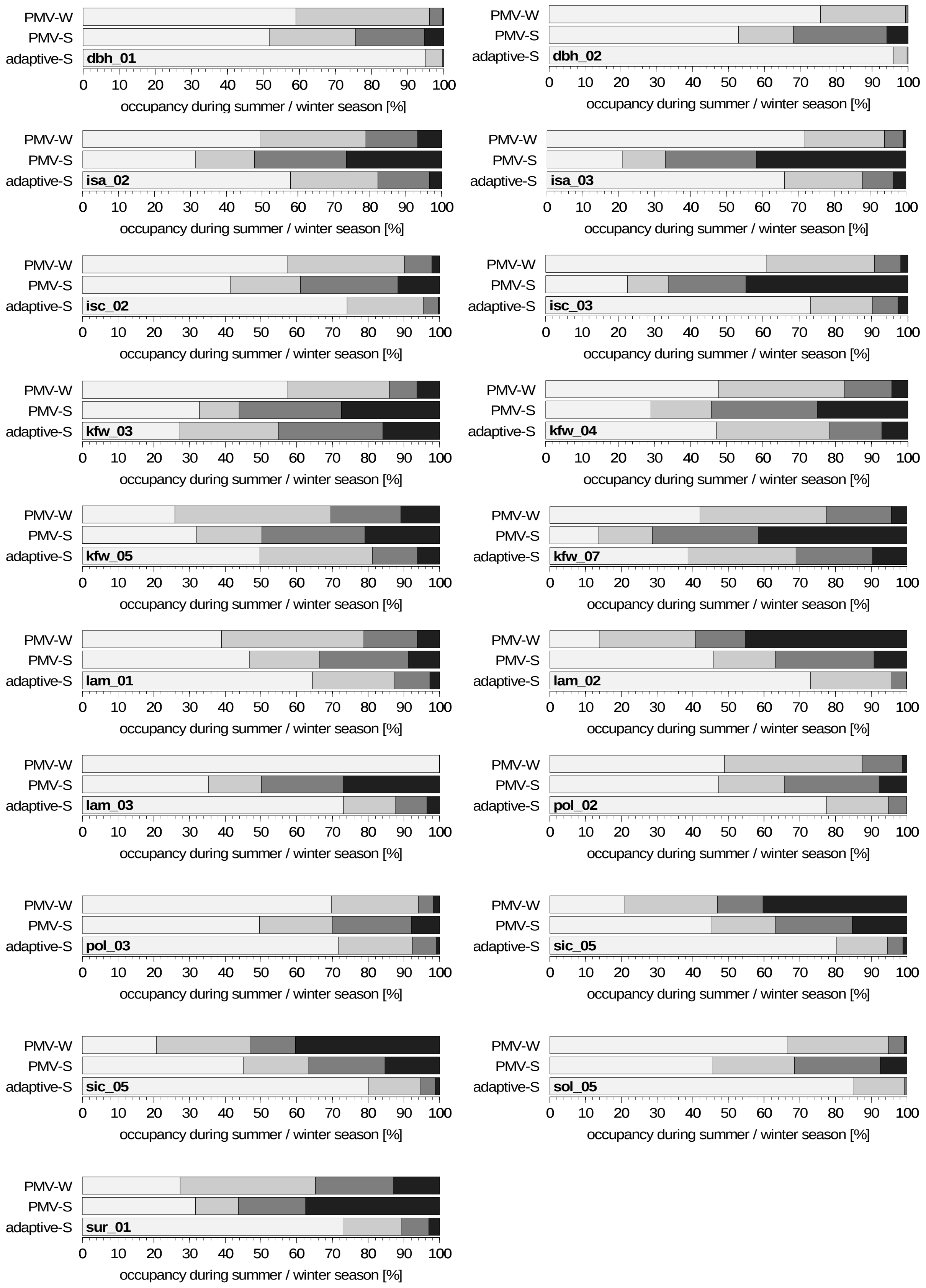
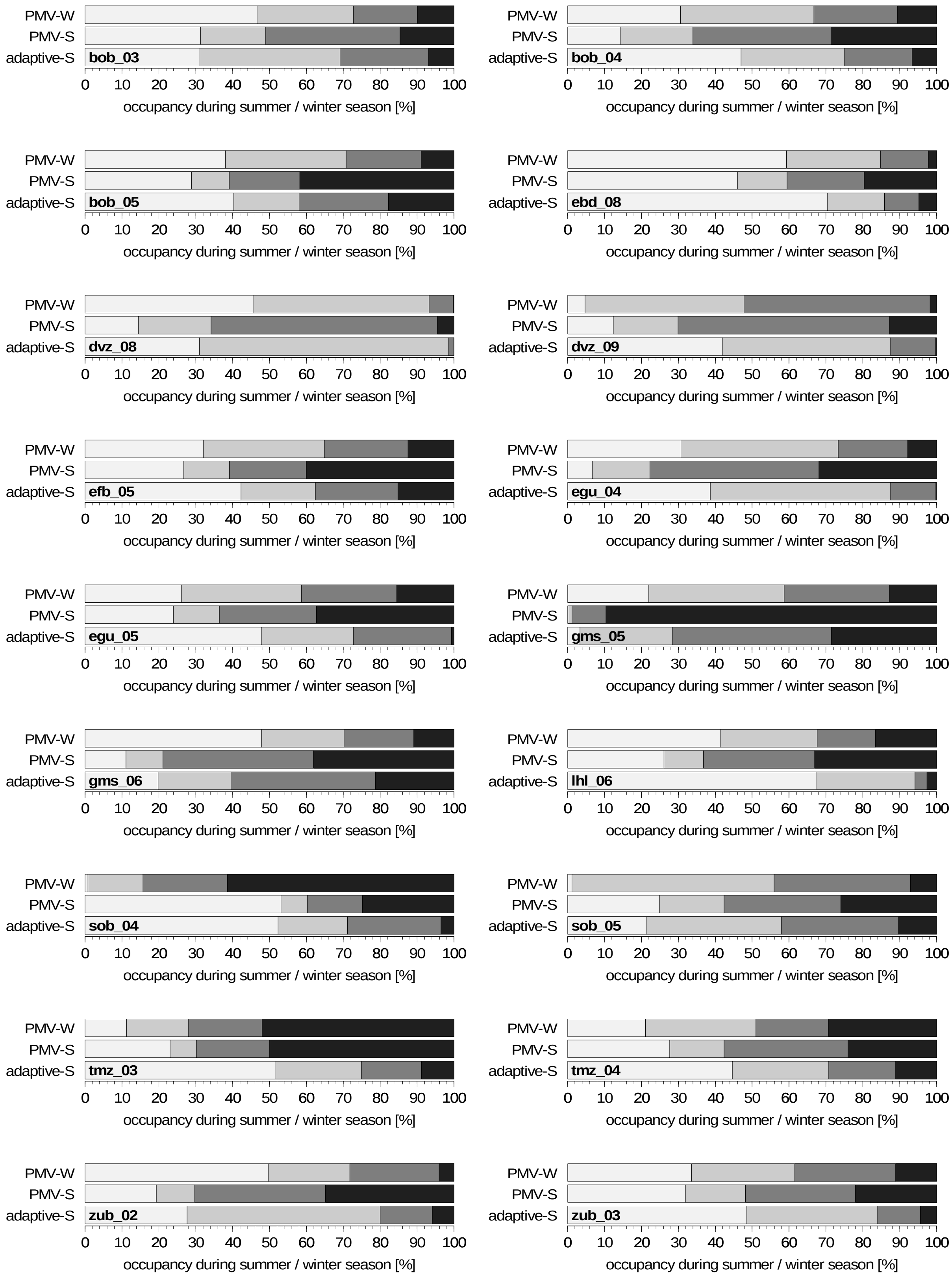


Figure 3 Evaluation of hourly measured operative temperatures of the building during occupancy [°C], that is the **median** of temperature records of all rooms. Temperature records presented for the time occupancy from 7 a.m. to 7 p.m. according to adaptive comfort approach for low-energy buildings with mechanical cooling and according to the PMV-PPD comfort approach for the air-conditioned building. The lines indicate the temperature range for comfort classes I, II and III.

AIR-BASED MECHANICAL COOLING



WATER-BASED MECHANICAL COOLING



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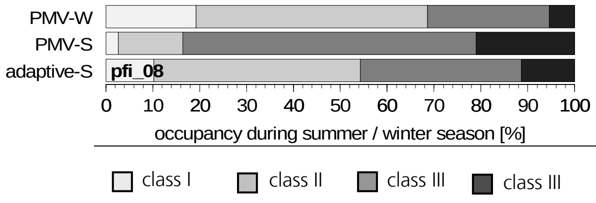

Figure 4 Footprint of the buildings in terms of thermal comfort: Classification I, II, III and IV corresponding to the adaptive and PMV-PPD comfort approach. Buildings are assigned to the corresponding thermal comfort class when 84 % of the recorded, hourly operative room temperature measurements remain within the defined comfort boundaries and the tolerance range of 5 % during time of occupancy from 7 a.m. to 7 p.m. Seasonal evaluation is carried out for (1) the summer season (indicated as “S”) with an running mean of the ambient air temperature greater 15 °C and (2) the winter season.

Acknowledgement

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6 References

[ASHRAE 55:2004-04] ASHRAE 55:2004-04 (2004), Thermal Environmental Conditions for Human Occupancy. ISSN 1041-22336.

[Bordass et al. 2001a] Bordass, B, Cohen, R, Standeven, M and Leaman, A (2001a,) Assessing building performance in use 2: Technical performance of the Probe buildings. Building Research & Information, Vol. 29, No. 2, pp. 103-113.

[de Dear et al. 2001] de Dear, R. and Brager, G. (2001), The adaptive model of thermal comfort and energy conservation in the built environment. International Journal of Biometeorology, 45:2s.

[DIN 4108-2:2003] DIN 4108-2:2003. Thermal protection and energy economy in buildings. Beuth Verlag GmbH, Berlin.

[EnOB 2009] EnOB Research for energy-optimized construction. German Federal Ministry of Economics and Technology (BMWi). www.enob.info/en, January 2009.

[EnSan 2009] EnSan Energy-optimized construction in refurbishment. German Federal Ministry of Economics and Technology (BMWi). www.enob.info/en/refurbishment, January 2009.

[EN 15251:2008-07] EN 15251:2008-07 (2007), Criteria for the indoor environment. Beuth Verlag GmbH, Berlin.

[EN ISO 7730:2005] EN ISO 7730:2005 (2005), Ergonomics of the thermal environment. Beuth Verlag GmbH, Berlin.

[Fanger 1970] Fanger, PO (1970), Thermal comfort analysis and applications. Environmental Engineering. Mc-Graw-Hill, New-York.

[Gossauer 2008] Gossauer, E (2008), Nutzerzufriedenheit in Bürogebäuden – eine Feldstudie. Dissertation University of Karlsruhe. Fraunhofer IRB Verlag (in German).

[Haldi et al. 2008] Haldi, F and Robinson, D (2008), On the behavior and adaptation of office occupants. Building and Environment, Vol. 43, No. 12, pp. 2163-2177.

[Hellwig et al. 2008] Hellwig, RT, Steiger, S, Hause, G, Holm, A and Sedlbauer, K (2008), Kriterien des nachhaltigen Bauens: Bewertung des thermischen Raumklimas – ein Diskussionsbeitrag. Bauphysik, Vol. 30, No 3, pp. 152-162 (in German).

[Kalz et al. 2009] Kalz, DE, Pfafferott, J, Herkel, S and Wagner, A (2009), Building Signatures correlating Thermal Comfort and Low-Energy Cooling: in-use performance. Building Research and Information Vol. 37, No. 4, pp. 413-432.

[Kwok et al. 2009] Kwok, AG and Rajkovich, NB (2009), Addressing climate change in comfort standards. Building and Environment, doi:10.1016/j.buildenv.2009.02.005.

[Leaman et al. 2007] Leaman, A and Bordass, B (2007), Are users more tolerant of 'green' buildings? Building Research & Information, Vol. 35, No. 6, pp. 662-673.

[Nicol et al. 2002a] Nicol, F and Humphreys, MA (2002), Adaptive thermal comfort and sustainable thermal standards for buildings. Energy and Buildings, Vol. 34, No. 6, pp. 563-572.

[Nicol et al. 2002b] Nicol, F and McCartney, K (2002), Developing an adaptive control algorithm for Europe. Energy and Buildings, Vol. 34, No. 6, pp. 623-635.

[Nicol et al. 2005] Nicol, F and Roaf, S (2005), Post-occupancy evaluation and field studies of thermal comfort. Building Research & Information, Vol. 33, No. 4, pp. 338-346.

[Olesen et al. 2002] Olesen, B. W. and Parsons, K. C. (2002), Introduction to thermal comfort standards and to the proposed new version of EN ISO 7730. Energy and Buildings, Vol. 34, No. 6, pp. 537-548.

[Olesen 2007] Olesen, BW (2007), The philosophy behind EN15251: Indoor environmental criteria for design and calculation of energy performance of buildings. Energy and Buildings, Vol. 39, No. 7, pp. 740-749.

[Roulet et al. 2006a] Roulet, CA, Johner, N, Foradini, F, Bluyssen, P, Cox, C, Fernandes, E, Müller, B and Aizlewood, C (2006a), Perceived health and comfort in relation to energy use and building characteristics. Building Research & Information, Vol. 34, No. 5, pp. 467-474.

[Roulet et al. 2006b] Roulet, CA, Flourentzou, F, Foradini, F, Bluyssen, P, Cox, C and Aizlewood, C (2006b), Multicriteria analysis of health, comfort and energy efficiency in buildings. Building Research & Information, Vol. 34, No. 5, pp. 475-482.

[van der Linden et al. 2006] van der Linden, AC, Boersta, AC, Raue, AK, Kuvers, SR and de Dear, RJ (2006), Adaptive temperature limits: A new guideline in The Netherlands – A new approach for the assessment of building performance with respect to thermal indoor climate. Energy and Buildings, Vol. 38, No. 1, pp. 8-17.

[Voss et al. 2006a] Voss, K., Pfafferott, J., Kalz, D. E., Hoffmann, C. and Neumann, C. (2006), Energieeinsparung contra Behaglichkeit? Heft 121, Reihe Forschungen, Bundesamt für Bauwesen und Raumordnung, Bonn (in German).

[Voss et al. 2006b] Voss, K, Löhnert, G, Herkel, S, Wagner, A and Wambsganß, M (2006), Bürogebäude mit Zukunft – Konzepte, Analysen, Erfahrungen, Solarpraxis Berlin, 2nd ed., ISBN-10: 3-934595-59-6 (in German).

[Voss et al. 2007] Voss, K, Herkel, S, Pfafferott, J, Löhnert, G and Wagner, A (2007) Energy efficient office buildings with passive cooling – Results and experiences from a research and demonstration programme. Solar Energy, Vol. 81, No. 3, pp. 424-434.

[Wagner et al. 2007] Wagner, A, Gossauer, E, Moosmann, C, Gropp, T and Leonardt, R (2007), Thermal comfort and workplace occupant satisfaction – Results of field studies in German low-energy office buildings. Energy and Buildings, Vol. 39; No. 7, pp. 758-769.