A Comparative Study on Cooling Period Thermal Comfort Assessment in Modern Open Office Landscape in Estonia

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Abstract: Local thermal comfort and draught rate has been studied widely. There has been more meaningful research performed in controlled boundary condition situations than in actual work environments involving occupants. Thermal comfort conditions in office buildings in Estonia have been barely investigated in the past. In this paper, the results of thermal comfort and draught rate assessment in five office buildings in Tallinn are presented and discussed. Studied office landscapes vary in heating, ventilation and cooling system parameters, room units, and elements. All sample buildings were less than six years old, equipped with dedicated outdoor air ventilation system and room conditioning units. The on-site measurements consisted of thermal comfort and draught rate assessment with indoor climate questionnaire. The purpose of the survey is to assess the correspondence between heating, ventilation and cooling system design, and the actual situation. Results show, whether and in what extent the standard-based criteria for thermal comfort is suitable for actual usage of the occupants. Preferring one room conditioning unit type or system may not guarantee better thermal environment without draught. Although some heating, ventilation and cooling systems observed in this study should create the prerequisites for ensuring more comfort, results show that this is not the case for all buildings in this study.

Keywords: thermal comfort; draught; cooling period; open office

1. Introduction

Modern low energy office buildings require energy efficient heating, ventilation, and air conditioning (HVAC) systems which can provide comfortable and healthy indoor environment. In temperate climate countries, mechanical ventilation and active cooling systems are common practice in such buildings. However, mechanical HVAC systems do not always provide satisfactory thermal conditions [1]. It is important to properly apply control strategies, design and install room cooling units and ventilation supply air elements, as well as to operate and maintain the systems to provide comfortable indoor climate without temperature fluctuations and draught risk in the cooling season [2–8]. Office plans, in terms of occupant positions and density, can be very different from initial design and vary significantly, resulting in changing conditions and dynamic settings which makes it difficult to design the systems adequately to ensure stable thermal environment. Open office layout design is used commonly in most office buildings mainly to allow flexibility in workspaces allocation [9]. This creates a difficult task for HVAC systems design, requiring careful planning to assure adequate conditions in the occupied zone in different layout cases.

As occupant satisfaction with thermal environment is dependent on many factors, such as gender, age, health, activity, mood, and other physiological and psychological factors, assessing thermal comfort (TC) based on temperature and air movement measurements is usually not sufficient for adequate estimation [6,10–13]. Thus, evaluation by questioning the occupants is usually also needed to specify the problems and get a comprehensive overview of the TC situation. Studies on office workers thermal sensation have shown that the predicted TC and actual sensation can differ significantly [12,14,15]. For example, gender specific analysis indicates higher dissatisfaction rates for female occupants [11,16–19]. Recent research has widely focused on individual perception of TC [20–22], developed methods to analyze the preferences for TC using machine learning algorithms [23,24] and adapt systems to provide preferable personal comfort by implementing Personalized Comfort Systems [20–22,25]. Utilization of such systems in buildings requires paradigm shifts in occupant interaction with HVAC systems as well as system design practices, integration of advanced controls and information technologies solutions [26,27].

In addition to the individual preferences and system specific aspects influencing thermal comfort (TC), there are many building related design factors that can affect the performance of HVAC systems and in turn influence the thermal environment. Of these factors, façade design, namely window sizes, layout, and glazing parameters, can have large impact on cooling load as well as radiant temperature asymmetry and thus major influence on the overall thermal conditions in the office [28,29]. Thalfeldt et al. [28] showed the importance of façade design by analyzing the effect on office buildings energy efficiency and cooling load in cold climate countries. Window-to-wall ratio (*WWR*) of 0.25 was found optimal for triple glazing window solutions. Larger glazing results in higher cooling loads and increase the need for larger room cooling units, higher cooled airflow rates or lower supply air temperatures to maintain the room temperature. The latter factors also increase the risk of draught in occupied spaces. In several studies, draught rate (*DR*) has been identified as the main cause of discomfort even if other thermal environment factors are at satisfactory levels [6,15,29,30].

Depending mainly on the cooling load, cooling plant solution, and interior design, different water based room cooling solutions are used in offices, which can be classified by supply water temperature as low temperature room cooling units e.g., fan coil units and high temperature units, such as thermally active building systems (TABS), passive cooling beams, or active cooling beams, combined with ventilation supply air terminals [31,32]. In low energy buildings, high temperature cooling is usually preferred to achieve higher energy efficiency for cooled water production by cooling plants [32]. The performance of these systems is extensively analyzed in various recent studies. Most of the research is based on either computer simulations, mainly computational fluid dynamics (CFD) studies or studies conducted in controlled laboratory environments [33–47]. The research in real office settings is mainly focused on buildings located in warm and hot climate countries, dominated by cooling need [48–51]. To the knowledge of the authors, only few extensive studies have been carried out in cold and temperate climates and in low energy buildings. In Germany, Pfafferott, Herkel, Kalz, and Zeuschner [14] have conducted research on summertime TC in 12 low energy office buildings which are passively cooled with local heat sink based TABS. Results showed, that 41% of occupants were dissatisfied with thermal environment in summer, but assessment, according to the standard CEN EN 15251 [52], showed measured indoor temperature-based classification relative to the indoor climate category I (highest) and II, indicating a gap between perceived and assessed TC conditions and the need for more detailed comfort assessment. Hens [15] investigated TC in two office buildings in Belgium cooled with active chilled beams and air-cooling systems. He found that the Fanger [53] predicted mean vote (*PMV*)/predicted percentage dissatisfied (*PPD*) curve underestimated the actual number of dissatisfied occupants and that standards should not be considered as absolute references. It was also concluded that one should be very careful when interpreting the results of TC studies.

The theoretical knowledge involved or access to expert engineers during office building design is feasible and implemented in practice in Estonia. However, the volatile quality of different parts of the design, building phase simplifications with budget cuts and the contradiction between the

initial task and the actual situation leads to a risk of an outcome failure regarding TC for the occupant. In the Estonian construction market, great emphasis is given on diplomas, professional certificates, software for both building information modeling (BIM), and product selection programs integrating BIM solutions in the building process. In reality, during the construction process the HVAC designer and after the warranty period, the constructor retreat. Therefore, in a short period of time during the design a huge effort is invested in the project definition, while after the realization phase much of the expert advice is ignored. Otherwise, complaints regarding draught or room temperature were not topical issues. In Estonia as well, in-depth research on cooling season TC and occupant satisfaction is practically non-existent, a few studies in office buildings have been conducted with the main focus on heating season performance and mostly aimed towards energy efficiency analysis. The conducted studies indicate problems and dissatisfaction with thermal environment but lack the detail to specify the causes and details of occupants' thermal conditions and HVAC systems performance in terms of room equipment.

Regardless of the design and performance of the HVAC systems installed in actual open offices, the hypothesis of this study proposes that high proportion of occupants are dissatisfied with the TC conditions. The goal of this study is to determine, whether the thermal sensation dissatisfaction of the occupants in modern office spaces is verifiable and in accordance with the valid standard criteria. This paper aims to fill the gap of summer TC assessment by extensive field studies and thorough occupant survey in modern office buildings in Estonia, a temperate climate country. We have investigated four recently constructed and one reconstructed office buildings with open plan office layouts designed with different ventilation and cooling solutions, including mixing and displacement ventilation, TABS, radiant cooling panels, fan coil units, and active cooling beams. The on-site measurements conducted in the offices consist of high resolution and accuracy temperature and air velocity measurements with *DR* and TC calculations, which are described in the following chapter.

2. Methods

The flow chart of research methodology is shown in Figure 1. Section of methods is divided between description of reference objects, measurement set-up and equipment specifications, data analysis, and indoor climate questionnaire (ICQ). We used standard-based [52,54,55] methods in this study to measure and calculate TC parameters and to perform an online ICQ survey. The TC measuring probe and tripod mobile and flexible kit set [56] we used was designed for research and development purposes.
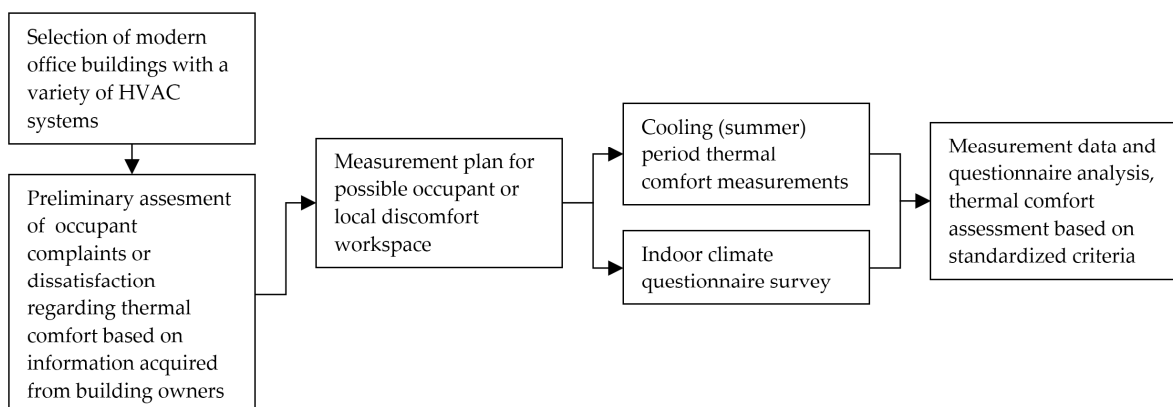

Figure 1. Flow chart of research methodology.

2.1. Reference Objects

General information regarding reference objects are provided in Table 1. The scope and range of measurement points with main building envelope characteristics, such as thermal transmittance for

main surfaces, such as walls, windows, floors on ground and roofs are listed with specific heat loss of external envelopes and window-to-wall ratios.

Table 1. General building information of reference objects.

Bldg	Year of Constr.	Net Floor Area (m²)/appr. Total Measured Area (%)	No of Floors/ No of Measured Floors	Thermal Transmittance W/(m² × K)	Specific Heat Loss of External Envelopes W/(m² × K)/Window-to-Wall Ratio/Glazing *g* Value
A	2015	10,800/30	13/4	U_{window} 0.80/U_{wall} 0.18 U_{roof} 0.09/U_{floor} 0.14	H/A 0.50 WWR 0.69 *g* 0.25
B	2018	7000/20	5/3	U_{window} 0.83/U_{wall} 0.12 U_{roof} 0.09/U_{floor} 0.13* (*above ambient air)	H/A 0.31 WWR 0.59 *g* 0.24
C	2017	18,900/10	14/2	U_{window} 0.65/U_{wall} 0.10 U_{roof} 0.10/U_{floor} 0.15	H/A 0.30 WWR 0.38 *g* 0.30
D	2018	13,900/100 (available office space)	2/2	U_{window} 1.0/U_{wall} 0.15 U_{roof} 0.14/$\underline{U_{floor}}$ < 0.15	H/A < 0.20 WWR < 0.25 *g* 0.30
E	Reconstr, 2014 (1982)	5300/20	6/1	U_{window} > 1.2/U_{wall} > 0.25 U_{roof} N/A/U_{floor} N/A	H/A > 0.50 WWR 0.90 *g* 0.40

In Buildings A, B, C, and D, measurements were also taken on the highest floor and in Buildings B and D on the lowest floor. The temperature of slabs was considered to be close to t_i and therefore the impact on operative temperature was not accounted for, as heat transmission through the building envelope in such low energy buildings is negligible compared to the heat gains through glazed surfaces and have little effect on TC. A variety of HVAC systems was involved in measurements zones (Table 2) including new and innovative solutions in the Estonian construction market.

Table 2. Heating, ventilation, and air conditioning room design solutions of reference objects.

Bldg.	Heating	Ventilation	Cooling
A	Water-based convectors (height 300 mm, length 700–1800 mm) below the windowsill. Installed room unit heating power 18 W/m².	Mixing ventilation 1.4 l/(s × m²) using active exposed chilled beams (effective length 2700–3300 mm) mounted in the open ceiling (height 2.75 m) for supply and circular valves (Ø 125 mm) for extract air (height 2.7 m).	Active exposed chilled beams (effective length 2700–3300 mm) mounted in the open ceiling (height 2.75 m). Installed room unit sensible cooling power 52 W/m².
B	Thermally active building system (slab, room height 3.0 m). Installed heating power 43 W/m².	Displacement ventilation 1.4 l/(s × m²) including duct diffusers (Ø 160–315 mm, nozzle angle 120–180 °C) for supply (height 2.7–2.8 m), mounted in the open ceiling to the perimeter of rooms. Wall and ceiling grilles with plenum box serving extract air (height 2.8 m on cornice, 2.6 m for ribbed suspended ceiling).	Thermally active building system (slab, room height 3.0 m). Installed sensible cooling power 41 W/m².
C	4-pipe active ceiling integrated chilled beams (effective length 900–1500 mm) mounted in suspended ceiling (height 2.7 m). Installed room unit heating power 17 W/m².	Mixing ventilation 1.7 l/(s × m²) using 4-pipe ceiling integrated chilled beams (effective length 900–1500 mm) for supply air and circular valves (Ø 100 mm) for extract air (height 2.7 m).	4-pipe active ceiling integrated chilled beams (effective length 900–1500 mm) mounted in suspended ceiling (height 2.7 m). Installed room unit sensible cooling power 46 W/m².
D	4-pipe radiant panels mounted in the open ceiling on the height of 2.4 m. Installed room unit heating power 24 W/m².	Mixing ventilation 2.1 l/(s × m²). Rectangular diffusers including directionally adjustable nozzles (plates 160 × 160 / 200 × 200 mm) mounted on plenum box for supply air and circular plate (Ø 200–250 mm) combined with plenum box for extract air in the open ceiling (height 2.7 m).	4-pipe radiant panels mounted in the open ceiling on the height of 2.4 m. Installed room unit sensible cooling power 10 W/m².
E	Electrical convectors (height 200 mm, length 1500 mm) in front of windows. Installed room unit heating power 60 W/m².	Mixing ventilation 1.3 l/(s × m²) with circular supply and extract air valves (Ø 160–250 mm) mounted in the suspended ceiling (height 2.5–2.7 m).	Multi-split fan coil units (without heating function) mounted in the suspended ceiling (height 2.7 m). Installed total cooling power 78 W/m². (Ventilation supply air is not chilled)

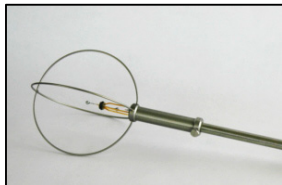Ø: diameter of air diffuser connection duct.

The buildings involved in this study were chosen from a range of modern office spaces in Tallinn. First criteria for reference objects was the correspondence with the Estonian energy efficiency regulations, which were first set in 2007 [57]. This created the prerequisites for new buildings and

HVAC systems criteria, such as envelope related parameters, such as air tightness, external wall insulation thickness, window glazing solutions, and HVAC system parameters, e.g., effectiveness of room units and energy sources, heat recovery effectiveness, specific fan power of ventilation units etc. Buildings A and B have high temperature heating systems and district heating. Building B is using low temperature heating and a ground source heat pump, Building D has high temperature heating water produced and a gas boiler and electrical heating convectors are installed in Building E. All of the studied buildings are equipped with dedicated outdoor air ventilation systems with heat recovery. Ventilation air distribution methods were classified as mixing ventilation, except for Building B, where supply air systems were built in a way to support displacement ventilation method. Buildings A and C were using active chilled beams for supply air distribution. Buildings A, C, and D are built with chillers to supply the cooling system. In all Buildings, except for E, high temperature cooling is used in room conditioning units as supply air is dehumidified in the air handling units. Multi-split fan coil units with refrigerant without the option of heating function were in operation in Building E. Room conditioning units in Buildings C and D, including the Building B with thermally active buildings system, operated both for heating and cooling purposes.

2.2. Measurement Equipment

Experimental measurements in this study were carried out with a TC measurement system Dantec Dynamics ComfortSense [56]. The system is designed for high quality multi-point measurements of v_a, t_i, *RH*, and t_o. The set is equipped with software, what allows easy setup for measuring sequence and positions giving researchers a comprehensive overview if the measured data. Measurement equipment probe data is described in Table 3.

Table 3. Specifications of measuring equipment [56].

	54T33 Draft Probe	54T37 Relative Humidity Probe	54T38 Operative Temperature Probe
Image			
Range	0.05–5 m/s −20 °C to +80 °C	0–100%	0 to +45 °C
Accuracy	±0.02 m/s ±0.2 K	+1.5%	±0.2 K

The set is mounted on a tripod including five draft probes, one humidity and one t_o probe. For a sitting position, ISO standard [55] recommends measuring heights for ankle level 0.1 m, abdomen level 0.6 m, and head level 1.1 m. Conformably to Fanger and Christensen [6], mean v_a and standard deviation at three heights around the sitting occupant body were measured according to heights shown on Figure 2. RH probe was set at 1.0 m as a fixed height for measuring has not been fixed for measurements. The t_o probe was mounted with the angle of 30° at the height of 0.6 m as the abdomen level of a sitting person [55].
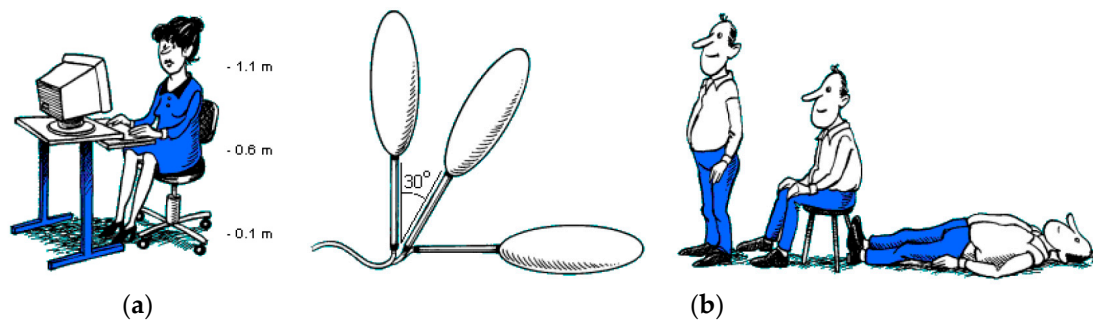
Figure 2. Recommended air velocity probe heights behind the feet, elbow, and neck for a sitting person (**a**); Recommended operative temperature probe person's angle factor to their surroundings (**b**) [58].

Probes were connected with 54N90 ComfortSense main frame [56], using 7 channels of 16. Main frame was in turn connected with laptop computer where the measurement data was stored using ComfortSense software version 4, (Dantec Dynamics A/S, Skovlunde, Denmark) [56]. Measurement period of 180 seconds as the least time recommended [59] was used.

2.3. Data Analysis

Measurement data, including t_i, v_a, *RH*, and t_o was recorded with the sampling rate 20 Hz with ComfortSense [56] and processed in Microsoft Excel. TC parameters are calculated for each measurement positions with equations for *Tu*, *DR*, *PMV*, and *PPD* followed. To assess *DR*, the fluctuation rate of v_a is described as *Tu*, which is calculated by [59]

$$Tu = \frac{SD}{v_a} \times 100 \ (\%),$$ (1)

where *SD* is standard deviation of measured local mean v_a (m/s) for one measurement. With t_i, v_a, and *Tu*, the percentage of people predicted to be dissatisfied because of draught may be calculated as [60]

$$DR = (34 - t_i) \times (v_a - 0.05)^{0.62} \times (0.37 \times v_a \times Tu + 3.14) \ (\%)$$ (2)

To predict the mean value of the subjective ratings of a group of people in a given environment, *PMV* index is used. Consisting of a set of parameters with sub-formulas, the *PMV* equation is given by [60]

$$PMV = [0.303 \times \exp(-0.036 \times M) + 0.028] \times [(M - W) - H_d - E_c - C_{res} - E_{res}]$$ (3)

The *PMV* index in Equation (3) was calculated using Equations (4)–(11). In the equations provided, *M* (W/m^2) is metabolic rate and *W* (W/m^2) is the effective mechanical power. Assumption of metabolic rate 1.2 met for sedentary activity for summer season provided in EN 16798-1 was used. Sedentary activity does not suppose producing effective mechanical power, therefore 0 (W/m^2) was used in analysis. The next symbol H_d in Equation (3) represents dry heat loss, which is found as

$$H_d = \frac{(mt_{sk} - t_{cl})}{I_{cl}} \left(\mathrm{W/m^2}\right),$$ (4)

where mt_{sk} is mean skin temperature [°C] and in Equation (4), t_{cl} is expressed using t$_o$ and calculated through iterative process, by

$$t_{cl} = 35.7 - 0.028 \times (M - W) - I_{cl} \times \{3.96 \times 10^{-8} \times f_{cl} \times [(t_{cl} + 273)^4 - (t_o + 273)^4] + I_{cl} \times f_{cl} \times h_c \times (t_{cl} - t_o)\} \ (°C)$$ (5)

In Equation (5), I_{cl} [(m^2 × K)/W] is the clothing insulation, f_{cl} is the clothing surface area factor, v_{ar} (m/s) is the relative air velocity, h_c [W/(m^2 × K)] is the convective heat transfer coefficient, and t_{cl} (°C) is the

clothing surface temperature. Clothing unit 0.5 clo for summer season provided in EN 16798-1 was used in calculations. Equation (5) includes h_c, which is given as

$$h_c = 2.38 \times |t_{cl} - t_i|^{0.25} \quad \text{for} \quad 2.38 \times |t_{cl} - t_i|^{0.25} > 12.1 \times \sqrt{v_{ar}} \quad \text{and}$$
$$12.1 \times \sqrt{v_{ar}} \quad \text{for} \quad 2.38 \times |t_{cl} - t_i|^{0.25} < 12.1 \times \sqrt{v_{ar}} \left[W/\left(m^2 \times K\right) \right], \tag{6}$$

where v_{ar} was set equal to the v_a as occupants were intended to be stationary sensing draught. Equation (5) includes f_{cl}, which is calculated by

$$f_{cl} = 1.00 + 1.290 \times I_{cl} \text{ for } I_{cl} \leq 0.078 \text{ and}$$
$$1.05 + 0.645 \times I_{cl} \text{ for } I_{cl} > 0.078 \tag{7}$$

Continuing the *PMV* index calculation, in Equation (3), evaporative heat exchange at the skin, when the person experiences a sensation of thermal neutrality E_c given as

$$E_c = 3.05 \times 10^{-3} \times [5733 - 6.99 \times (M - W) - p_a] + 0.42 \times (M - W - 58.15) \text{ (W/m}^2\text{)}, \tag{8}$$

where p_a is the water vapor partial pressure [Pa], calculated using measured *RH* by

$$p_a = \frac{RH}{100} \times 479 + (11.52 + 1.62 \times t_i)^2 \text{(Pa)}, \tag{9}$$

In addition, Equation (3) for *PMV* includes respiratory convective heat exchange C_{res}, calculated as

$$C_{res} = 0.0014 \times M \times (34 - t_i) \text{ (W/m}^2\text{)}, \tag{10}$$

and Equation (3) includes also respiratory evaporative heat exchange E_{res}, given as

$$E_{res} = 1.72 \times 10^{-5} \times M \times (5867 - p_a) \text{ (W/m}^2\text{)}, \tag{11}$$

Finally, to predict the rate of people dissatisfied in a thermal environment, the *PPD* index is used. Knowing *PMV*, *PPD* can be calculated as [60]

$$PPD = 100 - 95 \times \exp(-0.03353 \times PMV^4 - 0.2179 \times PMV^2) \tag{12}$$

Measured values are shown in Building result figures in the results chapter and used in Equations (1) and (2) for calculating *Tu* and *DR*, and in Equations (3) and (12) to calculate *PMV* and *PPD*.

2.4. Indoor Climate Questionnaire

To study occupant satisfaction we provided online questionnaires to the employees of the measured office spaces. As some organizations involved in this study are moving towards policy of a paperless work management, we used Google Forms [61] application. In addition to standard CEN EN 15251 [52] suggestions, we added also questions about age, gender, amount of time behind the desk during workday, and the working environment regarding cabinet or open office plan. The ICQ is presented in Appendix A.

2.5. On-Site Measurements

This section provides an overview of the TC measurement time and weather information (Table 4), followed by measurement results with calculated TC indicative parameters *Tu*, *DR*, *PMV,* and *PPD*. ICQ survey results are summarized at the end of the results sections.

Table 4. Time of measurements and weather information from the Estonian Weather Service [62].

Building	Time of Measurements	Weather Conditions	Maximum Outdoor Temp. °C	Mean Outdoor Temp. °C
A	06.08.2019 before midday	cloudy skies showers	+20.9	+15.2
B	14.08.2019 after midday	cloudy skies no precipitation	+19.7	+13.8
C	12.08.2019 after midday	cloudy skies light showers	+22.0	+17.3
D	29.08.2019 after midday	sunny skies no precipitation	+26.5	+20.6
E	05.08.2019 after midday	cloudy skies no precipitation	+19.7	+13.8

The experiments were carried out on regular workdays during August. Measurements were taken by two persons, by the main author of this article assisted by graduate students in different buildings. HVAC systems were in regular performance mode without disfunctions or failures recorded. Internal gains by occupants, office equipment, and lighting were in use by default as some desks were empty by unused space, duties, or vacation. No serious defects in HVAC design or construction were observed. Although, some air flow and velocity aspects were noticeable. As in Buildings A and C, active beams were in use, occupants were not always placed sitting according to rule of thumbs, according to the architectural layout, or number of persons. Possible air flow obstacles by lighting fixture (Figure 3a) were noticed with open ceiling in Building A. *DR* risk was also predictable in building E (Figure 3b) where some vanes were taped to closed position. *DR* risk was more carefully considered in Buildings B and D.

(a)　　　　　　　　　　　　　　　　　　　　　　(b)

Figure 3. Possible air flow obstacles with open active beam solution (**a**); modified airflow distribution with fan coil unit (**b**).

3. Results

Based on on-site measurements, the summary of v_a in each measurement position are shown below for each Building. According to three heights provided in Figure 2, v_a values during measurement period are shown with box and whiskers plot. Minimum and maximum are at the end of the whiskers, the lower and the upper line of the box are first and third quartiles, the line between is median and the cross shows mean v_a value of the measurement in one position.

On the box and whiskers plot, the category of the indoor climate category is colored according to the lowest criteria achieved during measurements, meaning if one of the three height is in III category, the measurement point is placed in the least, III category. In the table part on the result figures below the box and whiskers plot, measured values and calculated parameters are colored according to the

category reached to be more easily distinguishable. *Tu* and *RH* measured values are not colored as being not categorized. Nonetheless, measurement point indoor climate category is defined by the inferior measured value or calculated parameter reached altogether.

3.1. Building A Results

The v_a results and TC parameters in Building A equipped with open ceiling active chilled beams are provided below in Figure 4. In Building A, in 2/3 of the measured positions the v_a was below the first indoor climate category threshold. Five positions met the II category requirement and in one position the v_a was above the category II threshold. Measurement No 14 was taken in an office space with unusually high internal gains, where also multi-split fan coil units were additionally added to the environment due to the specifics of the lessee. The results of t_i and v_a including *DR*, *PMV*, and *PPD* are placed in the first category mainly.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
$t_{i(1.1\,m)}$	°C	24.5	23.7	23.8	24.1	24.5	24.6	24.1	24.0	24.5	24.4	23.6	24.2	23.5	22.1	24.2	23.9	23.8	24.5
$v_{a(1.1\,m)}$	m/s	0.07	0.08	0.04	0.05	0.03	0.07	0.06	0.07	0.06	0.15	0.15	0.08	0.11	0.61	0.07	0.08	0.13	0.08
$Tu_{(1.1\,m)}$	%	65.3	47.9	58.0	46.9	49.5	59.4	44.3	55.0	51.4	58.7	55.0	68.3	66.6	48.2	47.9	45.9	39.1	58.9
$DR_{(1.1\,m)}$	%	4.7	5.2	0.0	0.0	0.0	4.3	1.9	4.2	2.7	15.3	15.4	5.3	10.5	100.0	4.3	5.7	10.3	4.9
$t_{i(0.6\,m)}$	°C	24.2	23.5	23.6	23.9	24.2	24.3	23.9	23.8	23.8	24.2	23.5	23.9	23.3	22.2	24.1	23.8	23.7	24.4
$t_{o(0.6\,m)}$	°C	24.7	23.7	23.8	24.3	24.6	24.7	24.2	24.1	24.6	24.7	23.9	24.1	23.6	22.9	24.2	24.2	24.1	24.7
$v_{a(0.6\,m)}$	m/s	0.04	0.08	0.03	0.02	0.03	0.09	0.06	0.07	0.03	0.15	0.08	0.05	0.12	0.43	0.04	0.06	0.10	0.08
$RH_{(0.6\,m)}$	%	50.5	52.8	54.4	52.6	51.7	52.1	51.7	52.1	50.9	52.1	55.9	53.4	49.4	52.7	52.5	53.2	55.3	54.0
$PMV_{(0.6\,m)}$	–	0.0	−0.3	−0.2	−0.1	0.0	0.0	−0.1	−0.2	0.0	−0.2	−0.2	−0.1	−0.4	−1.3	−0.1	−0.1	−0.2	0.0
$PPD_{(0.6m)}$	%	5.0	6.4	6.0	5.2	5.0	5.0	5.2	5.5	5.0	5.5	5.7	5.3	8.6	39.2	5.3	5.2	5.5	5.0

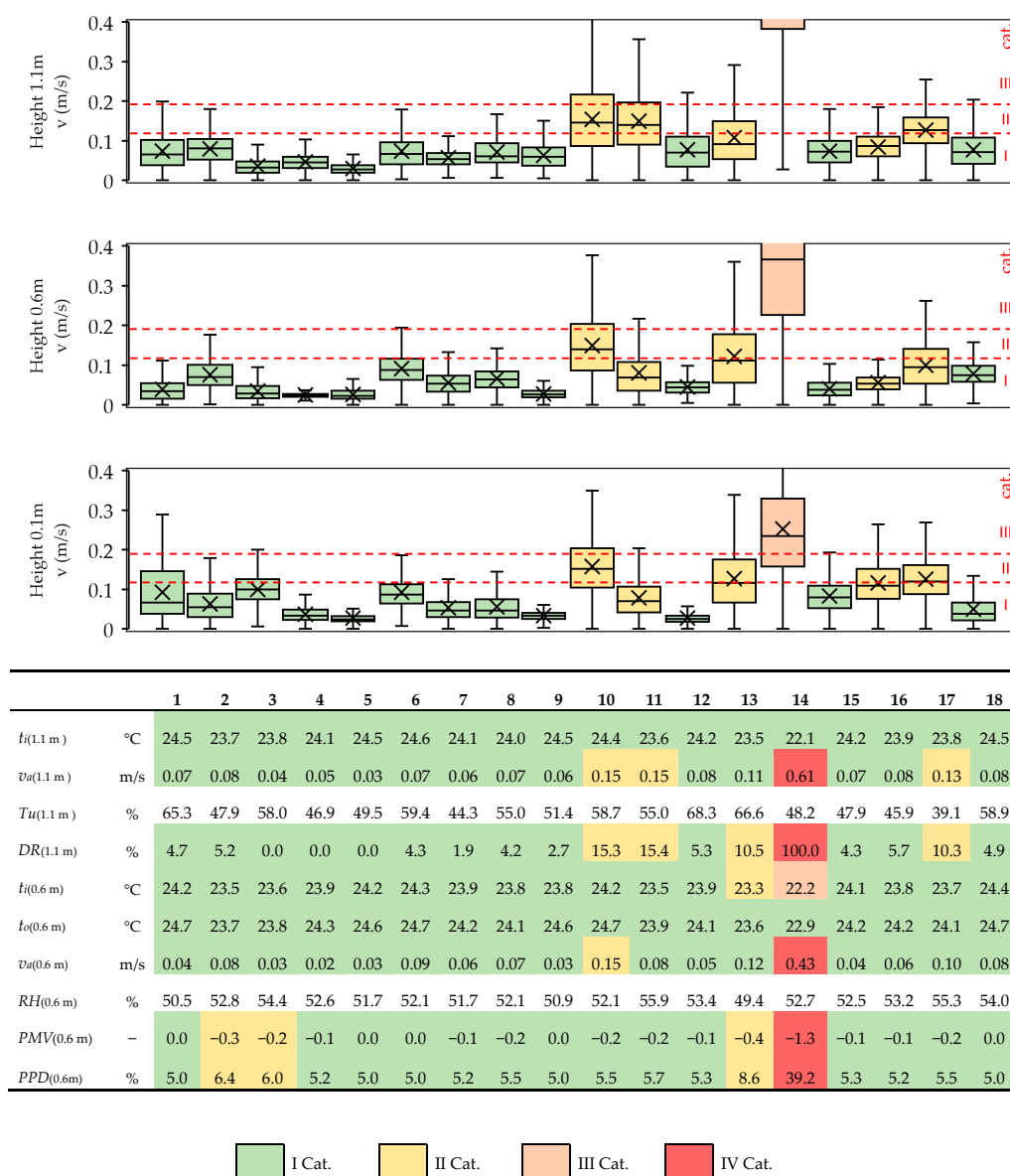☐ I Cat.   ☐ II Cat.   ☐ III Cat.   ☐ IV Cat.

Figure 4. Building A air velocity results in measurement points 1–18 and the thermal comfort parameters.

3.2. Building B Results

The v_a results and TC parameters of Building B with slab-based TABS system are given below in Figure 5. Building B had more measured points in the second category by *PMV* and *PPD* compared to Building A. *DR* met the II category in four measurement positions. Positions 4–8 were in an office, where the ventilation rate had been doubled by the request of the lessee. These four measurements stand out above the others. Regarding the other four buildings observed, displacement ventilation effect can be seen, as v_a fluctuates more near the floor.
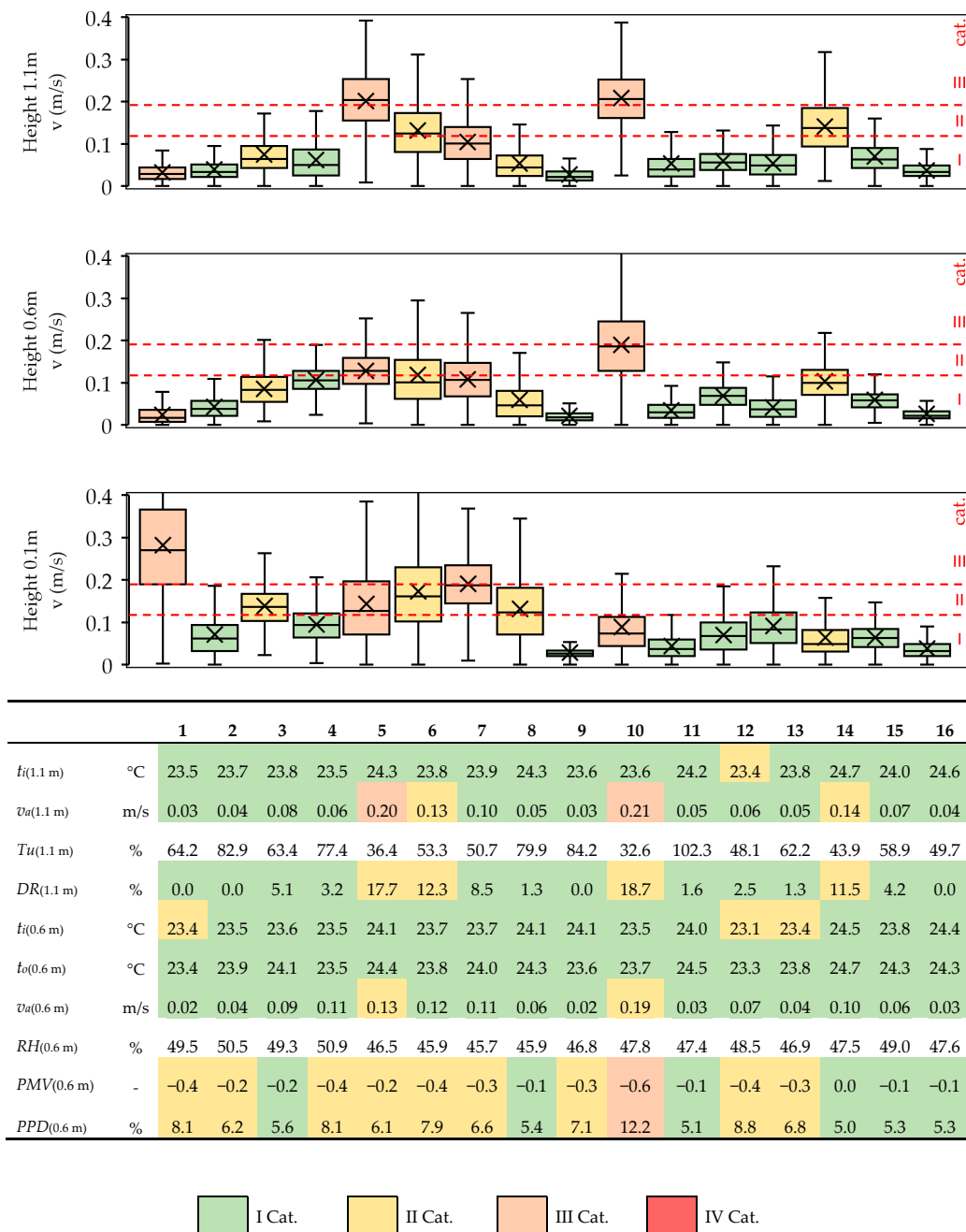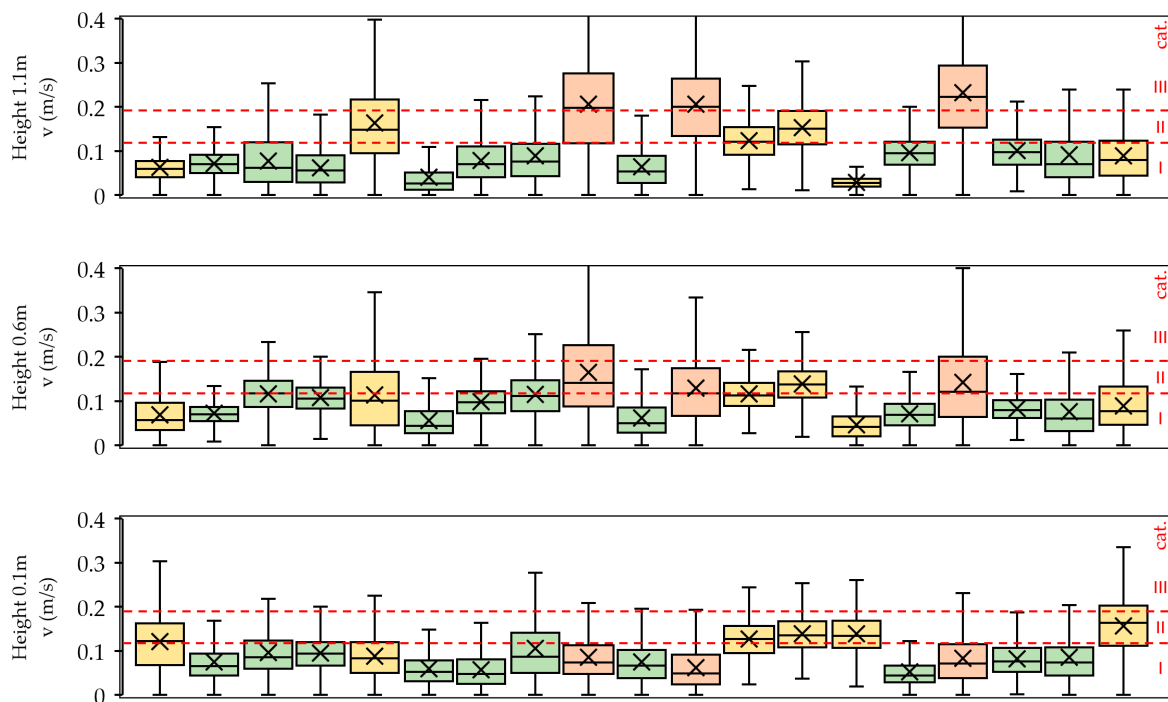
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
$t_{i(1.1\,m)}$	°C	23.5	23.7	23.8	23.5	24.3	23.8	23.9	24.3	23.6	23.6	24.2	23.4	23.8	24.7	24.0	24.6
$v_{a(1.1\,m)}$	m/s	0.03	0.04	0.08	0.06	0.20	0.13	0.10	0.05	0.03	0.21	0.05	0.06	0.05	0.14	0.07	0.04
$Tu_{(1.1\,m)}$	%	64.2	82.9	63.4	77.4	36.4	53.3	50.7	79.9	84.2	32.6	102.3	48.1	62.2	43.9	58.9	49.7
$DR_{(1.1\,m)}$	%	0.0	0.0	5.1	3.2	17.7	12.3	8.5	1.3	0.0	18.7	1.6	2.5	1.3	11.5	4.2	0.0
$t_{i(0.6\,m)}$	°C	23.4	23.5	23.6	23.5	24.1	23.7	23.7	24.1	24.1	23.5	24.0	23.1	23.4	24.5	23.8	24.4
$t_{o(0.6\,m)}$	°C	23.4	23.9	24.1	23.5	24.4	23.8	24.0	24.3	23.6	23.7	24.5	23.3	23.8	24.7	24.3	24.3
$v_{a(0.6\,m)}$	m/s	0.02	0.04	0.09	0.11	0.13	0.12	0.11	0.06	0.02	0.19	0.03	0.07	0.04	0.10	0.06	0.03
$RH_{(0.6\,m)}$	%	49.5	50.5	49.3	50.9	46.5	45.9	45.7	45.9	46.8	47.8	47.4	48.5	46.9	47.5	49.0	47.6
$PMV_{(0.6\,m)}$	-	−0.4	−0.2	−0.2	−0.4	−0.2	−0.4	−0.3	−0.1	−0.3	−0.6	−0.1	−0.4	−0.3	0.0	−0.1	−0.1
$PPD_{(0.6\,m)}$	%	8.1	6.2	5.6	8.1	6.1	7.9	6.6	5.4	7.1	12.2	5.1	8.8	6.8	5.0	5.3	5.3

I Cat.　　II Cat.　　III Cat.　　IV Cat.

Figure 5. Building B air velocity results in measurement points 1–16 and the thermal comfort parameters.

3.3. Building C Results

Building C was equipped with suspended ceiling active chilled beams and the results of v_a and parameters of TC are presented below in Figure 6. *PMV*, *PPD*, and t_i were similar to Buildings A and

B, at the same time v_a and *DR* were measured at two positions in the II category and three times in the III category. The v_a is more fluctuating on the height of the sitting person neck.

|		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
$t_{i(1.1\,m)}$	°C	24.8	24.3	24.3	24.1	23.8	24.1	23.7	23.9	23.8	24.1	23.4	23.7	23.4	24.3	24.3	24.4	24.0	24.3	24.0
$v_{a(1.1\,m)}$	m/s	0.06	0.07	0.08	0.06	0.16	0.04	0.08	0.09	0.21	0.06	0.21	0.12	0.15	0.03	0.10	0.23	0.10	0.09	0.09
$Tu_{(1.1\,m)}$	%	62.8	45.2	74.6	65.0	56.8	105.3	66.4	77.6	54.5	79.0	47.9	37.9	36.6	51.8	41.7	47.7	42.9	79.0	61.8
$DR_{(1.1\,m)}$	%	3.0	3.9	5.5	2.9	17.4	0.0	5.8	7.7	23.5	3.5	22.8	9.9	13.5	0.0	6.6	24.2	7.5	7.8	6.9
$t_{i(0.6\,m)}$	°C	24.5	24.1	24.0	23.9	23.9	23.9	23.4	23.9	23.9	24.0	23.5	23.5	23.4	24.0	24.2	24.3	23.9	24.2	23.8
$t_{o(0.6\,m)}$	°C	24.8	24.4	24.5	24.3	24.0	24.0	23.7	24.1	24.3	24.3	23.8	23.9	23.7	23.9	24.5	24.7	24.3	24.3	24.2
$v_{a(0.6\,m)}$	m/s	0.07	0.07	0.12	0.11	0.11	0.06	0.10	0.12	0.16	0.06	0.13	0.12	0.14	0.05	0.07	0.14	0.08	0.08	0.09
$RH_{(0.6\,m)}$	%	53.3	57.5	57.3	58.0	57.7	58.0	56.7	57.0	56.0	56.2	56.5	56.5	57.0	52.0	54.2	53.6	54.0	52.5	54.5
$PMV_{(0.6\,m)}$	-	0.1	0.0	−0.1	−0.1	−0.2	−0.1	−0.3	−0.2	−0.3	−0.1	−0.3	−0.3	−0.4	−0.2	0.0	−0.1	−0.1	−0.1	−0.1
$PPD_{(0.6\,m)}$	%	5.2	5.0	5.1	5.2	6.0	5.4	6.4	5.7	6.9	5.1	7.2	6.5	8.3	5.8	5.0	5.2	5.1	5.2	5.3

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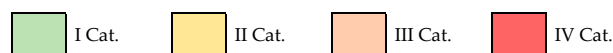
Figure 6. Building C air velocity results in measurement points 1–19 and the thermal comfort parameters.

3.4. Building D Results

Equipped with radiant cooling panels, results of v_a and parameters of TC in Building D are showed below in Figure 7. Compared to other buildings, Building D with the least number of positions had the best results on all analyzed parameters. In all cases, I category *DR* was achieved. At all times, mean v_a remained below 0.10 m/s being more fluctuating near the floor.
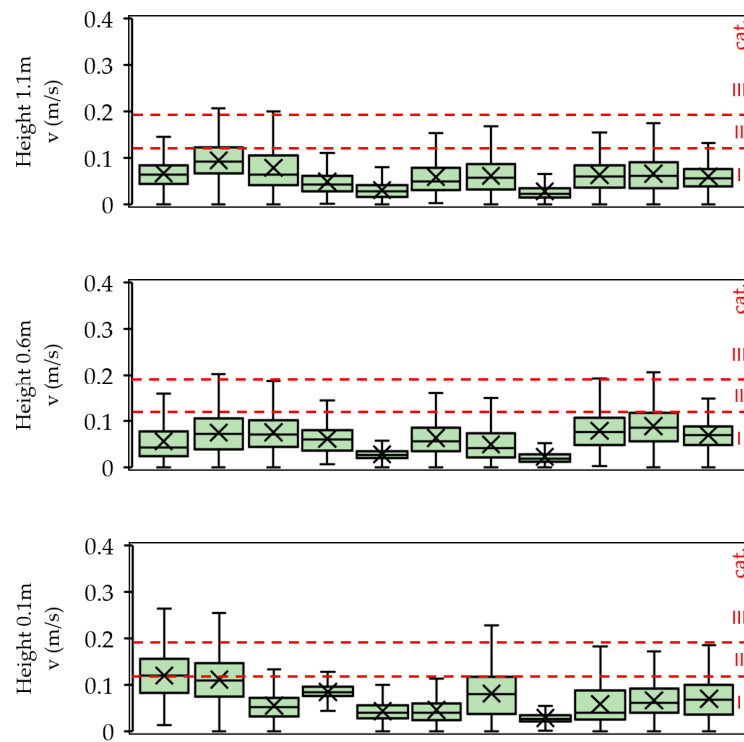
		1	2	3	4	5	6	7	8	9	10	11
$t_{i(1.1\,m)}$	°C	24.8	24.2	24.2	24.2	24.2	24.2	23.3	23.6	24.5	23.9	23.4
$v_{a(1.1\,m)}$	m/s	0.07	0.09	0.08	0.05	0.03	0.06	0.06	0.03	0.06	0.07	0.06
$Tu_{(1.1\,m)}$	%	53.5	47.5	66.6	72.1	66.1	73.6	62.7	84.2	58.8	59.9	48.1
$DR_{(1.1\,m)}$	%	3.2	6.8	5.5	0.0	0.0	2.4	2.9	0.0	2.9	3.6	2.5
$t_{i(0.6\,m)}$	°C	24.4	24.0	24.1	24.0	24.1	24.1	23.4	23.4	23.4	23.5	23.1
$t_{o(0.6\,m)}$	°C	24.3	23.8	24.0	24.0	24.0	24.0	23.1	23.6	24.8	23.7	23.3
$v_{a(0.6\,m)}$	m/s	0.06	0.07	0.07	0.06	0.03	0.06	0.05	0.02	0.08	0.09	0.07
$RH_{(0.6\,m)}$	%	58.0	57.8	57.2	57.4	57.8	58.0	59.9	46.8	57.2	59.7	48.5
$PMV_{(0.6\,m)}$	-	0.0	−0.2	−0.1	−0.1	−0.1	−0.1	−0.4	−0.3	0.1	−0.2	−0.4
$PPD_{(0.6\,m)}$	%	5.1	5.7	5.4	5.4	5.4	5.3	8.5	7.3	5.1	6.1	8.8

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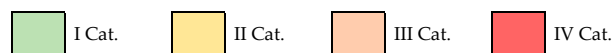
Figure 7. Building D air velocity results in measurement points 1–11 and the thermal comfort parameters.

3.5. Building E Results

According to the results, Building E achieved the worst TC values by categories. *DR* was in the II category in 4 positions of 14, t_i was in III category four times. *PMV* and *PPD* second category was not reached 5 times. Fluctuations of v_a were random depending on the height. The v_a results and TC parameters in Building E, with fan coil units mounted in the suspended ceiling, are compared below in Figure 8.
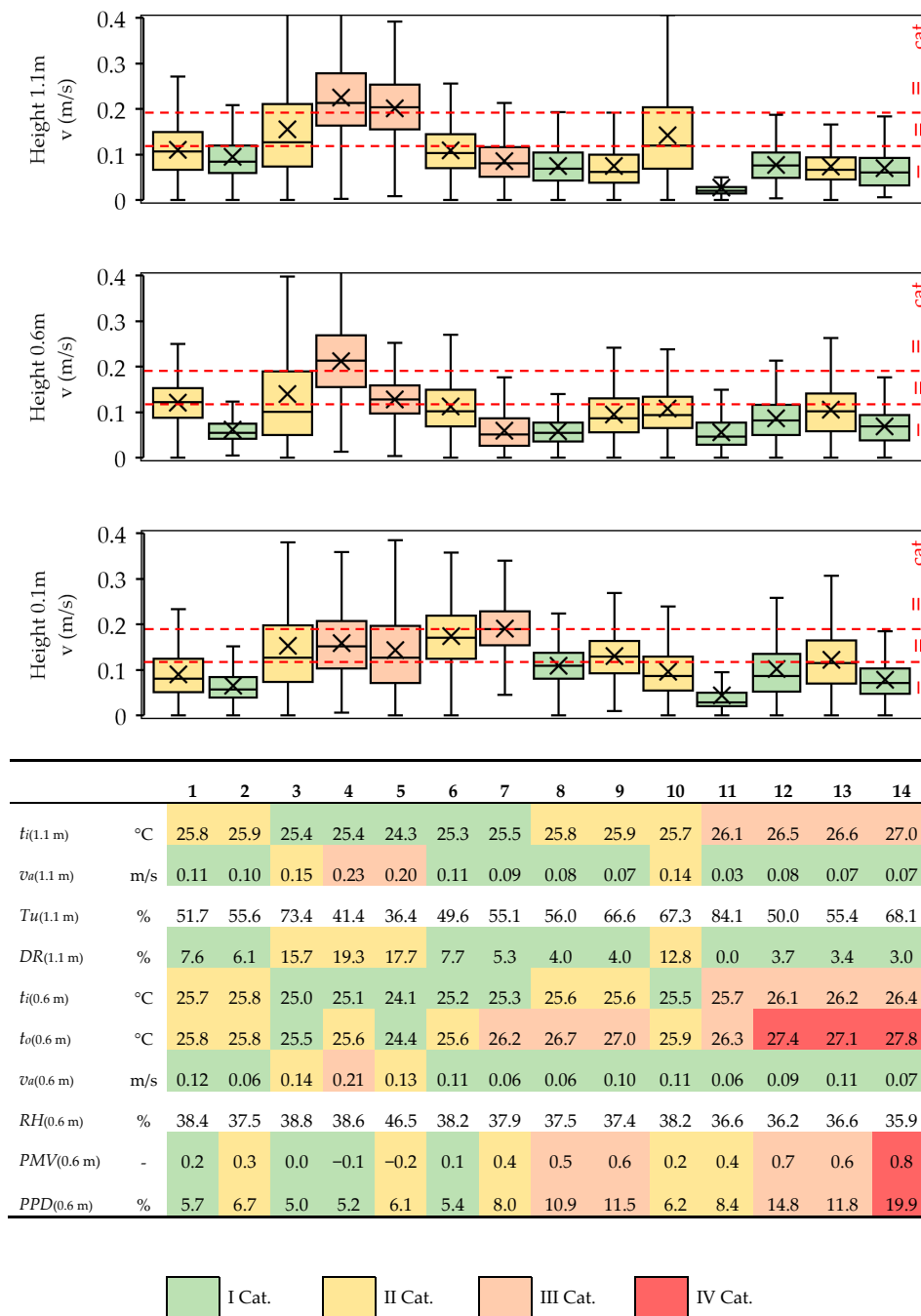
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
$t_{i(1.1\,m)}$	°C	25.8	25.9	25.4	25.4	24.3	25.3	25.5	25.8	25.9	25.7	26.1	26.5	26.6	27.0
$v_{a(1.1\,m)}$	m/s	0.11	0.10	0.15	0.23	0.20	0.11	0.09	0.08	0.07	0.14	0.03	0.08	0.07	0.07
$Tu_{(1.1\,m)}$	%	51.7	55.6	73.4	41.4	36.4	49.6	55.1	56.0	66.6	67.3	84.1	50.0	55.4	68.1
$DR_{(1.1\,m)}$	%	7.6	6.1	15.7	19.3	17.7	7.7	5.3	4.0	4.0	12.8	0.0	3.7	3.4	3.0
$t_{i(0.6\,m)}$	°C	25.7	25.8	25.0	25.1	24.1	25.2	25.3	25.6	25.6	25.5	25.7	26.1	26.2	26.4
$t_{o(0.6\,m)}$	°C	25.8	25.8	25.5	25.6	24.4	25.6	26.2	26.7	27.0	25.9	26.3	27.4	27.1	27.8
$v_{a(0.6\,m)}$	m/s	0.12	0.06	0.14	0.21	0.13	0.11	0.06	0.06	0.10	0.11	0.06	0.09	0.11	0.07
$RH_{(0.6\,m)}$	%	38.4	37.5	38.8	38.6	46.5	38.2	37.9	37.5	37.4	38.2	36.6	36.2	36.6	35.9
$PMV_{(0.6\,m)}$	-	0.2	0.3	0.0	−0.1	−0.2	0.1	0.4	0.5	0.6	0.2	0.4	0.7	0.6	0.8
$PPD_{(0.6\,m)}$	%	5.7	6.7	5.0	5.2	6.1	5.4	8.0	10.9	11.5	6.2	8.4	14.8	11.8	19.9

▩ I Cat.　　▩ II Cat.　　▩ III Cat.　　▩ IV Cat.

Figure 8. Building E air velocity results in measurement points 1–14 and the thermal comfort parameters.

3.6. Results of the Indoor Climate Questionnaire

Based on ICQ survey, summary of the results for thermal environment are shown below in Figure 9, the ICQ results for *PMV* and *PPD* are presented below in Figure 10. The highest number of answers were in the Building A with 36 responses divided between all age groups equally between men and women. A total of 83% were working in open office layout and 86% were spending most of the day at their workplace. For 83% of the respondents, t_i was described as suitable. Meanwhile, 6 occupants found it to be warm and 7 slightly cooler. A total of 89% had not or had perceived slight odor, 72% did not find lighting fixtures or sunlight to be disturbing, and 81% found ICQ to be suitable or better. A total of 61% perceived overall acoustics and 36% perceived other noises to be disturbing. Roughly half of the respondents rarely felt eye problems, headaches, or concentration matters and

64% rarely felt nasal or throat irritation. Extra comments mentioned occasional lack of ventilation and air dryness.
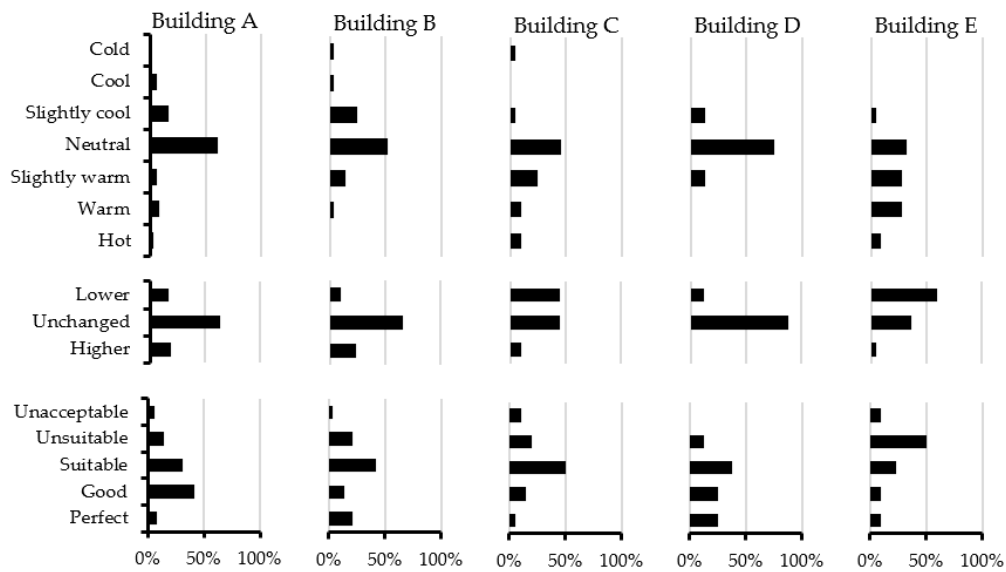
Figure 9. Indoor climate questionnaire results for indoor air temperature. The descriptions of y-axis are the room air temperature sensation question (upper) and verification questions (middle and lower) from the indoor climate questionnaire (see Appendix A).
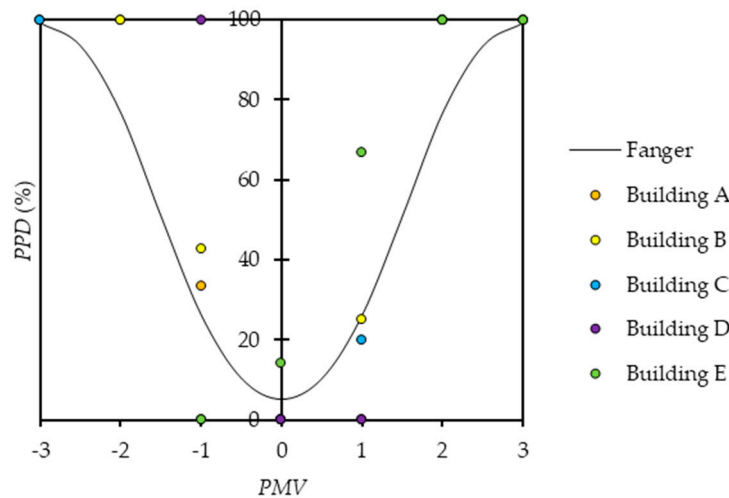

Figure 10. Indoor climate questionnaire results for predicted percentage of dissatisfied and predicted mean vote.

Respondents in the Building B were 38% females, 2/3 aged between 26–35 or 36–45 and 1/2 spending half of the workday behind the desk. A total of 72% of them working in open office environment. Ninety percent found t_i to be suitable. A total of 13 of the 29 respondents did not perceive odor. Lighting was disturbing for 21% and sunlight for 14%, meanwhile 14% were dissatisfied with ICQ. Seven percent did not find room acoustics and 17% general noise in office to be disturbing. Half of the respondents had rarely felt eye dryness or irritation, occur headaches or fatigue, and felt nasal problem or dry throat. A total of 62% had rarely felt concentration problems.

Seventy percent of the 20 ICQ respondents in Building C were women. Answers were divided between the age of 26 to 65 with the majority of them working in open office landscape, 2/3 working behind their desk most of the day. Perceived as too warm by 20%, t_i was suitable by 75% of the

occupants. Ninety percent had not perceived or had perceived slight odor. A total of 70% did not find lighting equipment to be disturbing and 75% was not disturbed by the sunlight. Forty percent of the respondents found air quality to be not suitable or unacceptable. A total of 85% perceived colleagues' speech and overall room acoustic to be somewhat disturbing, while 65% claimed other noises to be distracting. A total of 1/3 had rarely felt eye problems, occurred headaches, or tiredness. A total of 45% had rarely felt nasal or throat irritation and 20% had rarely had concentration issues. Extra comments mentioned lower fresh air rate in the end of the day.

Building D had only 8 responses for the online ICQ all of them working in the open office. For the majority of the answers, t_i was suitable. Odor was rarely noticed, lighting or sunlight was not disturbing. ICQ was suitable or better, while room acoustics was more disturbing than other noises. Nasal issues were more often to occur compared to eye dryness or headaches and concentration issues. Extra comments noted that open office may be cheaper option for the employer being unsuitable for the employees.

A total of 2/3 of the 22 respondents in Building E were in the second age group between 26–35 years and 36% in overall were females. A total of 77% of the tenants were working in an open office environment, while 2/3 of them were spending most of their day behind the desk. One-third found t_i to be suitable and 2/3 claimed the t_i to be slightly warm, warm, or hot. Fifty percent perceived weak or moderate odor. Room lighting equipment did not disturb 82% and the sun did not disturb 60% of the respondents. A total of 2/3 marked ICQ suitable, good, or very good. Room acoustic level was not claimed to be disturbing for 40% and other noise for 23% of the respondents. Fifty percent had rarely felt eye dryness or irritation, 64% had rarely occur headaches or fatigue, 82% had rarely felt nasal problems or dry throat, and 50% mentioned concentration issues sometimes, often, or all the time. Extra comments noted that air quality decreases in the second phase of the day and the missing option for opening windows was also described as a disadvantage.

Number of respondents of the ICQ is below the least recommended sample size [63], therefore the results of the ICQ include higher uncertainty (Figure 10). Thermal sensation voted by occupants covers significantly wider range than *PMV* calculated from measurements. Majority of the respondents were working in open office. The most unsatisfying t_i was in the Building E and the most suitable t_i was in the Building D. In general, unsuitable t_i was perceived more as warmer than cooler. In Buildings A, B, and D the t_i was perceived suitable for over 80% of the employees, while it was 67% in the Building E and the 60% in the Building C.

4. Discussion

The on-site measurement results showed, that the during cooling summertime *DR* risk can be stated in all observed buildings. Preconception of avoiding fan coil units for cooling does not immediately guarantee a superior thermal environment without draught. However, draught risk was the lowest in Building D with radiant cooling panels as room conditioning units.

Possible causes, v_a and *DR* was not significantly higher in the case of fan coil units in Building E was the taping of air distribution vanes (Figure 3b) and also positioning of the working stations was carried out avoiding direct draught from the fan coil units. This could explain the higher thermal environment temperatures. The induced airflow rate is manually adjustable for open ceiling active chilled beams in Building A and was adjusted into different positions for avoiding possible draught between two beams in various places. In Building C, few suspended ceiling active chilled beams had paper covers blocking air flow from the nozzles. These modifications were made due to the complaints, decrease in productivity or spatial plan and the layout of the workspaces. Described modifications in Buildings A, C, and E refer to possible ineffective floor space areas. Therefore, whether the design or construction may have been inaccurate or user-based thermal environment setpoints do not meet the requirements for v_a and *DR*.

The v_a limit values in EN 16798−1:2019 [54] have been calculated assuming t_o +23 °C and *Tu* 40%. Figure 11a illustrates that the *Tu* is considerably higher than the default value, which increases the

unsatisfaction with local TC. However, the measured t_o was higher than the default value in most of the measured positions in all buildings, which decreases the number of dissatisfied. Figure 11b shows that, in general, the *DR* calculated based on measured t_o and *Tu* is in the same scale with the one calculated with the default values.
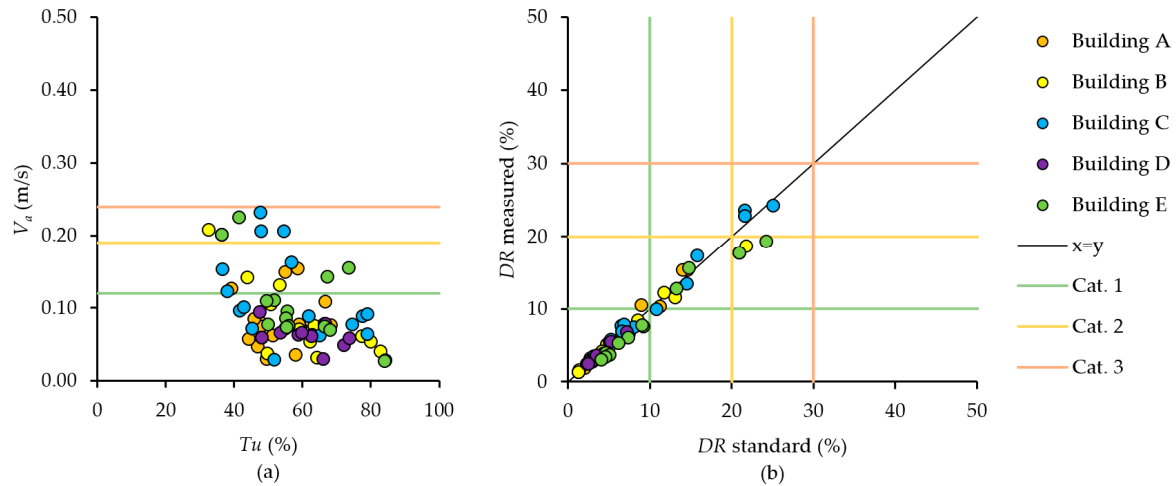

Figure 11. Air velocity and turbulence intensity results according to maximum air velocity categories I–III in summer (**a**); Draught rate correlation in measured and standard-based [54] conditions according to draught rate categories I–III (**b**).

In further analysis of this study t_i will be more deeply discussed, foreseeing to include transitional period and heating period measurements, façade inspection and t_i periodical data analysis in the reference buildings. Therefore, the performance of the cooling units according to t_i could be more clearly presented by period or duration curve. Periodical data analysis on t_i is mandatory as t_i presented in this study reflects only a fragment of the thermal environment. Positioning TC measurement values on periodical t_i data can indicate TC measurement accuracy and dispersion. IQC survey number of respondents also needs additional attention, how to achieve a higher response rate.

There are several limitations to this work. Authors had no control over the boundary conditions during measurements. This study only focuses on a few office spaces in five different building in Tallinn. More further studies of actual work environment need to be performed in order to be able to draw general conclusions about studied room conditioning solutions air distribution performance.

5. Conclusions

This study was based on TC measurements in open office environments in Tallinn. First or second category measured general thermal comfort in four buildings out of five were still inconvenient for significant number of occupants because of local thermal discomfort caused by draught and by some additional dissatisfaction indicated by questionnaires. Questionnaire survey showed deviation from predicted *PPD* in both directions. Some small occupant groups were either more satisfied or less satisfied at slightly cool or slightly warm thermal sensation, but at neutral sensation the results were more consistent. Less satisfied occupant groups exposed to higher air velocities has likely affected their satisfaction reported in thermal sensation questions because there was no specific draught question available.

Temperature measurements showed that air and operative temperature was the worst in Building E which was close to drop out from category III, while measurement results in Buildings A–D remained in between I and II category. According to the questionnaire over 80% of the employees in Buildings A, B, and C, and 75% in Building D were thermally satisfied. In the Building E, 59% of occupants found the thermal environment unsuitable or unacceptable. Generally, the average thermal satisfaction of occupants was well in line with the measurements.

Air velocity and draught rate measurements showed that modern offices do not necessarily reach to generally expected good indoor climate category II air velocity and draught rate values. A room conditioning solution with suspended ceiling active chilled beams in Building C, displacement ventilation in Building B with TABS and fan coil units in Building E showed category III performance only. Open ceiling active chilled beams in Building A corresponded to category II requirements and ceiling panels for room conditioning in Building D showed superior Category I performance. Category II and III results with active chilled beams indicate that dedicated air distribution solution together with proper design and sizing is needed to reach category II.

We found that existing standards do not provide enough detailed questionnaire for the assessment of occupant dissatisfaction. Our results suggest that questionnaire could be an easier compliance assessment method compared to measurements, which need an expensive equipment and carefully selected measurement days. For the compliance assessment with the measurement, there is more guidance needed especially how to select relevant measurement conditions and locations for draught rate measurement. Future office buildings with open-plan layouts revealed to be demanding environments where careful air distribution design is needed in order to meet comfort requirements.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

A	net floor area (m^2)
C_{res}	respiratory convective heat exchange (W/m^2)
DR	draught rate (%)
E_c	evaporative heat exchange at the skin, when the person experiences a sensation of thermal neutrality (W/m^2)
E_{res}	respiratory evaporative heat exchange (W/m^2)
f_{cl}	clothing surface area factor
g	solar radiation transmittance through window glass
H	heat loss (W/K)
H_d	dry heat loss (W/m^2)
h_c	convective heat transfer coefficient [W/(m^2 × K)]
HVAC	heating, ventilation, and air conditioning
I_{cl}	clothing insulation [(m^2 × K)/W]
ICQ	indoor climate questionnaire
M	metabolic rate (W/m^2)
mt_{sk}	mean skin temperature (°C)
p_a	water vapor partial pressure (Pa)
PMV	predicted mean vote
PPD	predicted percentage dissatisfied (%)
RH	relative humidity (%)
SD	standard deviation
TABS	thermally active building systems

TC	thermal comfort
t_{cl}	clothing surface temperature (°C)
t_i	indoor air temperature (°C)
t_o	operative temperature (°C)
Tu	turbulence intensity
U	thermal transmittance [W/(m^2×K)]
v_a	air velocity (m/s)
v_{ar}	relative air velocity (m/s)
W	effective mechanical power (W/m^2)
WWR	window-to-wall ratio

Appendix A

The ICQ form is for online survey is provided below.

1. Gender—( ) Female, ( ) Male
2. Age—( ) 18–25, ( ) 26–35, ( ) 36–45, ( ) 46–55, ( ) 56–65, ( ) 66+
3. Workstation—( ) Private office (max 3 people), ( ) Open office
4. Which amount of the workday you spend at your desk—( ) Whole workday, ( ) Half of the workday (up to 4–5 h), ( ) Few hours (max 1–2 h)
5. In which zone do you spend the most of your workday (1–n in picture)—( ) 1–n
6. How do you rate you thermal sensation (choose neutral if you do not want a change in temperature)—( ) Hot, ( ) Warm, ( ) Slightly warm, ( ) Comfortable, ( ) Slightly cool, ( ) Cool, ( ) Cold
7. How do you perceive odor intensity—( ) No odor, ( ) Weak, ( ) Moderate, ( ) Strong, ( ) Very strong, ( ) Unbearable
8. Would you prefer the room temperature to be—( ) Higher, ( ) Unchanged, ( ) Lower
9. Does the room lighting disturb working—( ) Yes, ( ) No
10. Does the sunlight disturb working—( ) Yes, ( ) No
11. Please rate (room temperature is)—( ) Perfect, ( ) Good, ( ) Suitable, ( ) Unsuitable, ( ) Unbearable
12. Please rate (air quality is)—( ) Perfect, ( ) Good, ( ) Suitable, ( ) Unsuitable, ( ) Unbearable
13. How do you perceive acoustic level (colleagues' speech and overall room acoustics)—( ) Does not disturb at all, ( ) Rarely disturbs, ( ) Sometimes disturbs, ( ) Often disturbs, ( ) Disturbs all the time
14. How do you perceive other noise in your workplace—( ) Does not disturb at all, ( ) Rarely disturbs, ( ) Sometimes disturbs, ( ) Often disturbs, ( ) Disturbs all the time
15. Whether and how often have you experienced the following symptoms (eye dryness or irritation)—( ) Never, ( ) Rarely, ( ) Sometimes, ( ) Often, ( ) All the time
16. Whether and how often have you experienced the following symptoms (headache or fatigue)—( ) Never, ( ) Rarely, ( ) Sometimes, ( ) Often, ( ) All the time
17. Whether and how often have you experienced the following symptoms (nasal or throat dryness or irritation)—( ) Never, ( ) Rarely, ( ) Sometimes, ( ) Often, ( ) All the time
18. Whether and how often have you experienced the following symptoms (concentration problems)—( ) Never, ( ) Rarely, ( ) Sometimes, ( ) Often, ( ) All the time

References

1. Seppanen, O. Ventilation Strategies for Good Indoor Air Quality and Energy Efficiency. *Int. J. Vent.* **2008**, *6*, 297–306.
2. Yang, Z.; Ghahramani, A.; Becerik-Gerber, B. Building occupancy diversity and HVAC (heating, ventilation, and air conditioning) system energy efficiency. *Energy* **2016**, *109*, 641–649. [CrossRef]
3. Mathews, E.H.; Botha, C.P.; Arndt, D.C.; Malan, A.G. HVAC control strategies to enhance comfort and minimise energy usage. *Energy Build.* **2001**, *33*, 853–863. [CrossRef]
4. Simmonds, P. The Utilization of Optimal-Design and Operation Strategies in Lowering the Energy-Consumption in Office Buildings. *Renew. Energy* **1994**, *5*, 1193–1201. [CrossRef]
5. Guo, W.; Zhou, M. Technologies toward thermal comfort-based and energy-efficient HVAC systems: A review. In Proceedings of the 2009 IEEE International Conference on Systems, Man and Cybernetics, San Antonio, TX, USA, 11–14 October 2009; pp. 3883–3888.
6. Fanger, P.O.; Christensen, N.K. Perception of draught in ventilated spaces. *Ergonomics* **1986**, *29*, 215–235. [CrossRef] [PubMed]

7.   Shahrestani, M.; Yao, R.M.; Cook, G.K. Decision Making for HVAC&R System Selection for a Typical Office Building in the UK. *Ashrae Trans.* **2012**, *118*, 222–229.

8.   Nemethova, E.; Stutterecker, W.; Schoberer, T. Thermal Comfort and HVAC Systems Operation Challenges in a Modern Office Building—Case Study. *Sel. Sci. Pap. J. Civ. Eng.* **2016**, *11*, 103–114. [CrossRef]

9.   Shahzad, S.S.; Brennan, J.; Theodossopoulos, D.; Hughes, B.; Calautit, J.K. Energy Efficiency and User Comfort in the Workplace: Norwegian Cellular vs. British Open Plan Workplaces. *Energy Procedia* **2015**, *75*, 807–812. [CrossRef]

10. Choi, J.H.; Loftness, V.; Aziz, A. Post-occupancy evaluation of 20 office buildings as basis for future IEQ standards and guidelines. *Energy Build.* **2012**, *46*, 167–175. [CrossRef]

11. Karjalainen, S. Thermal comfort and gender: A literature review. *Indoor Air* **2012**, *22*, 96–109. [CrossRef]

12. Schellen, L.; Loomans, M.G.L.C.; de Wit, M.H.; Olesen, B.W.; Lichtenbelt, W.D.V. The influence of local effects on thermal sensation under non-uniform environmental conditions-Gender differences in thermophysiology, thermal comfort and productivity during convective and radiant cooling. *Physiol. Behav.* **2012**, *107*, 252–261. [CrossRef] [PubMed]

13. Rupp, R.F.; Vasquez, N.G.; Lamberts, R. A review of human thermal comfort in the built environment. *Energy Build.* **2015**, *105*, 178–205. [CrossRef]

14. Pfafferott, J.U.; Herkel, S.; Kalz, D.E.; Zeuschner, A. Comparison of low-energy office buildings in summer using different thermal comfort criteria. *Energy Build.* **2007**, *39*, 750–757. [CrossRef]

15. Hens, H.S.L.C. Thermal comfort in office buildings: Two case studies commented. *Build. Environ.* **2009**, *44*, 1399–1408. [CrossRef]

16. Kolarik, J.; Toftum, J.; Olesen, B.W. Operative temperature drifts and occupant satisfaction with thermal environment in three office buildings using radiant heating/ cooling system. In Proceedings of the Healthy Buildings Europe 2015, Eindhoven, The Netherlands, 18–20 May 2015.

17. Griefahn, B.; Kunemund, C. The effects of gender, age, and fatigue on susceptibility to draft discomfort. *J. Therm. Biol.* **2001**, *26*, 395–400. [CrossRef]

18. Maykot, J.K.; Rupp, R.F.; Ghisi, E. A field study about gender and thermal comfort temperatures in office buildings. *Energy Build.* **2018**, *178*, 254–264. [CrossRef]

19. Maula, H.; Hongisto, V.; Ostman, L.; Haapakangas, A.; Koskela, H.; Hyona, J. The effect of slightly warm temperature on work performance and comfort in open-plan offices - a laboratory study. *Indoor Air* **2016**, *26*, 286–297. [CrossRef]

20. Wang, Z.; de Dear, R.; Luo, M.H.; Lin, B.R.; He, Y.D.; Ghahramani, A.; Zhu, Y.X. Individual difference in thermal comfort: A literature review. *Build. Environ.* **2018**, *138*, 181–193. [CrossRef]

21. Kim, J.; Zhou, Y.X.; Schiavon, S.; Raftery, P.; Brager, G. Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning. *Build. Environ.* **2018**, *129*, 96–106. [CrossRef]

22. Pazhoohesh, M.; Zhang, C. A satisfaction-range approach for achieving thermal comfort level in a shared office. *Build. Environ.* **2018**, *142*, 312–326. [CrossRef]

23. Enescu, D. A review of thermal comfort models and indicators for indoor environments. *Renew. Sustain. Energy Rev.* **2017**, *79*, 1353–1379. [CrossRef]

24. Laftchiev, E.; Nikovski, D. An IoT system to estimate personal thermal comfort. In Proceedings of the 2016 IEEE 3rd World Forum on Internet of Things (WF-IoT), Reston, VA, USA, 12–14 December 2016; pp. 672–677.

25. Ghahramani, A.; Castro, G.; Karvigh, S.A.; Becerik-Gerber, B. Towards unsupervised learning of thermal comfort using infrared thermography. *Appl. Energy* **2018**, *211*, 41–49. [CrossRef]

26. Jung, W.; Jazizadeh, F. Human-in-the-loop HVAC operations: A quantitative review on occupancy, comfort, and energy-efficiency dimensions. *Appl. Energy* **2019**, *239*, 1471–1508. [CrossRef]

27. Shi, J.; Yu, N.P.; Yao, W.X. Energy efficient building HVAC control algorithm with real-time occupancy prediction. In Proceedings of the 8th International Conference on Sustainability in Energy and Buildings, Turin, Italy, 11–13 September 2017.

28. Thalfeldt, M.; Pikas, E.; Kurnitski, J.; Voll, H. Facade design principles for nearly zero energy buildings in a cold climate. *Energy Build.* **2013**, *67*, 309–321. [CrossRef]

29. Kähkönen, E. Draught, Radiant Temperature Asymmetry and Air Temperature – a Comparison between Measured and Estimated Thermal Parameters. *Indoor Air* **1991**, *1*, 439–447. [CrossRef]

30. Kiil, M.; Mikola, A.; Thalfeldt, M.; Kurnitski, J. Thermal comfort and draught assessment in a modern open office building in Tallinn. *E3S Web Conf.* **2019**, *111*, 02013. [CrossRef]

31. Rhee, K.N.; Olesen, B.W.; Kim, K.W. Ten questions about radiant heating and cooling systems. *Build. Environ.* **2017**, *112*, 367–381. [CrossRef]

32. Saber, E.M.; Tham, K.W.; Leibundgut, H. A review of high temperature cooling systems in tropical buildings. *Build. Environ.* **2016**, *96*, 237–249. [CrossRef]

33. Schellen, L.; Loomans, M.G.L.C.; de Wit, M.H.; Olesen, B.W.; Lichtenbelt, W.D.V.M. Effects of different cooling principles on thermal sensation and physiological responses. *Energy Build.* **2013**, *62*, 116–125. [CrossRef]

34. Maula, H.; Hongisto, V.; Koskela, H.; Haapakangas, A. The effect of cooling jet on work performance and comfort in warm office environment. *Build. Environ.* **2016**, *104*, 13–20. [CrossRef]

35. Gao, S.; Wang, Y.A.; Zhang, S.M.; Zhao, M.; Meng, X.Z.; Zhang, L.Y.; Yang, C.; Jin, L.W. Numerical investigation on the relationship between human thermal comfort and thermal balance under radiant cooling system. *Energy Procedia* **2017**, *105*, 2879–2884. [CrossRef]

36. Cen, C.; Jia, Y.H.; Liu, K.X.; Geng, R.X. Experimental comparison of thermal comfort during cooling with a fan coil system and radiant floor system at varying space heights. *Build. Environ.* **2018**, *141*, 71–79. [CrossRef]

37. Kolarik, J.; Toftum, J.; Olesen, B.W.; Jensen, K.L. Simulation of energy use, human thermal comfort and office work performance in buildings with moderately drifting operative temperatures. *Energy Build.* **2011**, *43*, 2988–2997. [CrossRef]

38. Fonseca, N. Experimental study of thermal condition in a room with hydronic cooling radiant surfaces. *Int. J. Refrig.* **2011**, *34*, 686–695. [CrossRef]

39. Li, R.L.; Yoshidomi, T.; Ooka, R.; Olesen, B.W. Field evaluation of performance of radiant heating/cooling ceiling panel system. *Energy Build.* **2015**, *86*, 58–65. [CrossRef]

40. Saber, E.M.; Iyengar, R.; Mast, M.; Meggers, F.; Tham, K.W.; Leibundgut, H. Thermal comfort and IAQ analysis of a decentralized DOAS system coupled with radiant cooling for the tropics. *Build. Environ.* **2014**, *82*, 361–370. [CrossRef]

41. Chiang, W.H.; Wang, C.Y.; Huang, J.S. Evaluation of cooling ceiling and mechanical ventilation systems on thermal comfort using CFD study in an office for subtropical region. *Build. Environ.* **2012**, *48*, 113–127. [CrossRef]

42. Mustakallio, P.; Bolashikov, Z.; Kostov, K.; Melikov, A.; Kosonen, R. Thermal environment in simulated offices with convective and radiant cooling systems under cooling (summer) mode of operation. *Build. Environ.* **2016**, *100*, 82–91. [CrossRef]

43. Cehlin, M.; Karimipanah, T.; Larsson, U.; Ameen, A. Comparing thermal comfort and air quality performance of two active chilled beam systems in an open-plan office. *J. Build. Eng.* **2019**, *22*, 56–65. [CrossRef]

44. Kim, T.; Kato, S.; Murakami, S.; Rho, J. Study on indoor thermal environment of office space controlled by cooling panel system using field measurement and the numerical simulation. *Build. Environ.* **2005**, *40*, 301–310. [CrossRef]

45. Fredriksson, J.; Sandberg, M.; Moshfegh, B. Experimental investigation of the velocity field and airflow pattern generated by cooling ceiling beams. *Build. Environ.* **2001**, *36*, 891–899. [CrossRef]

46. Rhee, K.N.; Shin, M.S.; Choi, S.H. Thermal uniformity in an open plan room with an active chilled beam system and conventional air distribution systems. *Energy Build.* **2015**, *93*, 236–248. [CrossRef]

47. Koskela, H.; Haggblom, H.; Kosonen, R.; Ruponen, M. Air distribution in office environment with asymmetric workstation layout using chilled beams. *Build. Environ.* **2010**, *45*, 1923–1931. [CrossRef]

48. Indraganti, M.; Ooka, R.; Rijal, H.B. Thermal comfort in offices in summer: Findings from a field study under the 'setsuden' conditions in Tokyo, Japan. *Build. Environ.* **2013**, *61*, 114–132. [CrossRef]

49. De Vecchi, R.; Candido, C.; de Dear, R.; Lamberts, R. Thermal comfort in office buildings: Findings from a field study in mixed-mode and fully-air conditioning environments under humid subtropical conditions. *Build. Environ.* **2017**, *123*, 672–683. [CrossRef]

50. Azad, A.S.; Rakshit, D.; Wan, M.P.; Babu, S.; Sarvaiya, J.N.; Kumar, D.E.V.S.K.; Zhang, Z.; Lamano, A.S.; Krishnasayee, K.; Gao, C.P.; et al. Evaluation of thermal comfort criteria of an active chilled beam system in tropical climate: A comparative study. *Build. Environ.* **2018**, *145*, 196–212. [CrossRef]

51. He, Y.D.; Li, N.P.; Huang, Q. A field study on thermal environment and occupant local thermal sensation in offices with cooling ceiling in Zhuhai, China. *Energy Build.* **2015**, *102*, 277–283. [CrossRef]

52. CEN EN 15251:2007. *European Committee for Standardization, Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics*; European Committee for Standardization: Brussels, Belgium, 2007.

53. Fanger, P.O. *Thermal Comfort, Analysis and Applications in Environmental Engineering*; Danish Technical Press: Manhattan, KS, USA, 1970.

54. CEN EN 16798-1:2019. *Energy Performance of Buildings—Ventilation for Buildings—Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics—Module M1-6*; European Committee for Standardization: Brussels, Belgium, 2019.

55. ISO 7726:1998. *Ergonomics of the Thermal Environment—Instruments for Measuring Physical Quantities*; International Organization for Standardization: Geneva, Switzerland, 1998.

56. Dantec Dynamics. *ComfortSense specification*; Dantec Dynamics A/S, A Nova Instruments Company: Denmark, Skovlunde, 2019; Available online: http://www.dantecdynamics.jp/docs/products-and-services/thermal-comfort/PI264_ComfortSense.pdf (accessed on 5 June 2019).

57. Ministry of Economic Affairs and Communications. Estonian Regulation No 258: Minimum Requirements for Energy Performance. *Riigi Teataja* **2007**, *72*, 445.

58. Thermal Comfort. Innova AirTech Instruments A/S. 2002. Available online: http://www.labeee.ufsc.br/sites/default/files/disciplinas/Thermal%20Booklet.pdf (accessed on 10 July 2019).

59. CEN EN 15726:2011. *Ventilation for Buildings—Air Diffusion—Measurements in the Occupied Zone of Air-Conditioned/Ventilated Rooms to Evaluate Thermal and Acoustic Conditions*; European Committee for Standardization: Brussels, Belgium, 2011.

60. ISO 7730:2005. *Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria*; International Organization for Standardization: Geneva, Switzerland, 2005.

61. Google. Google Forms. Google Inc., Mountain View (CA), USA. 2019. Available online: https://www.google.com/forms/about/ (accessed on 1 July 2019).

62. EMHI. Observation Data. Estonian Weather Service: Tallinn, Estonia. 2019. Available online: https://www.ilmateenistus.ee/ilm/ilmavaatlused/vaatlusandmed/tunniandmed/?lang=en (accessed on 15 September 2019).

63. Wang, J.Y.; Wang, Z.; de Dear, R.; Luo, M.H.; Ghahramani, A.; Lin, B.R. The uncertainty of subjective thermal comfort measurement. *Energy Build.* **2018**, *181*, 38–49. [CrossRef]