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Article

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

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Abstract: Local thermal comfort (TC) and draught rate (DR) has been studied widely. There has been more meaningful research performed in controlled boundary condition situations than in actual work environments involving occupants. TC conditions in office buildings in Estonia have been barely investigated in the past. In this paper, the results of TC and DR assessment in five office buildings in Tallinn are presented and discussed. Studied office landscapes vary in heating, ventilation and cooling (HVAC) 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 TC and DR assessment with indoor climate questionnaire (ICQ). The purpose of the survey is to assess the correspondence between HVAC design and the actual situation. Results show, whether and in what extent the standard-based criteria for TC 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 HVAC 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 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 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

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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 indicate higher dissatisfaction rates for female occupants [11,16-19].

There are many building 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 [20,21]. Thalfeldt, Pikas, Kurnitski and Voll [20] 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 of 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 DR has been identified as the main cause of discomfort even if other thermal environment factors are at satisfactory levels [6,15,22,23].

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 [24,25]. In low energy buildings, high temperature cooling is usually preferred to achieve higher energy efficiency for cooled water production by cooling plants [25]. 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 [26-40]. The research in real office settings is mainly focused on buildings located in warm and hot climate countries, dominated by cooling need [41-44]. 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 [45] 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 [46] Predicted Mean Vote / Predicted Percentage of Dissatisfied (PMV/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.

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.

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 (AV) measurements with DR and TC calculations.

2. Methods

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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 [45,47] 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 [48] we used was designed for research and development purposes.

2.1. Reference objects

The buildings involved in this study where chosen from a range of modern office spaces in Tallinn. First criteria for reference objects (Table 1) was the correspondence with the Estonian energy efficiency regulations, which were first set in 2007 [49]. This created the prerequisites for modern elementary HVAC systems to be installed in reference objects.

Table 1. General building information of reference objects.

Building	Year of construction	Net floor surface [m^2]	No of floors	No of measured floors	Approx. total measured area [%}
A	2015	10 800	13	4	30
B	2018	7 000	5	3	40
C	2017	18 900	14	2	10
D	2018	13 900	2	2	100 (available office landscape)
E	Reconstructed 2014 (1982)	5 300	6	1	20

Secondly, it was important to involve a variety of HVAC systems (Table 2) including both common and also not widely and innovative solutions in the Estonian construction market. 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.

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

Building	Heating	Ventilation	Cooling
A	Water-based convectors below the windowsill	Mixing ventilation	Active chilled beams mounted in the open ceiling
B	Thermally active building system (slab)	Displacement ventilation	Thermally active building system (slab)
C	4-pipe active chilled beams mounted in suspended ceiling	Mixing ventilation	4-pipe active chilled beams mounted in suspended ceiling
D	4-pipe radiant panels mounted in the open ceiling	Mixing ventilation	4-pipe radiant panels mounted in the open ceiling
E	Electrical convectors in front of windows	Mixing ventilation	Multi-split fan coil units mounted in the suspended ceiling

All of the 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

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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 Building 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 [48]. The set is mounted on a tripod including five draft probes, one humidity and one operative temperature probe. For a sitting position ISO standard [47] 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 AV and standard deviation at three heights around the sitting occupant body were measured Figure 1. Additional two draft probes were mounted at the height of 1.7 m and 2.0 m, but the data from these probes is not analyzed in this article. Humidity probe was set at 1.0 m as a fixed height for measuring has not been set. The operative temperature probe was mounted with the angle of 30° at the height of 0.6 m as the abdomen level of a sitting person [47].

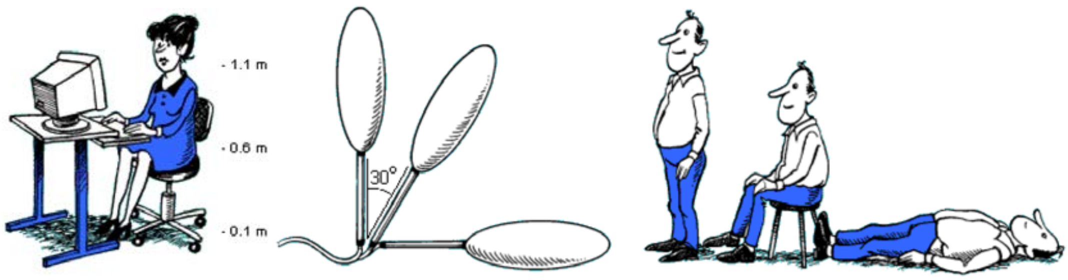
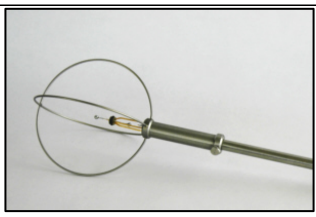
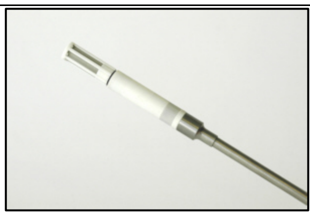
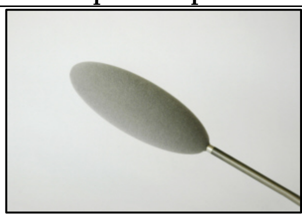


Figure 1. Recommended [6] and standard based [47] air velocity measurements behind the feet, elbow and neck [50].

Probes were connected with 54N90 ComfortSense main frame [48], 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 [48]. Measurement period 180 seconds as the least time recommended [51] was used. Measurement equipment probe data is described in Table 3.

Table 3. Specifications of measuring equipment [48].

	54T33 Draft probe	**54T37 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

2.3. Data analysis

Measurement data, including indoor air temperature (IAT), AV, relative humidity (RH) and TOP) was recorded with the sampling rate 20 Hz with ComfortSense [48] and processed in Microsoft Excel. TC parameter equations are followed.

Turbulence intensity (TI) is calculated by [51]:

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$$Tu = \frac{SD}{v_a} \cdot 100\ [\%], \quad (1)$$

where SD is standard deviation of air velocity [m/s] and v_a is local mean air velocity [m/s].

DR can be calculated as [52]:

$$DR = (34 - t_a) \cdot (v_a - 0.05)^{0.62}\ (0.37 \cdot v_a \cdot Tu + 3.14)\ [\%], \quad (2)$$

where t_a is air temperature [°C] and v_a is local mean air velocity [m/s].

PMV equation is given by [52]:

$$PMV = [0.303 \cdot \exp(-0.036 \cdot M) + 0.028] \cdot [(M - W) - H - E_c - C_{res} - E_{res}], \quad (3)$$

including dry heat loss H, what is found as:

$$H = \frac{(mt_{sk} - t_{cl})}{I_{cl}}\ [W/m^2], \quad (4)$$

including t_{cl}, which is given by:

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

including E_c given by:

$$E_c = 3.05 \cdot 10\text{-}3 \cdot [5733 - 6.99 \cdot (M - W) - p_a] + 0.42 \cdot (M - W - 58.15)\ [W/m^2], \quad (6)$$

including Pa, which is calculated by:

$$p_a = \frac{RH}{100} \cdot 479 + (11.52 + 1.62 \cdot t_a)^2\ [Pa], \quad (7)$$

including C_{res} calculated as:

$$C_{res} = 0.0014 \cdot M \cdot (34 - ta)\ [W/m^2], \quad (8)$$

including E_{res} given as:

$$E_{res} = 1.72 \cdot 10_{-5} \cdot M \cdot (5867 - p_a)\ [W/m^2], \quad (9)$$

including h_{cl} found by:

$$h_{cl} = \begin{cases} 2.38 \cdot |t_{cl} - t_a|^{0.25} & \text{for } 2.38 \cdot |t_{cl} - t_a|^{0.25} > 12.1 \cdot \sqrt{v_{ar}} \text{ and} \\ 12.1 \cdot \sqrt{v_{ar}} & \text{for } 2.38 \cdot |t_{cl} - t_a|^{0.25} < 12.1 \cdot \sqrt{v_{ar}}\ [W/(m^2 \cdot K)], \end{cases} \quad (10)$$

and including f_{cl} calculated by:

$$f_{cl} = \begin{cases} 1.00 + 1.290 \cdot I_{cl} & \text{for } I_{cl} \le 0.078 \text{ and} \\ 1.05 + 0.645 \cdot I_{cl} & \text{for } I_{cl} > 0.078 \end{cases} \quad (11)$$

where M is metabolic rate [W/m²], W is the effective mechanical power [W/m²], I_{cl} is the clothing insulation [m² · K/W], f_{cl} is the clothing surface area factor, ta is the air temperature [°C], mt_r is the mean radiant temperature [°C], v_{ar} is the relative air velocity [m/s], p_a is the water vapour partial pressure [Pa], h_c is the convective heat transfer coefficient [W/(m² · K)] and t_{cl} is the clothing surface temperature [°C]. Metabolic rate 1.2 met, clothing unit 0.5 clo and effective mechanical power 0 W/m² were used in analysis. Relative air velocity was set equal to the air velocity as occupants were intended to be stationary sensing draught.

PPD is calculated as [52]:

$$PPD = 100 - 95 \cdot \exp(-0.03353 \cdot PMV^4 - 0{,}2179 \cdot PMV^2), \quad (4)$$

2.4. Indoor climate questionnaire

To study occupant satisfaction we sent after 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 [53] application. In addition to standard CEN

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EN 15251 [45] 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.

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 TI, 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 [54].

Building	Time of measurements	Weather conditions	Maximum outdoor temperature [°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 normal working mode. 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 2 (a)) were noticed with open ceiling in Building A. DR risk was also predictable in building E (Figure 2 (b)) where some vanes were taped to closed position. DR risk was more carefully considered in Buildings B and D.

(a) (b)

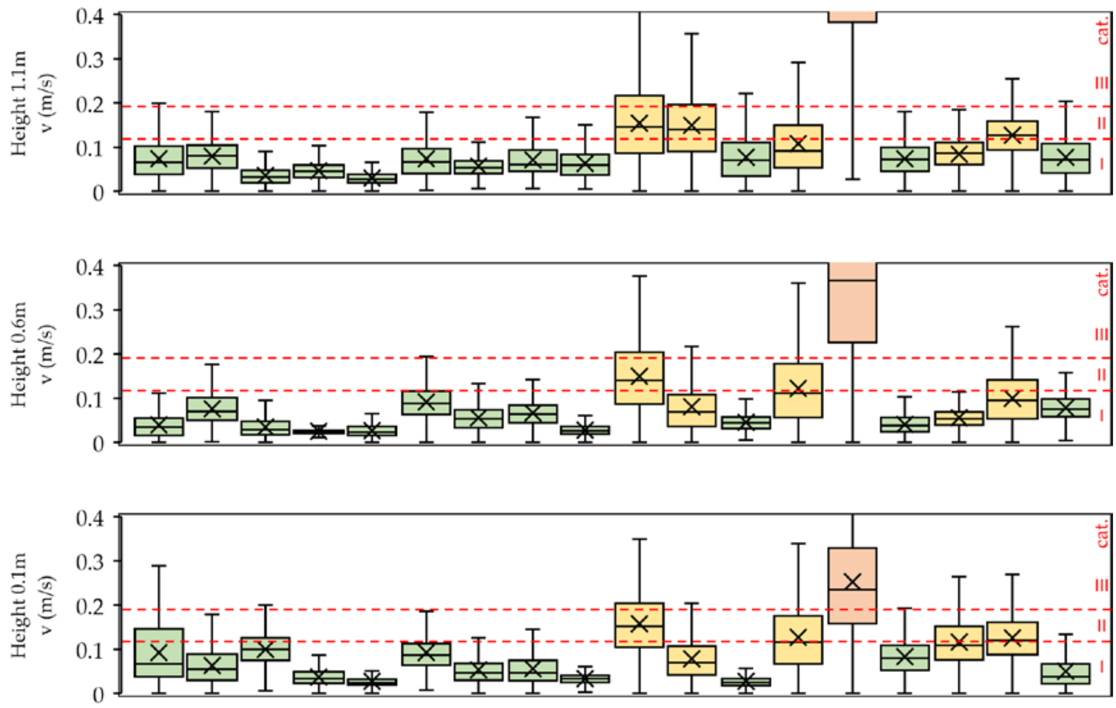
Figure 2. (a) Possible air flow obstacles with open active beam solution; (b) Modified airflow distribution with fan coil unit.

3. Results

The AV results and TC parameters follow. Measurements of AV are shown with box and whiskers, where 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 AV value of the measurement in one position.

3.1. Building A results

AV results and TC parameters in Building A equipped with open ceiling active chilled beams are provided below in Figure 3. In Building A, in 2/3 of the measured positions the AV was below the first indoor climate category threshold. Five positions met the II category requirement and in one position the AV 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. IAT and AV results including DR, PMV and PPD are placed in the first category mainly.



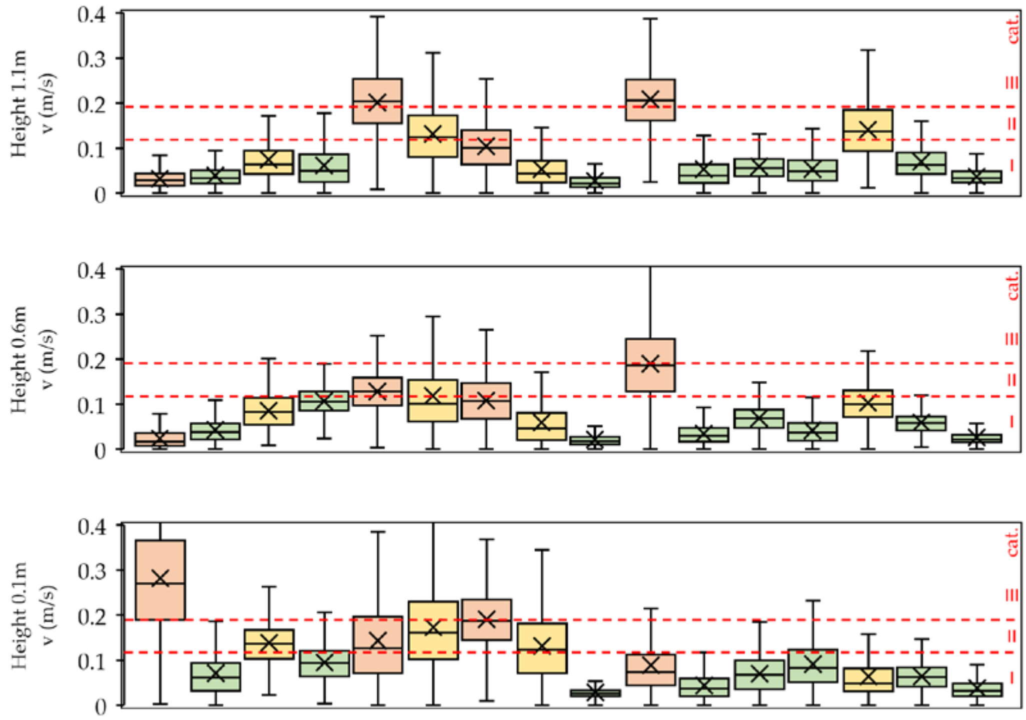
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
$t_{a(1.1m)}$	°C	24.5	23.7	23.8	24.1	24.5	24.6	24.1	24.0	24.5	24.4	23.6	24.2	23.5	22.1	24.2	23.9	23.8	24.5
$v_{a(1.1m)}$	m/s	0.07	0.08	0.04	0.05	0.03	0.07	0.06	0.07	0.06	0.15	0.15	0.08	0.11	0.61	0.07	0.08	0.13	0.08
$Tu_{(1.1m)}$	%	65.3	47.9	58.0	46.9	49.5	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
$DR_{(1.1m)}$	%	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
$t_{a(0.6m)}$	°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
$t_{o(0.6m)}$	°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
$v_{a(0.6m)}$	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
$RH_{(0.6m)}$	%	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
$PMV_{(0.6m)}$	-	0.02	-0.26	-0.22	-0.09	0.01	0.03	-0.11	-0.16	-0.01	-0.16	-0.18	-0.13	-0.42	-1.28	-0.12	-0.10	-0.16	0.05
$PPD_{(0.6m)}$	%	5.01	6.40	6.03	5.18	5.00	5.02	5.24	5.54	5.00	5.55	5.65	5.33	8.62	39.15	5.29	5.22	5.55	5.05

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

Figure 3. Building A air velocity results in measurement points 1 to 18 and the thermal comfort parameters.

3.2. Building B results

AV results and TC parameters of Building B with slab-based TABS system are given below in Figure 4. Building B had more measured points in second category by PMV and PPD compared to Building A. DR met the II category in four measurement positions. Positions 4 to 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 AV fluctuates more near the floor.



		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
$t_{a(1.1m)}$	°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
$v_{a(1.1m)}$	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
$Tu_{(1.1m)}$	%	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
$DR_{(1.1m)}$	%	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
$t_{a(0.6m)}$	°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
$t_{o(0.6m)}$	°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
$v_{a(0.6m)}$	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
$RH_{(0.6m)}$	%	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
$PMV_{(0.6m)}$	-	-0.39	-0.24	-0.17	-0.38	-0.23	-0.38	-0.28	-0.14	-0.32	-0.59	-0.07	-0.42	-0.29	-0.03	-0.12	-0.12
$PPD_{(0.6m)}$	%	8.10	6.17	5.59	8.07	6.07	7.93	6.60	5.39	7.12	12.17	5.10	8.77	6.75	5.02	5.30	5.28

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Figure 4. Building B air velocity results in measurement points 1 to 16 and the thermal comfort parameters.

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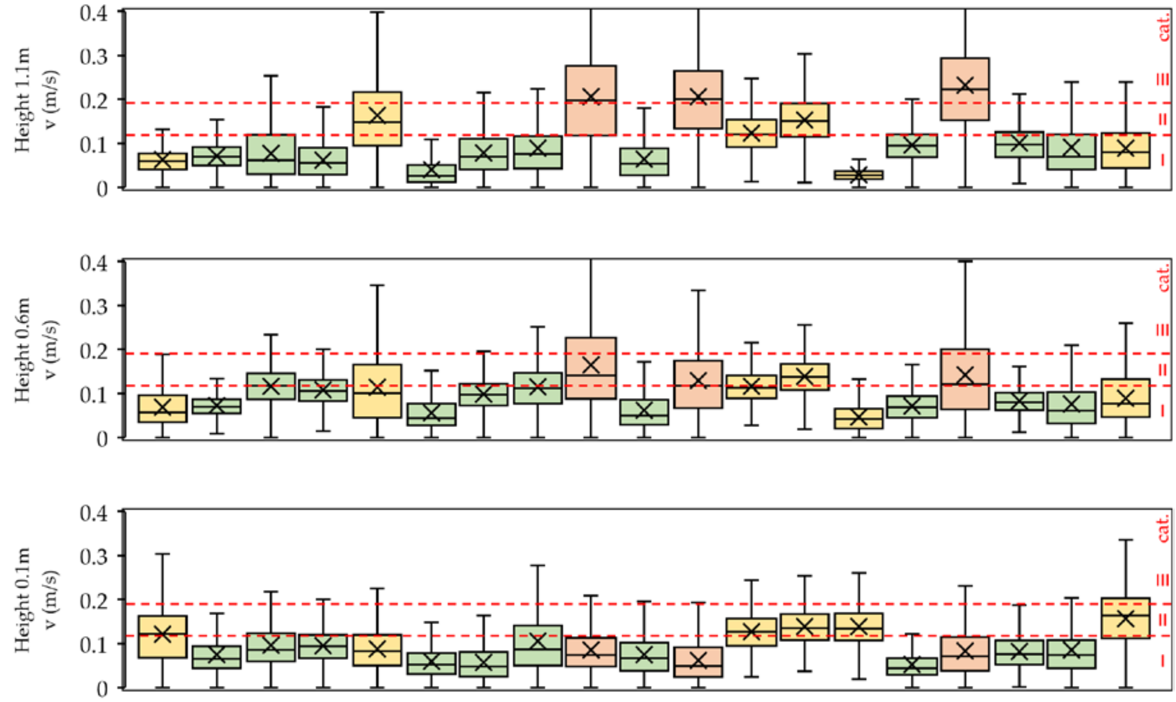
3.3. Building C results

Building C was equipped with suspended ceiling active chilled beams and the results of AV and parameters of TC are presented below in Figure 5. IAT, PMV and PPD were similar to Building A and B, at the same time AV and DR was measured at two positions in the II category and three times in the III category. AV 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
ta(1.1m)	°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
va(1.1m)	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(1.1m)	%	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(1.1m)	%	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
ta(0.6m)	°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
to(0.6m)	°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
va(0.6m)	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(0.6m)	%	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(0.6m)	-	0.09	-0.01	-0.08	-0.11	-0.22	-0.15	-0.26	-0.18	-0.31	-0.07	-0.32	-0.27	-0.40	-0.20	0.00	-0.11	-0.07	-0.09	-0.11
PPD(0.6m)	%	5.16	5.00	5.12	5.23	6.01	5.44	6.42	5.70	6.94	5.10	7.17	6.46	8.25	5.82	5.00	5.23	5.11	5.17	5.26

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

Figure 5. Building C air velocity results in measurement points 1 to 19 and the thermal comfort parameters.

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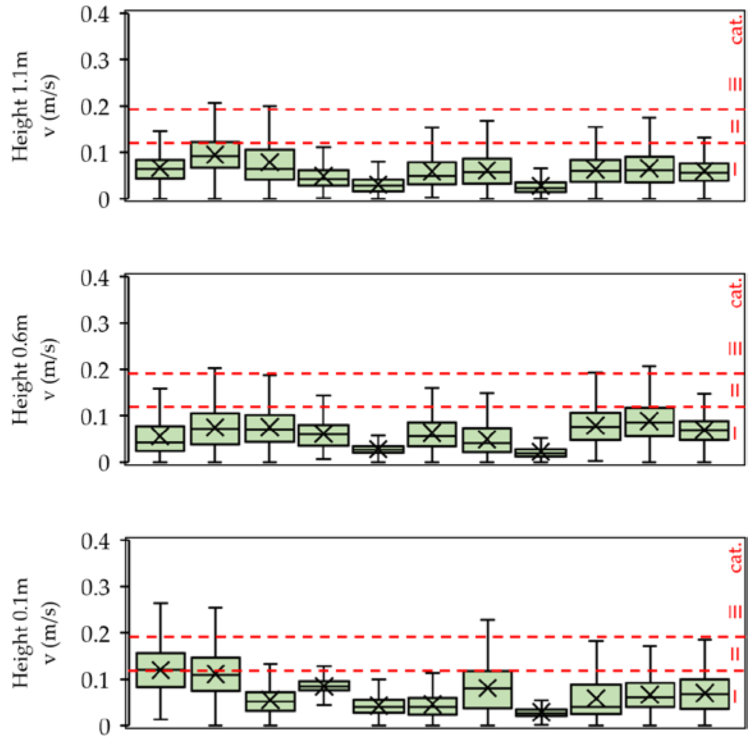
3.4. Building D results

Equipped with radiant cooling panels, results of AV and parameters of TC in Building D are showed below in Figure 6. 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 AV remained below 0.10 m/s being more fluctuating near the floor.



		1	2	3	4	5	6	7	8	9	10	11
$t_{a(1.1m)}$	°C	24.8	24.2	24.2	24.2	24.2	24.2	23.3	23.6	24.5	23.9	23.4
$v_{a(1.1m)}$	m/s	0.07	0.09	0.08	0.05	0.03	0.06	0.06	0.03	0.06	0.07	0.06
$Tu_{(1.1m)}$	%	53.5	47.5	66.6	72.1	66.1	73.6	62.7	84.2	58.8	59.9	48.1
$DR_{(1.1m)}$	%	3.2	6.8	5.5	0.0	0.0	2.4	2.9	0.0	2.9	3.6	2.5
$t_{a(0.6m)}$	°C	24.4	24.0	24.1	24.0	24.1	24.1	23.4	23.4	23.4	23.5	23.1
$t_{o(0.6m)}$	°C	24.3	23.8	24.0	24.0	24.0	24.0	23.1	23.6	24.8	23.7	23.3
$v_{a(0.6m)}$	m/s	0.06	0.07	0.07	0.06	0.03	0.06	0.05	0.02	0.08	0.09	0.07
$RH_{(0.6m)}$	%	58.0	57.8	57.2	57.4	57.8	58.0	59.9	46.8	57.2	59.7	48.5
$PMV_{(0.6m)}$	-	-0.05	-0.18	-0.14	-0.13	-0.13	-0.13	-0.41	-0.34	0.08	-0.23	-0.42
$PPD_{(0.6m)}$	%	5.05	5.67	5.38	5.36	5.36	5.35	8.46	7.34	5.13	6.11	8.77

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

Figure 6. Building D air velocity results in measurement points 1 to 11 and the thermal comfort parameters.

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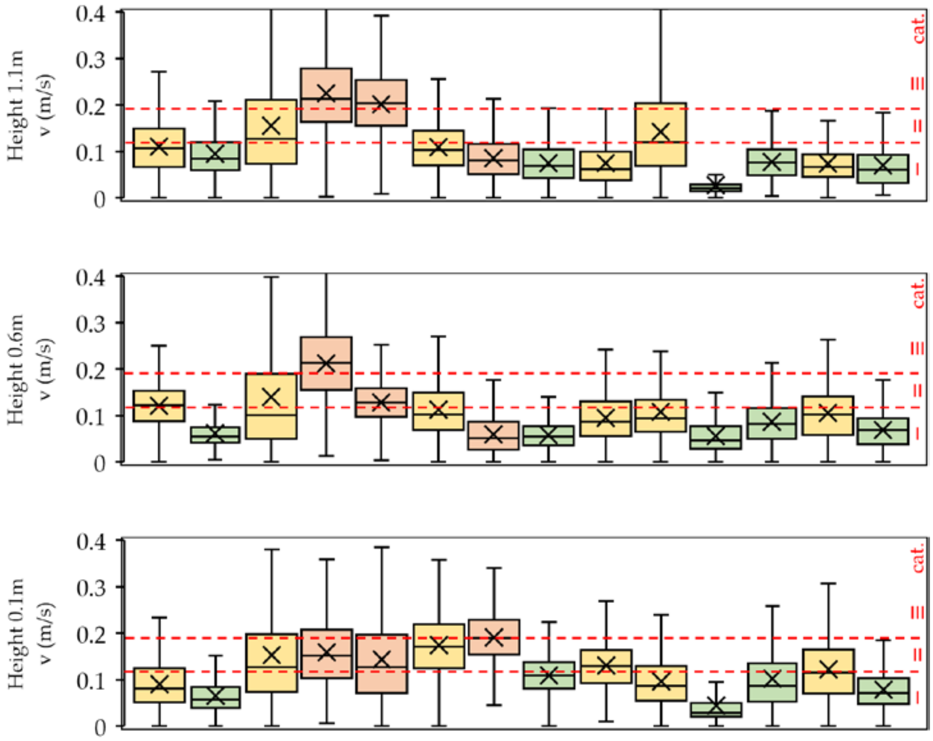
3.5. Building E results

According to the results, Building E achieved the worst TC values by categories. IAT was in III category four times, DR was in the II category in 4 positions of 14. PMV and PPD second category was not reached 5 times. AV fluctuations were random depending on the height. AV results and TC parameters in Building E, with fan coil units mounted in the suspended ceiling, are compared below in Figure 7.



		1	2	3	4	5	6	7	8	9	10	11	12	13	14
ta(1.1m)	°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
va(1.1m)	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(1.1m)	%	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(1.1m)	%	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
ta(0.6m)	°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
to(0.6m)	°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
va(0.6m)	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(0.6m)	%	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(0.6m)	-	0.18	0.29	0.02	-0.09	-0.23	0.14	0.38	0.53	0.56	0.24	0.40	0.68	0.57	0.84
PPD(0.6m)	%	5.65	6.70	5.01	5.17	6.10	5.41	7.99	10.90	11.52	6.16	8.36	14.83	11.79	19.89

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

Figure 7. Building E air velocity results in measurement points 1 to 14 and the thermal comfort parameters.

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3.6. Results of the indoor climate questionnaire

The IAQ results for thermal environment are shown below in Figure 8, the IAQ results for PMV and PPD are presented below in Figure 9 (a) and the measured results for PMV and PPD are given in Figure 9 (b). The highest number of answers were in the Building A with 36 responses divided between all age groups equally between men and women. 83% were working in open office layout and 86% were spending most of the day at their workplace. IAT was described as suitable by 64% of the respondents, meanwhile 6 occupants found it to be warm and 7 slightly cooler. 89% had not or had perceived slight odor, 72% did not find lighting fixtures or sunlight to be disturbing and 81% found IAQ to be suitable or better. 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.

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. 72% of them working in open office environment. 2/3 found IAT to be suitable. 13 of the 29 respondents did not perceive odor. Lighting was disturbing for 21% and sunlight for 14%, meanwhile 14% were dissatisfied with IAQ. 7% did not find room acoustics and 17% general noise in office to be disturbing. 1/2 of the respondents had rarely felt eye dryness or irritation, occur headaches or fatigue and felt nasal problem or dry throat. 62% had rarely felt concentration problems.

70% of the 20 IAQ 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. IAT was perceived as warm by 40% and as suitable by 50% of the occupants. 90% had not perceived or had perceived slight odor. 70% did not find lighting equipment to be disturbing and 75% was not disturbed by the sunlight. 40% of the respondents found air quality to be not suitable or unacceptable. 85% perceived colleagues' speech and overall room acoustic to be somewhat disturbing, while 65% claimed other noises to be distracting. 1/3 had rarely felt eye problems, occurred headaches or tiredness. 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. IAT was suitable for the majority of the answers. Odor was rarely noticed, lighting or sunlight was not disturbing. IAQ 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.

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. 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. 1/3 found IAT to be suitable and 2/3 claimed the IAT to be slightly warm, warm or hot. 50% perceived weak or moderate odor. Room lighting equipment did not disturb 82% and the sun did not disturb 60% of the respondents. 2/3 marked IAQ suitable, good or very good. Room acoustic level was not claimed to be disturbing for 40% and other noise for 23% of the respondents. 50% 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.

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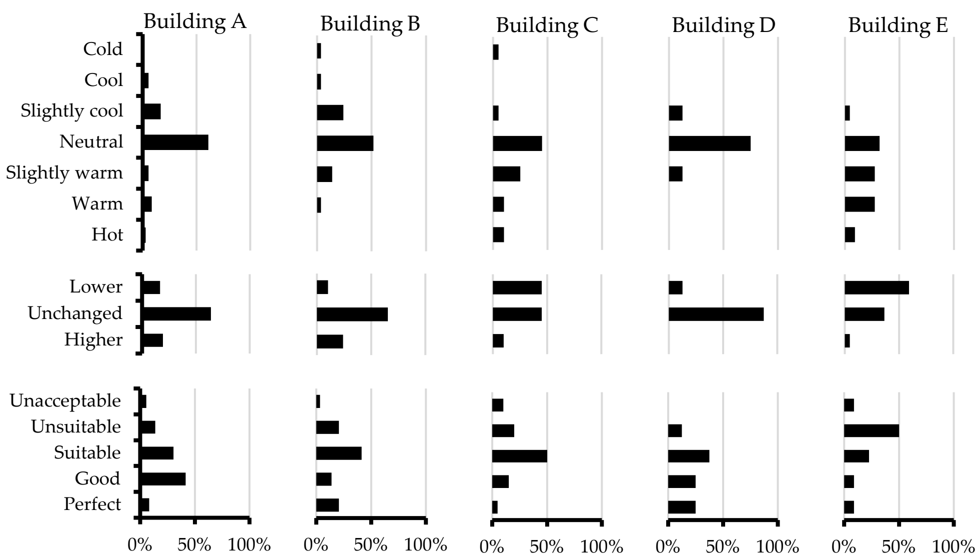

Figure 8. Indoor climate questionnaire results for indoor air temperature.

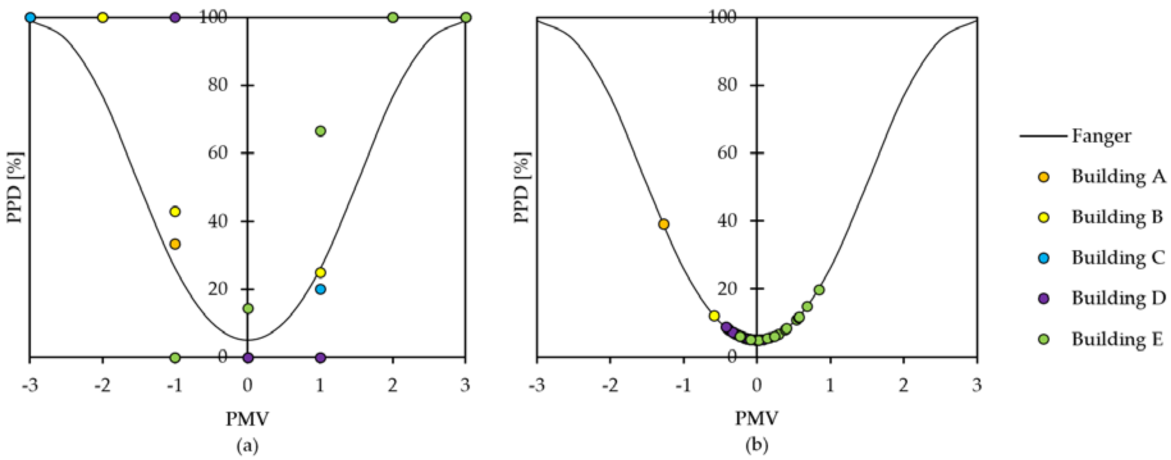

Figure 9. (a) Indoor climate questionnaire results for predicted percentage of dissatisfied and predicted mean vote; (b) Measured results for predicted percentage of dissatisfied and predicted mean vote.

Number of respondents of the ICQ is below the least recommended sample size [55], therefore the results of the ICQ include higher uncertainty (Figure 9 (a)). Thermal sensation voted by occupants covers significantly wider range than PMV calculated from measurements. In the Figure 9 (b) measurement-based PMV and PPD is presented. Most of the positions measured remain in the II category area between -0.5 and 0.5. Different from Buildings A to D, Building E values are located on the right side of the middle point 0, where IAT is considered unchanged and suitable. Majority of the respondents were working in open office. The most unsatisfying IAT was in the Building E and the most suitable IAT was in the Building D. In general, unsuitable IAT was perceived more as warmer than cooler. In Buildings A, B and D the IAT 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, AV and DR was not significantly higher in the case of fan coil units in Building E was the taping of air distribution vanes (Figure 2 (b)) and also positioning of the working stations

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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 Building 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 AV and DR.

The AV limit values in EN 16798-1:2019 [56] have been calculated assuming operative temperature +23°C and TI 40% TI. Figure 10 (a) illustrates that the TI is considerably higher than the default value, which increases the unsatisfaction with local TC. However, the measured operative temperature was higher than the default value in most of the measured positions in all buildings, which decreases the number of dissatisfied. Figure 10 (b) shows that in general the DR calculated based on measured operative temperature and TI is in the same scale with the one calculated with the default values.

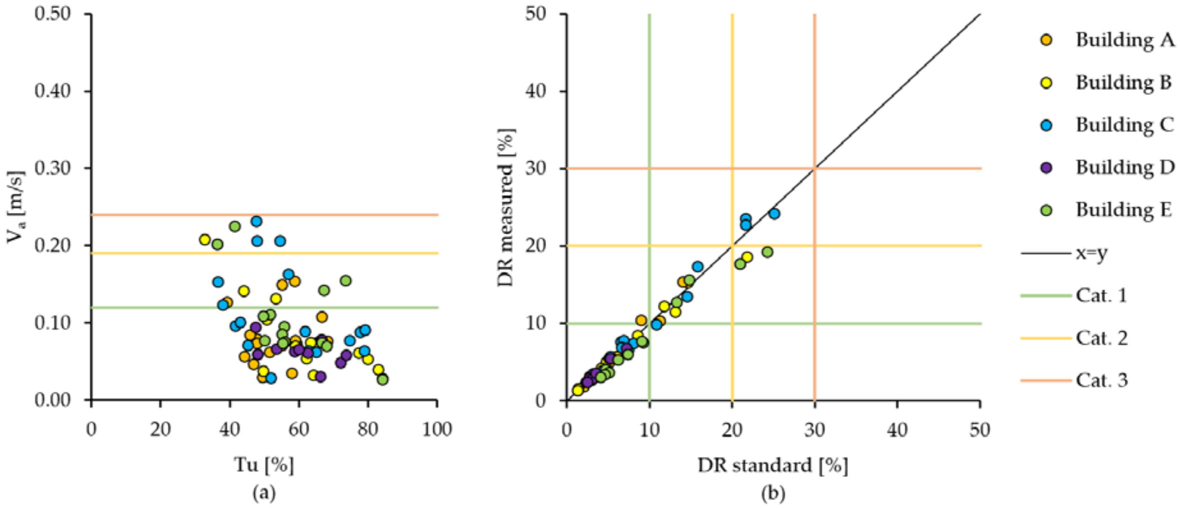

Figure 10. (a) Air velocity and turbulence results according to maximum air velocity categories I to III in summer; (b) Draught rate correlation in measured and standard-based [56] conditions according to draught rate categories I to III.

IAT will be more deeply discussed in further analysis of this study, foreseeing to include transitional period and heating period measurements, façade inspection and IAT periodical data analysis in the reference buildings. Periodical data analysis on IAT is mandatory as IAT presented in this study reflects only a fragment of the thermal environment. IQC survey number of respondents also needs additional attention, how to achieve a higher response rate. We suspect that dissatisfied employees tend to complain more than dissatisfied and therefore are more prone to respond.

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 IAT were still inconvenient for significant number of occupants as ICQ survey indicated broader dissatisfaction than measurements positioned by indoor climate category. DR showed similar values with both measurement-based calculations and with standard operative temperature and TI values used. Only room conditioning solution with suspended ceiling active chilled beams in Building C reached some category III performance. Open ceiling active chilled beams in Building A, slab-based TABS with displacement ventilation in Building B and fan coil units in Building E remained in category II requirements. Ceiling panels for room conditioning in Building D showed superior Category I performance.

Temperature measurements showed that IAT and operative temperature was the worst in Building E reaching III category, while it was mainly in category I in other four office buildings. Measurement results in Buildings A to D remained in between I and II category, while Building E reached IV category. According to ICQ, the IAT was perceived as suitable for over 80% of the employees in Building A, B and C. It was 67% in the Building E and the 60% in the Building C. We suggest that existing standards are not able to explain all dissatisfaction reported by occupants. Future office buildings with open-plan layouts demand more higher criteria for designers and builders to meet architectural, commercial and TC requirements.

Author Contributions: J.K. conceived and designed the experiments. M.K. prepared agreements with the building owners, performed the measurements and analyzed the data. M.T. and J.K. helped to perform the data analysis. M.K, R.S, M.T. and J.K. wrote this paper.

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

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