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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 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.

Bldg	Year of Constr.	Net Floor Area (m <sup>2</sup> )/appr. Total Measured Area (%)	No of Floors/ No of Measured Floors	Thermal Transmittance $W/(m^2 \times K)$	Specific Heat Loss of External Envelopes W/(m <sup>2</sup> × K)/Window-to-Wall Ratio/Glazing $g$ Value
А	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
В	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
С	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	$\frac{U_{window} \ 1.0/U_{wall} \ 0.15}{U_{roof} \ 0.14/\underline{U_{floor}}} < 0.15$	H/A < 0.20 WWR < 0.25 g 0.30
E	Reconstr, 2014 (1982)	5300/20	6/1	U <sub>window</sub> > 1.2/U <sub>wall</sub> > 0.25 U <sub>roof</sub> N/A/U <sub>floor</sub> N/A	H/A > 0.50 WWR 0.90 g 0.40

Table 1. General building information of reference objects.

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	g. Heating	Ventilation	Cooling
A	Water-based convectors (height 300 mm, length 700–1800 mm) below the windowsill. Installed room unit heating power 18 W/m <sup>2</sup> .	Mixing ventilation 1.4 l/(s $\times$ m <sup>2</sup> ) 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/m <sup>2</sup> .
В	Thermally active building system (slab, room height 3.0 m). Installed heating power 43 W/m <sup>2</sup> .	Displacement ventilation $1.4 \text{ l/(s} \times \text{m}^2)$ 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/m <sup>2</sup> .
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/m <sup>2</sup> .	Mixing ventilation 1.7 l/(s × m <sup>2</sup> ) 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/m <sup>2</sup> .
D	4-pipe radiant panels mounted in the open ceiling on the height of 2.4 m. Installed room unit heating power 24 W/m <sup>2</sup> .	Mixing ventilation 2.1 $l/(s \times m^2)$ . Rectangular diffusers including directionally adjustable nozzles (plates $160 \times 160 / 200 \times 200$ mm) mounted on plenum box for supply air and circular plate ( $O$ 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/m <sup>2</sup> .
E	Electrical convectors (height 200 mm, length 1500 mm) in front of windows. Installed room unit heating power 60 W/m <sup>2</sup> .	Mixing ventilation 1.3 l/(s $\times$ m <sup>2</sup> ) with circular supply and extract air valves ( $\emptyset$ 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/m <sup>2</sup> . (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, 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.

Image	54	54T33 Draft Probe	54T37 Relative Humidity Probe	54T38 Operative Temperature Probe
	ge			
Range $0.05-5 \text{ m/s} \\ -20 \degree \text{C to } +80 \degree \text{C}$ $0-100\%$ $0 \text{ to } +45 \degree \text{C}$	ge _	0.05–5 m/s –20 °C to +80 °C	0–100%	0 to +45 °C
Accuracy $\frac{\pm 0.02 \text{ m/s}}{\pm 0.2 \text{ K}}$ +1.5% $\pm 0.2 \text{ K}$	асу	±0.02 m/s ±0.2 K	+1.5%	±0.2 K

Table 3. Specifications of measuring equipment [56].

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]

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

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]

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

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<sup>2</sup>) is metabolic rate and W (W/m<sup>2</sup>) 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<sup>2</sup>) was used in analysis. The next symbol  $H_d$  in Equation (3) represents dry heat loss, which is found as

$$H_{d} = \frac{(mt_{sk} - t_{cl})}{I_{cl}} (W/m^{2}),$$
(4)

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

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

In Equation (5),  $I_{cl}$  [(m<sup>2</sup> × 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<sup>2</sup> × 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

$$h_{c} = 2.38 \times |t_{cl} - t_{i}|^{0.25} \text{ for } 2.38 \times |t_{cl} - t_{i}|^{0.25} > 12.1 \times \sqrt{v_{ar}} \text{ and}$$

$$12.1 \times \sqrt{v_{ar}} \text{ for } 2.38 \times |t_{cl} - t_{i}|^{0.25} < 12.1 \times \sqrt{v_{ar}} \left[ W/(m^{2} \times K) \right],$$
(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

$$f_{cl} = 1.00 + 1.290 \times I_{cl} \text{ for } I_{cl} \le 0.078 \text{ and} \\ 1.05 + 0.645 \times I_{cl} \text{ for } I_{cl} > 0.078$$
(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

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

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

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

In addition, Equation (3) for PMV includes respiratory convective heat exchange C<sub>res</sub>, calculated as

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

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

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

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]

$$PPD = 100 - 95 \times \exp(-0.03353 \times PMV^4 - 0.2179 \times PMV^2)$$
(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.

Building	Time of Measurements	Weather Conditions	Maximum Outdoor Temp. °C	Mean Outdoor Temp. °C
А	06.08.2019 before midday	cloudy skies showers	+20.9	+15.2
В	14.08.2019 after midday	cloudy skies no precipitation	+19.7	+13.8
С	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

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

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.



**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.



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.



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.

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.



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.





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 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.

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#### Nomenclature

Α	net floor area (m <sup>2</sup> )
Cres	respiratory convective heat exchange (W/m <sup>2</sup> )
DR	draught rate (%)
E <sub>c</sub>	evaporative heat exchange at the skin, when the person experiences a sensation of thermal neutrality (W/m <sup>2</sup> )
Eres	respiratory evaporative heat exchange (W/m <sup>2</sup> )
f <sub>cl</sub>	clothing surface area factor
8	solar radiation transmittance through window glass
Н	heat loss (W/K)
$H_d$	dry heat loss (W/m <sup>2</sup> )
$h_c$	convective heat transfer coefficient $[W/(m^2 \times K)]$
HVAC	heating, ventilation, and air conditioning
I <sub>cl</sub>	clothing insulation $[(m^2 \times K)/W]$
ICQ	indoor climate questionnaire
М	metabolic rate (W/m <sup>2</sup> )
mt <sub>sk</sub>	mean skin temperature (°C)
pa	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 <sub>cl</sub>	clothing surface temperature (°C)
$t_i$	indoor air temperature (°C)
to	operative temperature (°C)
Ти	turbulence intensity
U	thermal transmittance [W/(m <sup>2</sup> ×K)]
$v_a$	air velocity (m/s)
var	relative air velocity (m/s)
W	effective mechanical power (W/m <sup>2</sup> )
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

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