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**Kolarik, Jakub; Olesen, Bjarne W.**

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# Influence of measurement uncertainty on classification of thermal environment in buildings according to European Standard EN 15251

***Jakub Kolarik[1,*], Bjarne W. Olesen[2]***

[1]Department of Civil Engineering, Section for Building Energy, Technical University of Denmark, Kgs. Lyngby, Denmark
[2]Department of Civil Engineering, International Centre for Indoor Environment and Energy, Technical University of Denmark, Kgs. Lyngby, Denmark
[*]*Corresponding email: jakol@byg.dtu.dk*

## SUMMARY

European Standard EN 15 251 in its current version does not provide any guidance on how to handle uncertainty of long term measurements of indoor environmental parameters used for classification of buildings. The objective of the study was to analyse the uncertainty for field measurements of operative temperature and evaluate its effect on categorization of thermal environment according to EN 15251. A data-set of field measurements of operative temperature four office buildings situated in Denmark, Italy and Spain was used. Data for each building included approx. one year of continuous measurements of operative temperature at two measuring points (south/south-west and north/north-east orientation). Results of the present study suggest that measurement uncertainty needs to be considered during assessment of thermal environment in existing buildings. When expanded standard uncertainty was taken into account in categorization of thermal environment according to EN 15251, the difference in prevalence of exceeded category limits were up to 17.3%, 8.3% and 2% of occupied hours for category I, II and III respectively.

## KEYWORDS

Measurement uncertainty, thermal environment, EN 15251, operative temperature

## INTRODUCTION

European standard EN 15251 (EN 2007) includes a categorization methodology for indoor environment in buildings that specifies four categories for indoor environmental quality. They can be, besides building design and certification, used also for long term evaluation of indoor environment in existing buildings. The standard is closely related to European Commission’s Energy Performance of Buildings Directive (EPBD 2003) and states that information regarding indoor environment should be included with building’s energy certificate. The design of long term measurements and used instruments must fulfil International Standard EN/ISO 7726 (ISO 2002). The standard specifies required and desired (preferable) measuring accuracy for used instruments (for example required accuracy of air temperature measurement: ± 0.5 K within 10-30 °C range). However, the standard EN 15251 does not provide any guidance on how to handle the influence of measurement accuracy, not to say uncertainty of long term measurements on allocation of buildings in particular categories. Amount of literature focused on the topic is quite limited. Studies of d’Ambrosio Alfano et al. (2013) and d’Ambrosio Alfano et al. (2011) focused explicitly on accuracy of instruments used for evaluation of thermal environment. Both studies concluded that when measurement accuracy was taken into account, a reliable attribution of the building categories (according to EN (2007)) was very difficult. The authors indicated a need for in-depth discussion focused on the topic, which would lead to standardization of both measuring and calibration protocols for long term measurements as well as redefinition of the building categories used in the EN 15251 standard. The study of Dell’Isola et al. (2012) considered broader aspects of measurement uncertainty during assessment of thermal environment and came to very similar conclusions as the two previously mentioned studies.

The objective of the present study was to contribute to the discussion on the topic of measurement uncertainty in the field of thermal environment assessment. Our approach was to analyse the uncertainty for field measurements of operative temperature and evaluate its effect on categorization of thermal environment according to EN 15251 (EN 2007).

# METHODS

## Investigated buildings

Table 1 summarizes the four investigated office buildings. Continuous measurements of operative temperature (*To*), conducted at two workplaces in each building, were used for the analyses in the present paper. Measurement points were chosen to represent north or north-east and south or south-west part of the typical office floor in the building. All measurements were taken at less than 4 meters from windows. Grey sphere-shaped sensors (Simone et al. 2007) were used for *To* measurements. Two types of Onset HOBO data loggers U12 012 and U12 013 were used to store the measured value in 10 minutes intervals. Figure 1 illustrates placement of operative temperature sensor at workstations. Data sets collected in all buildings were further processed to exclude weekends and holidays (official national holidays for particular country were considered) as well as periods when particular building was not occupied. Occupancy periods for studied buildings as well as whole measurement periods are shown in Table 1.

**Table 1 - Overview of investigated buildings**

| Building name (construction year) | Location: town, country | Floor area [$m^2$] | Heating/cooling system; ventilation | Solar shading | Measurement period | Occupied hours |
|---|---|---|---|---|---|---|
| Viborg Town Hall (2011) | Viborg, Denmark | 19400 | Floor heating/cooling; Natural vent. with aut. control | No external solar shading | Feb. 2013<sup></sup>(2) – Feb. 2014 | 8:00-20:00 |
| COWI headquarters (2012) | Aalborg, Denmark | 12000 | TABS(1); Mechanical vent. | Internal venetian blinds | April 2013 – July 2013 | 8:00-18:00 |
| IDOM headquarters (2010) | Madrid, Spain | 16000 | TABS; Combined mechanical and natural vent. | South/west double façade with vegetation | Dec. 2012 – Jan. 2014 | 9:00-20:00 |
| TiFS headquarters (2004) | Padua, Italy | 2200 | TABS; Mechanical vent. | South-double façade with horizontal blinds | July 2013 – Sept. 2014 | 9:00-19:00 |

(1) TABS – Thermo active building system – pipes embedded in storey construction, (2) Data from north part of the building available form from May 2013

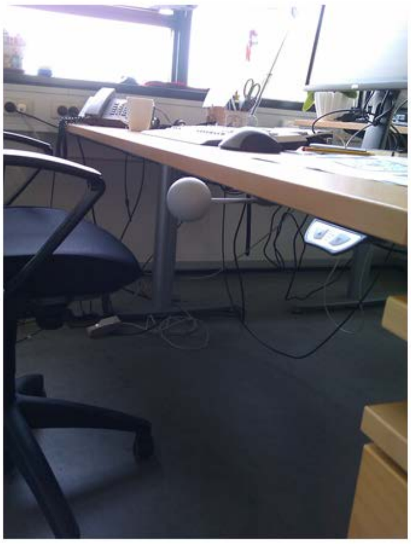

**Figure 1 - (Left) Illustrative placement of an operative temperature sensor at a workplace, (Right) A set of grey sphere-shaped sensor and data logger**

## Data processing and calculation of measurement uncertainty

Grey sphere-shaped sensors were equipped by Pt100 resistance thermometers. Voltage signal from the grey sphere-shaped sensors was logged via external input channel of the HOBO logger. Hourly mean values of the voltage signal $V_h$ were calculated from the data. According to the logger's manufacturer, accuracy of the external input channel - $\Delta_b(V_h)$ was ±2 mV ± 2.5% of absolute reading. Based on this accuracy specification, standard uncertainty of the external input channel reading - $u_a(V_h)$ was estimated according to equation (1) (ISO/IEC 2008).

$$u_a(V_h) = \frac{\Delta_b(V_h)}{\sqrt{3}} \tag{1}$$

Combined standard uncertainty of the hourly mean values - $u_c(V_h)$ was determined according to ISO/IEC (2008) as a combination of standard uncertainty related to repeated measurements, expressed as a standard error of the hourly mean - $u_r(V_h)$ and standard uncertainty related to the accuracy $u_a(V_h)$ (2).

$$u_c(V_h) = \sqrt{u_r(V_h)^2 \cdot u_a(V_h)^2} \tag{2}$$

Prior to the measurements, the grey sphere-shaped sensors were calibrated in a climatic chamber (Simone et al. 2007). From the calibration, slope (*a*) and intercept (*b*) of the linear relationship between voltage signal and the operative temperature - $T_o$ was established (Simone et al. 2007; Simone et al. 2013). This resulted into a correction function (3).

$$T_o = a \cdot V + b \tag{3}$$

Equation (3) was used to determine hourly mean operative temperature $T_{o,h}$. Combined standard uncertainty of the hourly mean operative temperature - $u_c(T_{o,h})$ was determined as combined standard uncertainty of an indirectly measured quantity according to equation (4).

$$u_c(T_{o,h}) = \sqrt{\left(\frac{\partial T_o}{\partial V}\right)^2 \cdot u_c(V_h)^2} \tag{4}$$

Finally expanded standard uncertainty - $U(T_{o,h})$ of the operative temperature measurement was determined using coverage factor $k = 2$, which represents 95% level of confidence (ISO/IEC 2008) (5).

$$U(T_{o,h}) = k \cdot u_c(T_{o,h}) \tag{5}$$

## Statistical analysis

The statistical software R version 2.15.3 (R Core Development Team 2014) was used to analyse the data. Inspection of Quantile-Quantile plots (QQ plots) test were used to test whether the values of $U(_{To,h})$ were normally distributed. The dataset was scanned for extreme values of $U(T_{o,h})$. The extreme value was defined according to Hill & Lewicki (2007) (6).

$$U(T_{o,h})_{(i)} > UBV + 3 \cdot (UBV - LBV) \mid U(T_{o,h})_{(i)} < LBV - 3 \cdot (UBV - LBV) \tag{6}$$

where $U(T_{o,h})_{(i)}$ is the particular value of expanded standard uncertainty corresponding to the particular mean operative temperature from the data set, $UBV$ is the overall mean of $U(T_{o,h})$ + 75th percentile for all hours of measurements at particular measuring point (location) and $LBV$ is the overall mean of $U(T_{o,h})$ − 25th percentile for all hours of measurements at particular measuring point (location).

## Influence of $U(T_{o,h})$ on categorization of thermal environment according to EN 15 251

Classification of thermal environment in investigated buildings was based on requirements specified in European standard EN 15 251 (EN 2007). The standard specifies four categories for indoor environmental quality in buildings. For the purpose of this paper, only requirements regarding operative temperature were considered. Such requirements together with description of the building categories are summarized in Table 2. For the purpose of the present study only outer operative temperature borders for categories I, II and III were used (marked bold in the Table 2). This was done because no information was available about exact duration of heating/cooling periods in the investigated buildings.

**Table 2 – Temperature ranges for hourly calculation of cooling and heating energy according to (EN 2007) for offices and spaces with similar activity (sedentary activity ~1.2 met)**

| Category | Operative temperature for heating [ºC] ($I_{cl}$ = 1.0 clo)$^{(1)}$ | Operative temperature for cooling [ºC] ($I_{cl}$ = 0.5 clo) $^{(1)}$ |
|---|---|---|
| I<br>(High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons) | $^{(2)}$**21.0** – 23.0 | 23.5 – **25.5** |
| II<br>(Normal level of expectation and should be used for new buildings and renovations) | **20.0** – 24.0 | 23.0 – **26.0** |
| III<br>(An acceptable, moderate level of expectation and may be used for existing buildings) | **19.0** – 25.0 | 22.0 – **27.0** |
| IV | < 19.0 | > 27.0 |

| | | |
|---|---|---|
| (Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year) | | |

(1) $I_{cl}$ represents typical clothing insulation value for given season-operational period
(2) Upper - $T_{o,up}$ and lower - $T_{o,dw}$ limit values used for the analysis are printed in bold

Method "A" from the Annex F of EN 15 251 (EN 2007) for long term evaluation of general thermal conditions was applied on the data. The method lies in calculation of number of % of occupied hours when operative temperature exceeds a specific range defined by upper – $T_{o,up}$ and lower - $T_{o,dw}$ limit operative temperatures (see Table 1). A building was considered to lie within the particular category in the case that $T_{o,h}$ has not exceeded the limits for more than 5% of occupied time.

Classification of the thermal environment was done twice on the data set. The first case represented current practice, thus hourly mean values ($T_{o,h}$) were confronted with limits as stated in Table 2. In the second case $T_{o,h}$ values were expanded/narrowed by adding/subtracting corresponding $U(T_{o,h})$ to account for lowest/highest possible true value of mean operative temperature (on the 95% level of confidence). For example a comparison of hourly mean value $T_{o,h} = 26.3 \pm 1.4$ ºC ($T_{o,h} \pm U(T_{o,h})$) to the upper limit value for category II ($T_{o,up} = 26$ ºC) would in the Case 1 (see Table 3) mean exceeded limit for category II (26.3 > 26 ºC), but in the Case 2 the requirements of the category II would be still fulfilled (26.3 – 1.4 = 24.9 < 26.0 ºC).

**Table 3 – Method for comparison of hourly mean $T_{o,h}$ to limit conditions for building categories with and without measurement uncertainty taken into account**

| | | Limit conditions for building categories according to EN 15 251 [ºC] | | |
|---|---|---|---|---|
| Case | Description | Category I | Category II | Category III |
| 1 | Measurement uncertainty not considered | $21.0 < T_{o,h} < 25.5$ | $20.0 < T_{o,h} < 26.0$ | $19.0 < T_{o,h} < 27.0$ |
| 2 | Measurement uncertainty included | $(T_{o,h} - U(T_{o,h})) < 25.5 \wedge$<br>$(T_{o,h} + U(T_{o,h})) > 21.0$ | $(T_{o,h} - U(T_{o,h})) < 26.0 \wedge$<br>$(T_{o,h} + U(T_{o,h})) > 20.0$ | $(T_{o,h} - U(T_{o,h})) < 27.0 \wedge$<br>$(T_{o,h} + U(T_{o,h})) > 19.0$ |

# RESULTS

## General analysis of observed $U(T_{o,h})$

Figure 2 and Figure 3 show box plots of hourly mean operative temperature ($T_{o,h}$) and corresponding expanded uncertainty for all measuring points in investigated buildings. As it can be seen from Figure 2, operative temperature levels differed among the buildings. As expected, median operative temperature was highest in south European buildings (Madrid and Padua). The operative temperature levels in Viborg Town Hall were following temperatures in south European buildings. This was most probably caused by the fact that the building is not equipped by external solar shading system and thus solar heat gains mean significant contribution to heat loads of the building. COWI headquarters in Aalborg had lowest hourly mean operative temperature levels from all investigated buildings. Figure 3 clearly shows that median $U(T_{o,h})$ *and its* percentile range differed among the investigated buildings and in some cases even between measuring points in a specific building (TiFS Padua and Viborg Town Hall). South office in IDOM Madrid and south-west office in Viborg Town Hall represent measuring points (workplaces) with highest spread of $U(T_{o,h})$ values. This means that highest fluctuations of operative temperature happened at those measuring points. General level of $U(T_{o,h})$ observed in the study, represented by geometric mean (25th, 75th percentile) of the median values for all investigated buildings was 1.33 (1.30, 1.37) ºC.

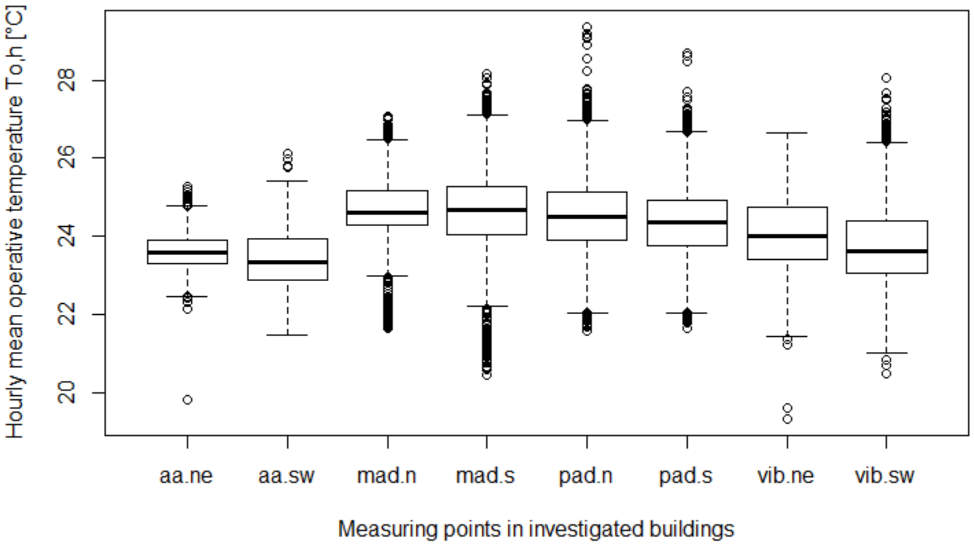

**Figure 2 – Measured mean operative temperatures in investigated buildings, measuring points are abbreviated as follows: first two letters – building: aa – COWI Aalborg, mad – IDOM Madrid, pad – TiSF Padua, vib – Town Hall Viborg; second two letters – orientation: n – North, ne – North-east, s – South, sw – South-west**

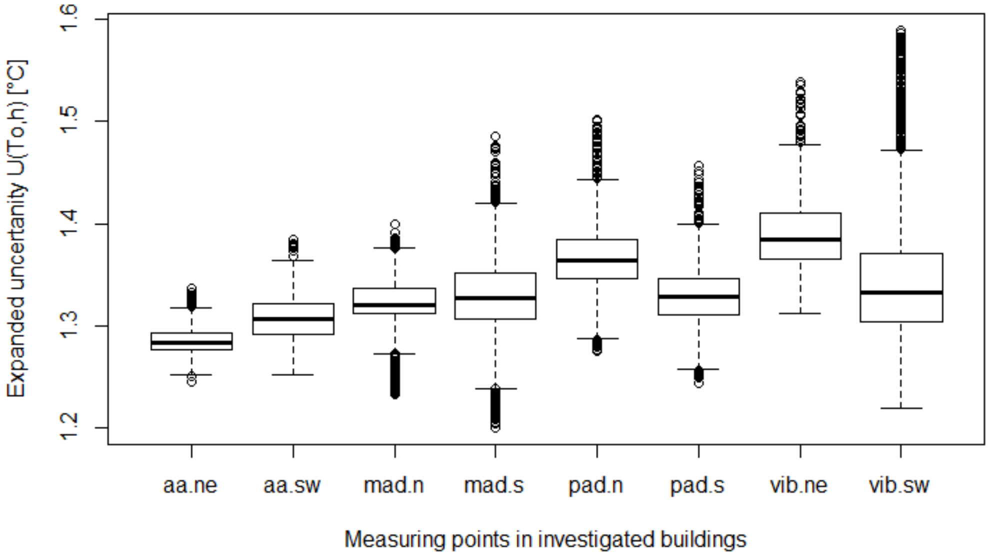

**Figure 3 – Expanded uncertainty of hourly mean operative temperature in investigated buildings, abbreviation of measurement points is identical to Figure 2**

## Influence of $U(T_{o,h})$ on categorization of thermal environment

Table 4 shows a comparison of the two analyzed cases (see Table 3). It is clear from the table, that accounting for expanded uncertainty of the measurement changed the whole picture of the building classification. It can be seen that none of the investigated buildings had problems with keeping the $T_{o,dw}$ limits. As it can also be seen form Figure 2, $T_{o,h}$ was rarely below 21 ºC in all buildings. On the other hand, in both buildings situated in southern Europe, the building category II limit of $T_{o,uo}$ = 26 ºC was exceeded during more than 5% of occupied time at all measurement points. $T_{o,uo}$ = 25.5 ºC (category I) was exceeded for more than 5% of occupied time in the south-western office of Viborg Town Hall, but exceedance of category II for the same room was below 5%. When expanded uncertainty of the measurement was taken into account, none of the buildings had problems to meet category I requirements.

## DISCUSSION

The present paper means only a small step in the process of investigation of the influence of measurement uncertainty on evaluation of thermal environment in buildings. It is obvious that not all possible sources of uncertainty were included in the $U(T_{o,h})$ calculation. The present work deals with uncertainty originating from the measurement process (related to repetition of the measurement) and the uncertainty related to the accuracy of the used instrumentation. More analyses would be needed to account for other uncertainty sources like time drift of the resistance thermometers, calibration etc. The accuracy of the reading for the external voltage signal in the HOBO data logger was used to account for measurement accuracy. However other publications reporting data measured with the same type of instruments (grey sphere-shaped sensors) define their accuracy simply as a temperature range of ± 0.3 K (Simone et al. 2013; Simone et al. 2007). As the $T_o$ is an indirectly measured quantity, the approach adopted in the present paper seems to be more appropriate, but as the measurement accuracy of the external input of the logger is dependent on actual value of measured voltage, resulting $U(T_{o,h})$ values are about 0.75 K higher than those calculated using constant accuracy of ± 0.3 K. We calculated a new expanded standard uncertainty $U(To,h)^*$ to explore the effect of using constant value of accuracy on building categorization for south office in IDOM Madrid (this measuring point had the highest prevalence of exceeded limits according to (EN 2007). Figure 4 shows that when constant accuracy range was used, the final expanded uncertainty was smaller and thus the percentage of hours with exceeded limits increased (note the difference between red and green bars in the figure). On the other hand, it is also clear from the figure, that building categorization was significantly changed when measurement uncertainty was taken into account, independently of how the accuracy was expressed.

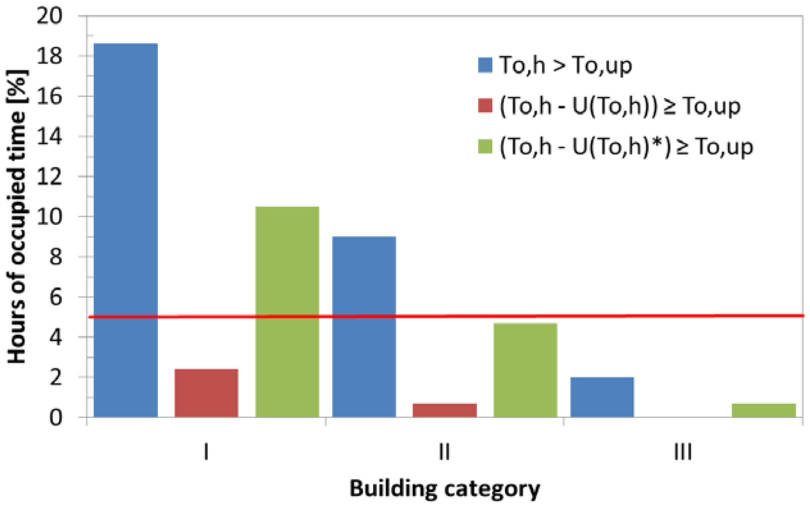

**Figure 4 – Comparison of % of occupied hours with exceeded limits of To according to (EN 2007) for south office space in IDOM Madrid for different methods of establishing the limit conditions: blue - Case 1, red - Case 2 and green – constant measurement accuracy ± 0.3 K; the red line indicates 5% limit for exceeding category requirements**

**Table 4 – Percentage of occupied time with exceeded $T_o$ limits**

| Measuring point | Building category | Occupied time outside building category [%] | | | |
|---|---|---|---|---|---|
| | | $T_{o,h} > T_{o,up}$ {Case 1}(1) | $(T_{o,h} - U(T_{o,h})) \geq T_{o,up}$ {Case 2} | $T_o < T_{o,dw}$ {Case 1} | $(T_{o,h} + U(T_{o,h})) \leq T_{o,dw}$ {Case 2} |
| aa.ne | I | 0.0 | 0.0 | 0.2 | 0.0 |
| aa.ne | II | 0.0 | 0.0 | 0.0 | 0.0 |
| aa.ne | III | 0.0 | 0.0 | 0.0 | 0.0 |
| aa.sw | I | 1.4 | 0.0 | 0.0 | 0.0 |
| aa.sw | II | 0.2 | 0.0 | 0.0 | 0.0 |
| aa.sw | III | 0.0 | 0.0 | 0.0 | 0.0 |
| mad.n | I | **17.4** | 0.1 | 0.0 | 0.0 |
| mad.n | II | **8.1** | 0.0 | 0.0 | 0.0 |
| mad.n | III | 0.1 | 0.0 | 0.0 | 0.0 |
| mad.s | I | **18.6** | 2.4 | 0.8 | 0.0 |
| mad.s | II | **9.0** | 0.7 | 0.0 | 0.0 |
| mad.s | III | 2.0 | 0.0 | 0.0 | 0.0 |
| pad.n | I | **16.7** | 2.0 | 0.0 | 0.0 |
| pad.n | II | **8.8** | 0.5 | 0.0 | 0.0 |
| pad.n | III | 1.7 | 0.2 | 0.0 | 0.0 |
| pad.s | I | **12.3** | 0.7 | 0.0 | 0.0 |
| pad.s | II | **6.1** | 0.2 | 0.0 | 0.0 |
| pad.s | III | 0.5 | 0.1 | 0.0 | 0.0 |
| vib.ne | I | 4.9 | 0.0 | 0.1 | 0.0 |
| vib.ne | II | 1.5 | 0.0 | 0.1 | 0.0 |
| vib.ne | III | 0.0 | 0.0 | 0.0 | 0.0 |
| vib.sw | I | **7.9** | 0.4 | 0.2 | 0.0 |
| vib.sw | II | 4.3 | 0.1 | 0.0 | 0.0 |
| vib.sw | III | 0.4 | 0.0 | 0.0 | 0.0 |

(1) For description of the cases see Table 3

The fact that measurement uncertainty/accuracy can have a significant in influence on building categorization in the case of use of field measurements was previously pointed out by d’Ambrosio Alfano et al. (2011) as well as Dell’Isola et al. (2012). d’Ambrosio Alfano et al. (2011) focused on accuracy of instruments for measuring indoor environmental parameters used in PMV/PPD model (ISO 2005; Fanger 1970). Authors pointed out a significant influence of accuracy for mean radiant temperature measurements as well as the need for an in-depth discussion focused on the measurement protocols and types of used instruments that would reduce reduction required accuracy levels reported in the ISO 7726 (ISO 2002). Despite the fact that the paper did not deal with expanded standard uncertainty of the particular measurements needed to determine PMV index, the authors indicated a need for broadening of the building categories specified in ISO 7730 and EN 15251 standards (ISO 2005; EN 2007). This was due to observed significant sensitivity of PMV to the measurement accuracy. Dell’Isola et al. (2012) focused directly on measurement uncertainty adopting the conformity range of measurements approach according to (UNI EN/ISO 2001). In contrast to the present study, their work was focused on comparison of different types of instruments and their ability to provide reliable input to PMV/PPPD model. Nevertheless, their results suggested that unambiguous attribution of the best building category was difficult and often impossible unless instruments with very good accuracy were used. Moreover, the use of instruments having parameters according to ISO 7726 (ISO 2002) resulted in comparable results, but often ambiguous attribution to the building category. Taking into account the results of previous research as well as the results of the present study it is clear that it would be beneficial to discuss the issue of measurement uncertainty during revision of EN 15251 standard (EN 2007), which is currently ongoing (Olesen 2015).

## CONCLUSIONS

- Analysis of filed measurement data for four European office buildings showed that expanded standard uncertainty of grey sphere-shaped operative temperature sensors was in a range (1.2, 1.6) ºC with geometric mean (25th, 75th percentile) 1.33 (1.30, 1.37) ºC.
- When expanded standard uncertainty was taken into account in categorization of thermal environment according to standard EN 15251, the difference in prevalence of exceeded category limits were up to 17.3%, 8.3% and 2% of occupied hours for category I, II and III respectively.
- Use of constant measurement accuracy of ± 0.3 K for final reading of operative temperature instead of accuracy for row voltage signal from the resistance thermometer linearly dependent on absolute voltage reading had a significant effect prevalence of exceeded category limits. The difference observed for a measuring point with generally highest percentage of hours above category limits was 8% for category I and 4% for category II.
- The results of the present study indicate that measurement uncertainty needs to be considered during assessment of thermal environment in existing buildings.

## ACKNOWLEDGEMENT

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