

Long-term monitoring of the thermal environment in office buildings



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Abstract

Existing guidelines on monitoring of Indoor Climate Quality (ICQ) do not adequately address long term monitoring. A better understanding of the collection and analysis of monitored data, extending over a long-time period is required. This study aimed at addressing the aforementioned research gaps. The study took place in two office buildings, during two periods each: February & May (case I) and April & June (case II). Thermal environment data was obtained across several locations in the room. Results showed that measurement of temperature was most critical in the open-plan office floors. Local heat sources had a significant

influence on the measured temperatures. To collect representative data with the help of building management system (BMS) sensors, existence and fluctuation of local heat sources should be considered at the start of the ICQ assessment. Based on this information, the minimal distance between BMS sensor and workplace location can be determined. In the design process, the field study protocol can be used as a tool to predict the number of sensors and distance from occupants.

Recent studies have put focus on the importance of monitoring buildings during their operation and maintenance phases [1–4]. The body of data obtained through

such monitoring provides essential information about a building's energy consumption and Indoor Climate Quality (ICQ) and can be used to control and optimize its performance [1–3,5]. The accuracy and applicability of the conclusions from the gathered data depends on the quality of the data (reliability) gathered and data interpretation (data-analysis) [6]. Compared to energy consumption and service control, ICQ monitoring is less addressed. Current standards like ISO 7730 [7], NEN-EN 15251 [8], ANSI/ASHRAE standard 55 [9] and Dutch ISSO guidelines also do not provide details for long-term ICQ monitoring [6,10–12]. Drawing uninformed conclusions during monitoring and analysis may affect the comfort perception, well-being, and productivity of occupants [8,12–14] and building energy use [6,8,15]. Reliability of the ICQ data is strongly dependent on sensor location. Sensor location is usually chosen in accordance with guidelines, as from ISSO publication 31 [16]. However, such guidelines are cursory, making ICQ assessment at a detailed level a topic in need of comprehensive investigation. For this reason, the current work investigates the influence of the location of the building management sensor on its measurement and recommendations were formulated for long-term monitoring needs.

Method

Case studies

Indoor climate of two existing open-plan offices in the Netherlands were monitored, during two periods each (Table 1). Both environments are ventilated, cooled and heated by an induction system and regulated by one BMS sensor located on the wall (at 1.5 m height from floor). The BMS sensor records indoor temperature

and relative humidity every five minutes. Data from the BMS sensor is analysed with the help of a data platform [17]. In both case studies is the data platform developed by the same company, to oversee buildings remotely and to optimize their maintenance. In both locations, occupants have the possibility to effect small changes to air temperature by local thermostats and are able to avoid direct sunlight by using indoor sunscreens. There was no outdoor sun protection.

Objective measurement

Indoor climate data from different locations in the open-plan work environment was collected and compared with the data from the data platform to assess differences in ICQ over the whole floor. The measurement locations have been given in Figure 1 and Figure 2. At the start of the measurement period, the measurement equipment was calibrated and the BMS sensors' measurements were compared against the calibrated equipment to avoid discrepancies.

Objective measurements were undertaken at three levels: room level, local level and micro level (Figure 3). The room level gave insight to the overall conditions of the room and was measured with the help of two kinds of sensors: 'BMS sensor' and 'room sensor'. Room level sensors were placed according to the Dutch guidelines [16,18]. At this level, air temperature, relative humidity and CO₂-concentration were determined every 2 minutes using transmitters (Table 2). Since the recorded air temperature may be affected by radiant sources and may not provide a measure of solely the air temperature, we refer to the measured values as 'exposed temperature' (ET).

Table 1. General information about the case studies. (Measurement period 1 and 2 are defined as M1 and M2).

Case	Year of construction	Location	Surface area [m ²]	Max. # occupants	Parameters BMS sensor	M1	M2
Case A	2010	Son	~140	41	-Exposed temp	Feb	May
Case B	1956 (renovated: 2007-2009)	's-Hertogenbosch	~620	68	-Exposed temp -Relative humidity	Apr	Jun

Table 2. Overview of the measurement equipment.

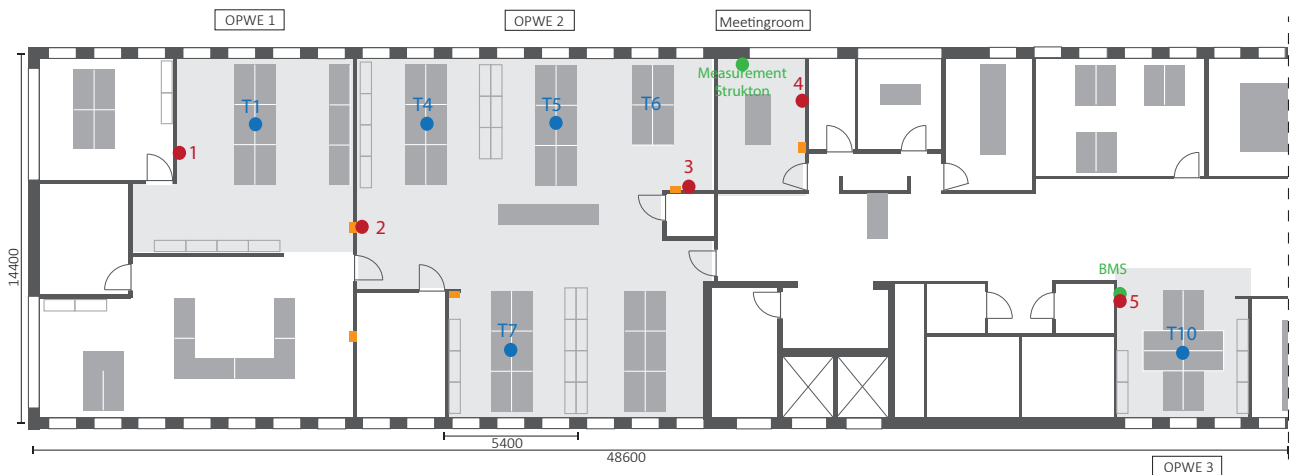
Measurement	Device	Type	Accuracy	
Room level & Local level	T/RH/CO ₂ sensor	Eltek GD47 Transmitter	Temp.	± 0.4°C (-5°C to 40°C)
			RH	± 2°C (10% to 90%)
			CO ₂	25°C: 0 – 5000 ppm < ± 50 ppm + 3% of measured value. Temperature dependence: 2 ppm $\frac{CO_2}{°C}$ over the range 0 to +50°C
	Data logger	Grant SQ 1000 series	-	± 0.1 of reading
Micro level	iButton	Maxim DS1921	Temp.	± 0.4°C (15°C to 46°C)

Local level thermal conditions around workstations were measured in the same way as the room level. At this level, the sensors (GD47 transmitter) were placed near each workplace group, at a height of 1.1 m above the floor. Micro level measurements focused on individuals, i.e., the thermal condition around a person. On each measurement day, four to six of the participants who had volunteered to be a part of the study were selected to represent random location on the floor-plan. IButtons (DS1921, Maxim) were placed next to the

chair of the participant, where they recorded ET every minute. The best location for the iButton was explored through a set of preliminary measurements to limit the influence of the body heat.

Data-analysis

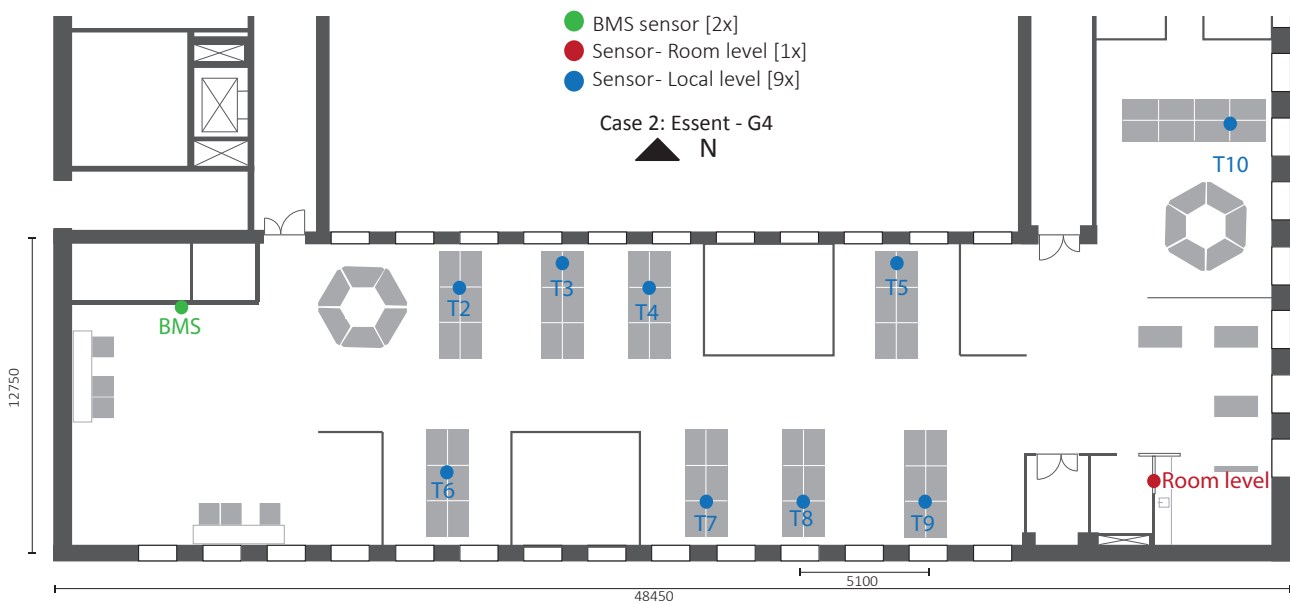
The collected data was collated using Matlab (R2016b). IBM SPSS Statistics 23 was used for statistical analysis. Only data corresponding to working hours (8:00 AM-06:00 PM) was processed. Preliminary analysis



Case 1: Strukton Workspere - Floor 2

Figure 1. Floor plan second floor of Case A. In the gray accented areas, objective measurements were performed (Open-plan work environments 1, 2 and 3 and Meetingroom).

- BMS sensor [1x]
 - Sensor- Room level [5x]
 - Sensor- Local level [5x]
 - Sensor- Micro level
 - Thermostat
- ◀ N



Case 2: Essent - G4
▲ N

Figure 2. Floor plan for observed area of Case B. The BMS sensor is located in the left corner. An extra room sensor was placed on the right side of the floor. The sensors at local level are illustrated in blue.

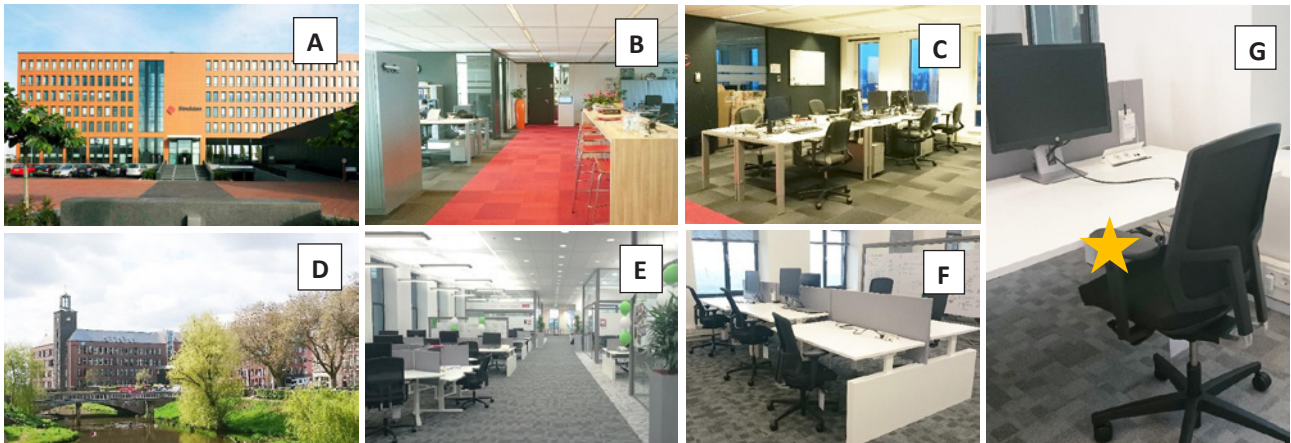


Figure 3. Images from Case B (a-c) and Case A (d-f), depicting the buildings and the different localities of monitoring: b) & e) room level, c) & f) local/desk level. The micro environment for temperature measurements is depicted in g) where the star marks sensor location.

showed the indoor conditions did not correlate with outdoor weather conditions, and hence observations for both periods were analysed together. The two buildings were examined separately. Statistically significant differences were examined with the Mann-Whitney U test. Significance was tested at 5% level. Correlations were determined by the ‘*Pearson product moment correlation*’.

Results & Discussion

BMS data in relation to data at room level, local level and micro level

Data from room, local and micro level were compared and linked to the BMS data. In both case studies, differences in CO₂-concentration and relative humidity between the room sensor and local sensor were relatively small and no practically significant difference between the measured values could be found. Based on these results it may be concluded that the original BMS sensor location could provide representative data related to the CO₂-concentration and relative humidity for the examined open plan spaces.

However, variation of ET through the open-plan work environments was significant. The results have been plotted in cumulative frequency distribution (CFD) graphs (**Figure 4**). Differences between sensors are smaller when data behaves in a similar pattern and plotted lines had a similar temperature range. In the best case, the difference between the BMS data and the rest of the monitoring levels are limited, so that BMS data is representative of the local conditions.

For most cases, the local ET exceeded BMS measurements by 1°C or more. The only exception was for OPWE 3 at Case A (**Figure 1**). We believe the differences in the ETs were mainly due to local heat sources, for example, the occupants, computers, and solar radiation through windows. Therefore, the distance between BMS sensor and workplaces is important when it comes to reliability of the measurements. In both locations, the BMS sensors were more than 3 m away from occupied workplaces. When distance between room level and local level sensors were less than 3 m, the differences in

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recorded ETs were minimal. For instance, in OPWE 3 of Case A, the BMS sensor was within 2 m of the work stations. No significant difference could be found

between the ETs at local level and BMS. The impact of the distance between sensors is clarified using correlations between the BMS, room, local and micro sensors.

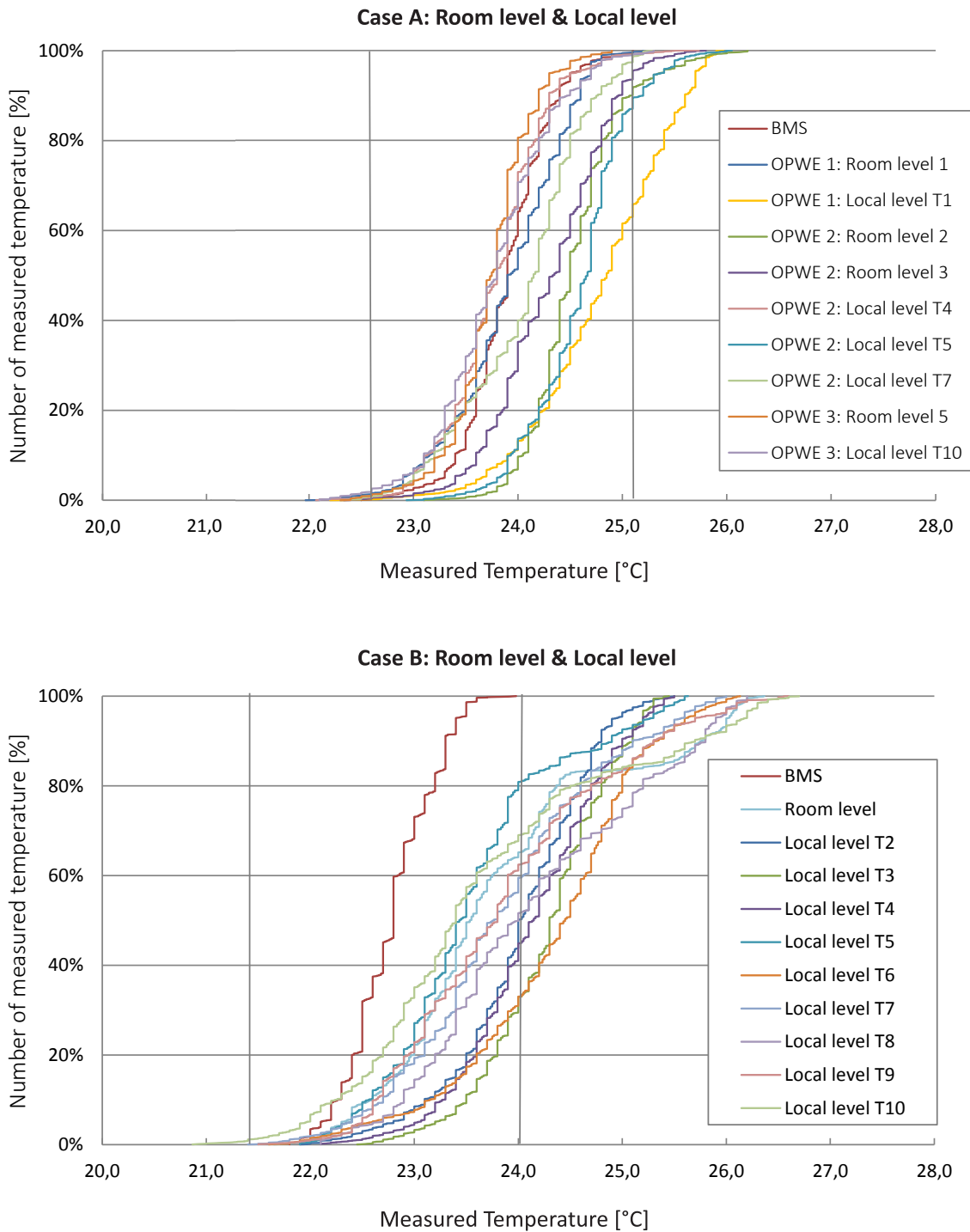


Figure 4. CFD-graph from room level (top) and local level (bottom) of Case A & Case B. The graph shows the distribution (smallest to largest) and frequency temperature range of each sensor. The temperature range of the BMS sensor is illustrated with the vertical lines.

Table 3 and **Table 4** show the correlations for both case studies. In Case B, larger distance between sensors resulted in weaker correlations (**Figure 5**). Better correlation may thus be achieved between local and BMS ETs by using a larger number of BMS sensors, spread across the open plan workspace. Notice for example in **Table 3** that the room sensor position has a stronger correlation with local & micro level than the BMS position. Thus, a minimum number of BMS sensors are required in order to have a representative indication of the ICQ.

For Case A, because the floor has been divided into multiple spaces (OPWE 1, 2 & 3 and Meeting room) the situation was different. Regardless of the distance between sensors, the sensor located in a different space always had a weak correlation with the BMS sensor ($r < 0.306$, $p < 0.05$) (**Figure 6**). To collect representative thermal data in Case A, a BMS sensor would be required for each space. Adding extra room sensors increases the strength of the correlations in both cases,

where the closest room sensor has the strongest correlation with the relevant local and micro sensor. Overall, ET at room level (BMS sensor and room sensors) was better correlated to ET at local level than the temperature at micro level.

The relation with micro level was more complex. Only 65% of the correlations (local with micro) were of a high enough value (**Table 3 & 4**). Due to the large differences in micro ET for each table and each person, no reliable relationship or trend could be found. Accurate measurements at micro level are dependent on several parameters. For instance, the activity of the person sitting in the chair, the position of the chair and distance to local heat sources can be important information to explain differences in micro measurements.

Objective data collection

Though quantitative conclusions from this study are case specific, certain qualitative conclusions regarding objective data measurement for indoor climate quality

Table 3. Pearson product moment correlation BMS-Room-Local-Micro (Case B) for four local situations, here $p < 0.001$. The distance between sensors has influence at the strength of the correlation (T4 strongest correlation with the BMS sensor, T10 weakest correlation). Moreover, a weaker correlation is found on the south side of the floor plan, due to solar radiation (T6).

Table	BMS sensor		Room sensor		Local sensor	
T4	BMS ~ Local T4	0.847	Room ~ Local T4	0.717		
	BMS ~ Micro T4	0.434	Room ~ Micro T4	0.685	Local T4 ~ Micro T4	0.755
T6	BMS ~ Local T6	0.687	Room ~ Local T6	0.678		
	BMS ~ Micro T6	0.512	Room ~ Micro T6	0.655	Local T6 ~ Micro T6	0.624
T8	BMS ~ Local T8	0.657	Room ~ Local T8	0.881		
	BMS ~ Micro T8	0.634	Room ~ Micro T8	0.704	Local T8 ~ Micro T8	0.868
T10	BMS ~ Local T10	0.095	Room ~ Local T10	0.891		

Table 4. Pearson product moment correlation BMS-Room-Local-Micro (Case A) for three local situations. Here $p < 0.001$.

Table	BMS sensor		Room sensor		Local sensor	
T1	BMS ~ Local T1	0.306	Room ~ Local T1	0.855		
	BMS ~ Micro T1	0.401	Room ~ Micro T1	0.357	Local T1 ~ Micro T1	0.352
T5	BMS ~ Local T5	0.267	Room ~ Local T5	0.728		
	BMS ~ Micro T5	0.279	Room ~ Micro T5	0.479	Local T5 ~ Micro T5	0.492
T10	BMS ~ Local T10	0.955	Room ~ Local T10	0.941		

monitoring may be provided. In order to have a representative indication of the ICQ, the maximum distance between sensors should be considered during design of the monitoring system. The number of sensors depends on the floor plan design specifically, obstacles and boundaries. The number of sensors can be optimized by test measurements on different measurement levels.

The spacing of sensors can also be affected by local heat sources as they can influence the ET. If local heat sources, such as occupancy and solar radiation, are relatively consistent, CO₂-concentration, relative humidity, and ET can be determined at room level with a distance of 3 m to the workplaces, assuming the ventilation system is effective. Moreover, a higher frequency for recording data would be recommended to register

fluctuations in ET. In Case A and Case B, local heat sources cannot be ignored in the comfort analysis due to changing occupancy and lack of outdoor shading. Hence, for these office spaces, BMS sensors need to be placed at a closer distance (< 3 m) to workstations.

Conclusion

This study provides results from field measurements that can aid decision making regarding the position of BMS sensors and the collection of objective data in open-plan offices. Results of the objective measurements show little differences in CO₂-concentration and relative humidity between BMS, room and local sensors. A larger difference is found for ETs. The existing BMS sensors did not yield a representative indication for the complete floor space when it came to ET.

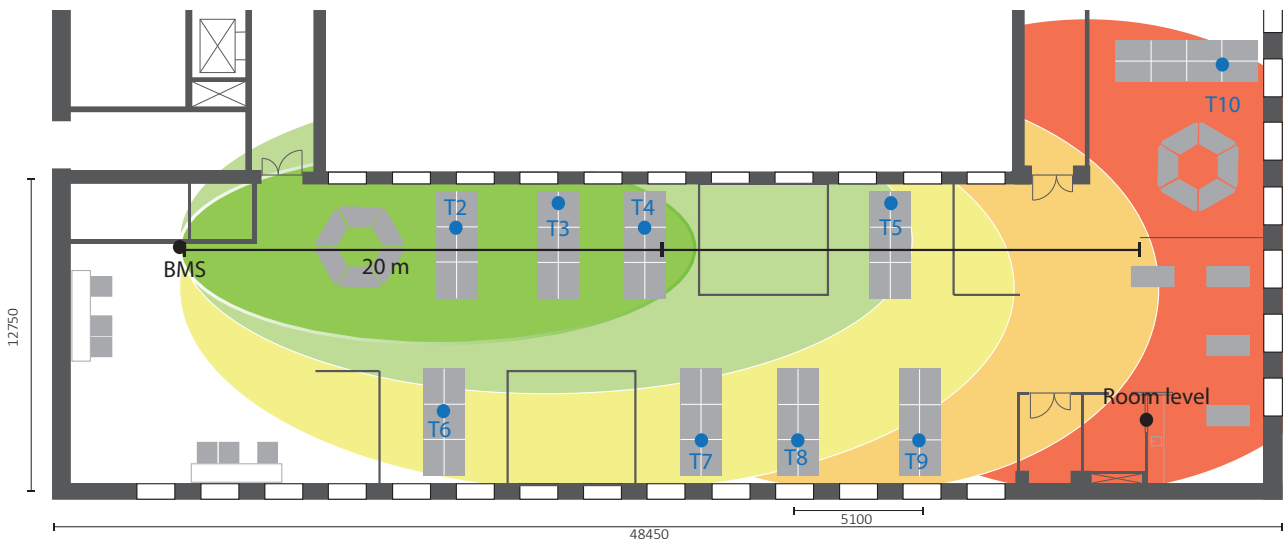


Figure 5. The influence of distance between sensors and solar radiation for the correlation between the BMS sensor and local sensors.

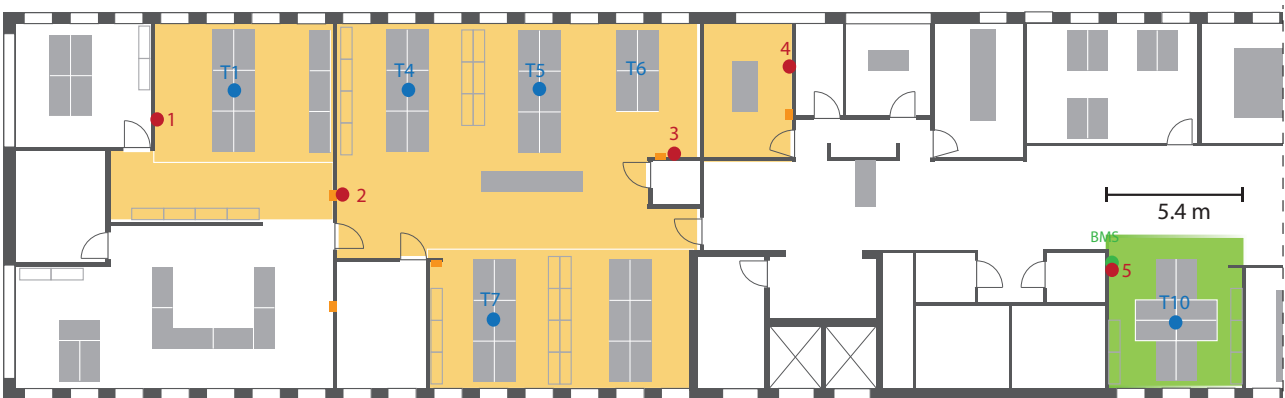


Figure 6. The correlation is weak when sensors are not located in the same room (regardless of the distance between sensors).

Local heat sources and distance between sensors have a significant influence on the measured value of ET. These parameters need to be considered during design of the monitoring system. Floor plan (enclosed spaces, obstacles, and floor area) and the existence and fluctuation of local heat sources influence sensor positioning requirements. The field study protocol as described in this method is useful for determining monitoring level and sensor separation.

As results of this study are based on just two office buildings with an induction system under specific

weather conditions, it is recommended to further develop the application of the method in more varied office settings, occupant demographics, and outdoor weather conditions to further the conclusions and recommendations formulated herein. ■

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