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# Assessment of thermal comfort at the building level: Evaluation of aggregation methods with a Danish case study of a campus building

*Simon* P. Melgaard[1*], *Anna* Marszal-Pomianowska[1], *Samuel* Petit[2], *Lasse* Rohde[1], *Hicham* Johra[1], *Rasmus* L. Jensen[1], *Per K.* Heiselberg[1]

[1]Department of the Built Environment, Aalborg University, Thomas Manns Vej 23, 9220, Aalborg, Denmark
[2]INSA Lyon, 20 Av. Albert Einstein, 69100 Villeurbanne, France

**Abstract.** Six methods for aggregating local thermal comfort scores in six offices to a single global score are investigated. using data collected by the building management system in a campus building of Aalborg University. Three static: 1) number of rooms weighted mean, 2) area-weighted mean, 3) desk-weighted mean, and three dynamic: 4) simple occupancy-weighted mean (PIR sensors), 5) advanced occupancy-weighted mean (PIR sensors mixed with the number of desks), 6) number of the occupants-weighted mean (camera readings). A notable disparity emerged between static methods, which rely solely on fixed parameters, and dynamic methods, which account for time-dependent factors over short timeframes. Dynamic methods consistently yielded lower global scores, irrespective of individual room performance. The difference can be up to 15% monthly. The PIR sensors, which are now commonly used in office or education buildings to control artificial lighting are a good indication of the occupancy (only present and not present). The information on number of occupants in the offices, collected by installed cameras, did not provide significantly better results in the analysed case study.

## 1 Introduction

The energy efficiency measures and, thereby, reduction of energy use in the building sector have been part of national and international roadmaps towards energy neutrality for decades. The growing focus on solely achieving high levels of energy efficiency during building operations has left the considerations on the created indoor environment in the building in the shadow. Since people spend more than 90% of their time indoors [1], the potential influence on occupant comfort, health and wellbeing is substantial [2]. Evaluation of building performance, including only energy use, is insufficient and may lead to misleading conclusions (e.g., a building with low energy use and an inferior indoor environment would be evaluated as performing better over a building with higher energy use and an excellent indoor environment).This understanding is reflected in the most recent Buildings Directive that puts more emphasis on consideration and documentation of Indoor Environmental Quality (IEQ) performance [3].

The energy performance of a building is translated to a single indicator expressed in kWh/m$^2$ per year, yet evaluation of the indoor environment is more challenging, particularly for more complicated buildings, such as office and campus buildings. These buildings often include multiple zones, mixed functions, and different layouts of indoor spaces, i.e., open-layout spaces, single-person offices, group rooms, and lecture halls. These indoor spaces are often exposed to varying outdoor conditions, specifically wind and solar radiation. As so many diverse factors impact the indoor environment in the building, it becomes essential to consider different dimensions that collectively contribute to occupants' comfort.

Researchers have dedicated their efforts to analyse the impact of various parameters on overall IEQ in the operation phase of a building. Wargocki et al. [4] developed the multi-parameters criteria rating scheme "TAIL", which aims to compare the disparity in IEQ between buildings before and after deep renovation. TAIL only includes one indicator for thermal, one for acoustic, one for visual performance, and only Indoor Air Quality (IAQ) has nine parameters. TAIL always uses the lowest performing evaluation on all levels, both for 1) individual parameters measured over several seasons (worst season), 2) for each interim rating e.g., the worst performing IAQ parameter determines the IAQ component rating, and 3) the overall quality level of the building is equal to the lowest component quality. Larsen et al. [5] proposed a new approach to evaluating IEQ for dwellings, called the IEQ-Compass. This approach breaks down each IEQ parameter into multiple subcategories, with a starting point where all four IEQ categories are equal. This approach enables the translation of individual criteria into a comprehensive description of IEQ. Each criterion (e.g., drafts) is scored on a scale from 0 to 100%, resulting in a final score for

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[*] Corresponding author: simonpm@build.aau.dk

each parameter (e.g., Thermal) on a 0-100% scale. A global score is then assigned, corresponding to a letter grade from A (>85%) to G (<35%), similar to the energy label used to indicate the energy performance of buildings. Each letter grade is also associated with a colour. Both TAIL and IEQ-Compass have their limitations. They give the four IEQ categories equal weight, as the combined literature on a hierarchy of category weights is inconclusive. IEQ-Compass has relative weights on the parameters within the IEQ category, meaning that daylight performance contributes more to visual performance than direct sunlight. Both TAIL and IEQ-Compass have aggregation rules that ensure extra attention to the lowest-performing categories when making the global assessment of IEQ. The reason for this is that occupants are known to put the most emphasis on the poorest performing parameter. Also, this is a strategic decision to create an incentive to improve the poorest-performing areas of the IEQ. Finally, TAIL requires an extensive measurements campaign to be conducted before and after renovation and IEQ-compas is limited to residential buildings. Olesen et al. [6] aimed to develop distinct yearly thermal comfort scores based on various seasonal schemes to mirror the widely used approach in energy labelling, which involves assessing energy consumption yearly, typically presented as the energy used per unit area during a year (kWh/m²/year). The thermal comfort assessment is conducted by considering the occupation hours and aggregating the time spent in each of the four categories defined in EN 16798 [7]. To facilitate the comparison of thermal comfort among different heating-cooling concepts and express it using a single value, the yearly Thermal Comfort Score (TCS) was introduced. The TCS was derived by considering the percentage of occupied hours. The scheme assigned weighted values for each score corresponding to the proportion of time spent in each category, ultimately generating a comprehensive assessment value ranging from one (indicating the best comfort) to five (reflecting the worst comfort) for a particular zone or building.

In any of the presented methods, the aspect of aggregation of either one or all IEQ categories from a local level (e.g., room) to a global level (e.g., zone or building) is not addressed. However, the method for aggregation of the local IEQ scores to a single global score is crucial if comfort is to be equally important as the energy performance of buildings.

### 1.1 Contribution

This paper aims to narrow the thermal comfort assessment gap by evaluating six methods for aggregating local thermal comfort scores to a single global score. Six aggregation methods are analysed, including three static: 1) number of rooms weighted mean, 2) area-weighted, 3) desk-weighted, and three dynamic: 4) simple occupancy-weighted (PIR sensors), 5) advanced occupancy-weighted (PIR sensors mixed with the number of desks), 6) number of occupants-weighted (camera readings). In this work, thermal comfort is understood as the ability of the HVAC systems to consistently maintain the heating (HS) and cooling (CS) setpoints in each room at any given moment and will be called thermal performance in the following sections. A case study is a campus building in northern Denmark, including data from 23 weeks (March-July).

## 2 Case study, sensors, data

The case study is a campus building of Aalborg University, located in Aalborg, Denmark. The building is approximately 9000 m$^2$ and is divided into three ventilation zones and two heating zones (decentralised approach). Each zone is connected to a technical room (in total four technical rooms) equipped with a district heating substation for space heating and production of domestic hot water and the central Air Handling Unit (AHU) with Variable Air Volume (VAV) control for fresh air supply. The investigation includes six rooms in the northwest corner on the third floor, see Figure 1. These rooms were selected because they were equipped with cameras to collect the real occupation of the rooms, which could be used as inputs in the sixth analysed aggregation method. Table 1 provides the characteristics of the analysed offices.

**Table 1**. Characteristic of each office.

| Room | Area [m$^2$] | No. of desks | Orientation |
|---|---|---|---|
| **A** | 23.7 | 4 | West |
| **B** | 23.6 | 3 | West |
| **C** | 18.8 | 3 | West |
| **D** | 33.1 | 6 | West & North |
| **E** | 22.7 | 4 | North |
| **F** | 25.1 | 4 | North |

A detailed description of the case study building can be found in [8].

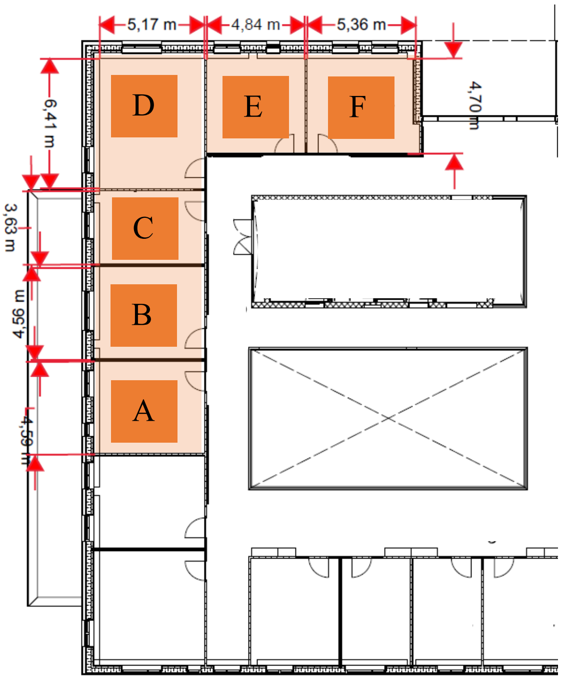

**Fig. 1.** Location and layout of the six investigated rooms (marked in orange).

## 2.1 Sensors

In every space, the room operative temperature is measured by the sensor integrated into the Schneider control panel located on the wall next to the door. The same control panel is used by the occupants to indicate the local offset (K). The PIR sensor is placed in every room to monitor occupancy and is used for automatic light control.

## 2.2 Temperature control

The rooms have individual controls for the heating and ventilation system. The heating and ventilation system in the rooms is controlled based on a central setpoint, which is the same for all the offices. This setpoint is further called the global setpoint ($G_{SP}$). At the same time, local adjustment is also possible in each room. This adjustment is known as the local offset ($K$), which can be adjusted in the span of ±2.5 °C, meaning that the local setpoint for control in each room ($L_{SP}$) is $G_{SP}$ +K. From the room's setpoint, a deadband ($\alpha$) is added to set the heating setpoint ($HS$) and cooling setpoint ($CS$) for the room. This deadband varies depending on the room and time of day. For the rooms under investigation in this case study, a constant deadband of 1.5 °C is present in all the rooms during working hours. This deadband means the HS is 1.5 °C lower than the room setpoint, while the CS is 1.5 °C above. The control principles are presented on Figure 2.

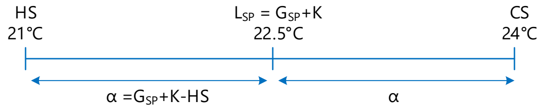

**Fig. 2.** Example of setpoints for a room.

## 2.3 Collected data

The data are collected by the Building Management System (BMS) and logged every five minutes. The dataset from every room includes 5-minute readings of the room operative temperature, HS and CS, occupancy from PIR sensors, and 1-minute images from the camera installed in the room. The data were collected for 23 weeks from March to August 2023, including a few weeks of the full heating season with a minimum outdoor temperature of -12.9 °C on March 8th, a transition period, and a few weeks of full summer with a maximum outdoor temperature of 27.9 °C on June 17th. A dataset with a detailed description can be found in [9].

# 3 Methods

To evaluate the ability of the HVAC systems to consistently maintain the heating (HS) and cooling (CS) setpoints in each room at any given moment, we have adopted the shape of the PPD function to rate the room on a scale from 0-100, see Figure 3. When the operative temperature is within the operator range (- α, α), the maximum score is given, and the points outside the range are given using the PPD shape function. The local score of individual rooms ($LS$) is calculated every hour according to the following equations:

$$\alpha = |L_{SP}-HS| = |L_{SP}-CS|$$

$$\Delta T = T_{measured} - L_{SP}$$

$$if\, \Delta T < -\alpha \quad (T_{measured} < HS)$$

$$LS = 100e^{-0.03353*(\Delta T+\alpha)^{\wedge}4-0.2179*(\Delta T+\alpha)^{\wedge}2} \tag{1}$$

$$if\, \Delta T > \alpha \quad (T_{measured} > CS)$$

$$LS = 100e^{-0.03353*(\Delta T-\alpha)^{\wedge}4-0.2179*(\Delta T-\alpha)^{\wedge}2} \tag{2}$$

The aggregation methods were split into two different groups, based on their use of static or dynamic room weighting characteristics. Static characteristics are understood as parameters that do not change during building in-use time, and a dynamic characteristic might change every hour. The static methods comprise: 1) all local scores have equal weights (Mean), 2) the local score is weighted with the floor area of a specific room (Area), and 3) the local score is weighted with the number of fixed working spaces assigned to each room (Desk). The dynamic methods comprise 4) the local score is weighted with one during hours when people are present in the room and zero for the hours with no people present (PIR), 5) for hours when people are present in the room the local score is weighted with the assigned number of desks for the remaining hours the local score is weighted with 0 (DeskPIR), and 6) the local score is weighted with the current number of people present in the room (Camera).

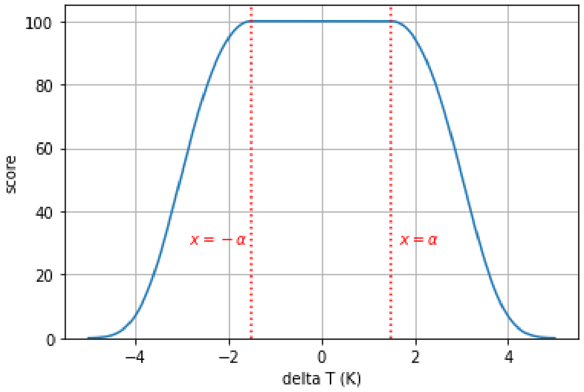

**Fig. 3.** Shape of the scoring function used, with the local setpoint located at delta T = 0 and the HS and CS on the left and right red dotted lines respectively.

To compare the static and dynamic methods, it is important to consider the time people are expected to be there; otherwise, the static methods will evaluate many hours outside of normal working hours, while the dynamic methods will mainly include normal working hours, generally causing the static methods to look much better than the dynamic methods falsely.

The in-use hours were therefore assessed for three different cases, a) classic Danish working hours (8-16), b) a Danish guideline used for dimensioning of office buildings (7-17) [10], and 3) optimized in-use hours based on the PIR measurements (7-15). It was found that the choice of in-use hours had little impact on the results between the methods, but in general just added an almost constant offset when assessed over longer periods. It was therefore chosen to proceed with 8-16 as the in-use hours. For each timestep (*t*) during in-use hours, the following calculations are made to aggregate the local scores of individual rooms (*LS*) into the global score (GS):

$$GS_{Mean} = (LS_{1,t} + \ldots + LS_{p,t})/N \tag{3}$$

$$GS_{Area} = (A_1 \cdot LS_{1,t} + \ldots + A_p \cdot LS_{p,t})/\Sigma_1^p A_p \tag{4}$$

$$GS_{Desk} = (D_1 \cdot LS_{1,t} + \ldots + D_p \cdot LS_{p,t})/\Sigma_1^p D_p \tag{5}$$

$$GS_{PIR} = (PIR_{1,t} \cdot LS_{1,t} + \ldots + PIR_{p,t} \cdot LS_{p,t})/\Sigma_1^p PIR_{p,t} \tag{6}$$

$$GS_{PIR\_Desk} = (PIR_{1,t} \cdot D_1 \cdot LC_{1,t} + \ldots + PIR_{p,t} \cdot D_p \cdot LS_{p,t})/ \Sigma_1^p PIR_{p,t} \cdot D_p \tag{7}$$

$$GS_{Camera} = (C_{1,t} \cdot LS_{1,t} + \ldots + C_{p,t} \cdot LS_{p,t})/\Sigma_1^p C_{p,t} \tag{8}$$

where:
*N* is the number of rooms; *A* is the floor area of a room; *D* is the number of fixed working spaces in the room; *C* is the number of people present in the room.

## 4 Results

The GS of the thermal performance in the analysed zone consisting of six offices is presented in Table 2. The results are divided into three periods, to reflect the impact of the outdoor temperature on the global score. On one hand, during the 14 days in March 2023, with a mean outdoor temperature of 2.7 °C during the in-use hours, all six methods gave the same GS results of 100. It means that the HVAC system can maintain the heating setpoints in each room for the in-use hours. On the other hand, during June 2023, which was the warmest month with a mean outdoor temperature of 20 °C during in-use hours, the difference between the six methods was visible, with the simplest method *Mean* having the highest GS and the most complex dynamic method *Camera* the lowest GS. The difference was six points.

The static methods and dynamic methods were grouped around the same GS. The analysis of the full dataset, including six months, presented the same pattern as the summer period. The maximum difference between the static methods was 0.5 points, which is negligible and indicates that additional information on the rooms' size and number of working stations did not impact the GS. This may also be due to the rooms similarity in size and desks. Among the dynamic methods, a distinguished difference was noticed between the *Camera* method and *PIR* and *PIR_Desk* methods. The two later methods gave almost the same result, indicating that for the given case study the HVAC system provides good thermal performance when the room is partly and fully occupied. The three dynamic methods do not account for the utilisation of the rooms (i.e. ratio of the actual number of occupants to the number of working stations (maximum occupation). This aspect could be the potential next step of the presented methods, yet currently, only the Camera method provides inputs enabling the calculation of this ratio.

Figure 4 shows that the dynamic methods were consistently lower during the first 40% of the analysed period, and then stabilised during the following 20% of the timeframe. All methods achieved GS equal to 100 for over 40% of the total calculation period. The *PIR*, *PIR_Desk* and *Camera* methods did not reach 100% on the x-axis. This occurred because rooms were empty even during in-use hours and these hours were excluded from the calculation of the GS. However, another approach could be that for the hours when no one occupies the room, the $LS_{PIR}$ equals 100, as maintaining a good room temperature in unoccupied spaces is unnecessary. The images from the installed cameras were only available for approximately 280 hours between March-August 2023, which corresponds to approximately 35% of the total in-use hours during the six months. It is worth mentioning that for allmethods, there were hours where the HVAC system was unable to meet the local setpoints (GS<100). These hours took place primarily during periods with high outdoor temperatures.

**Table 2.** Global score calculated by the six methods.

| **Method** | **8th-21st March** | **1st-30th June** | **March-August** |
|---|---|---|---|
| Mean | 100.0 | 57.6 | 83.1 |
| Area | 100.0 | 56.8 | 82.9 |
| Desk | 100.0 | 57.5 | 83.4 |
| PIR | 100.0 | 53.0 | 79.4 |
| PIR_Desk | 100.0 | 53.1 | 79.9 |
| Camera | 100.0 | 51.6 | - |

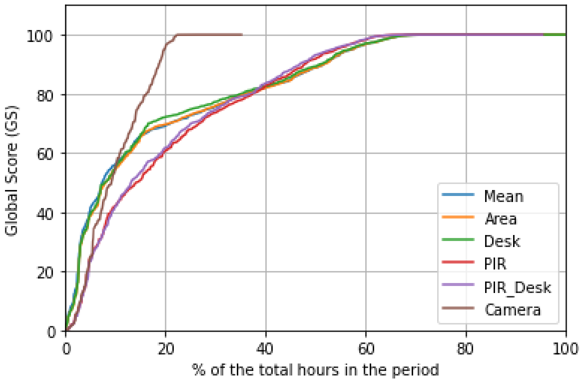

**Fig. 4.** Cumulative distribution of hourly GS for six methods during March-August.

### 4.1 The impact of the in-use hour, occupation level and outdoor temperature

The *Mean* and *PIR* methods were selected to investigate the impact of the occupation level and outdoor temperature. These two methods were selected due to their similarity to the Area and Desk, and PIR_Desk methods, respectively.

Figure 5 shows clearly that the difference between the two methods was the smallest when all rooms were occupied since, in this situation, the number of inputs for GS calculation was the same for both methods. It is also clear that when outdoor temperature is above 10 °C the HVAC system cannot meet the local setpoints. The difference between these two methods was the biggest when outdoor temperature is high and only one room is occupied.

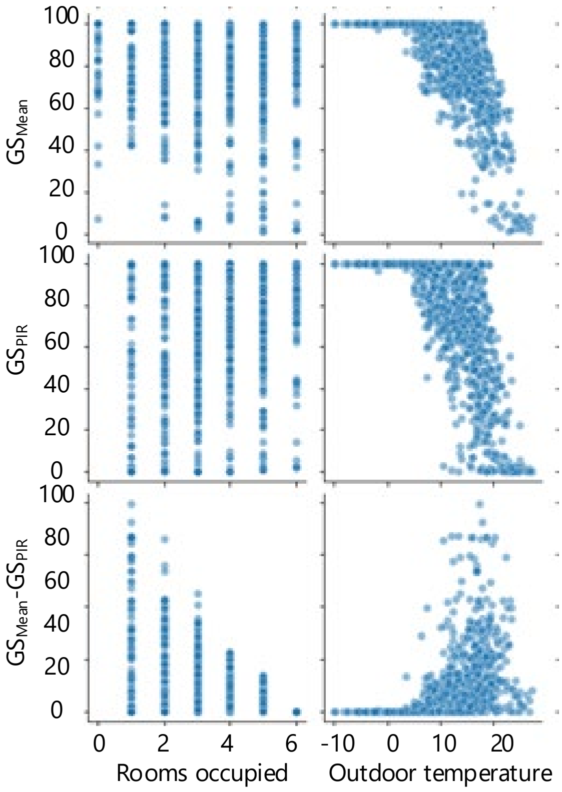

**Fig. 5.** Scatter plots of the outputs with respect to some input variables.

### 4.2 The impact of timeframes

This section describes how the GS changes when looking on the GS results in various resolutions. The *Mean* method has been selected as the reference method to identify any significant variances in comparison.

Figure 6 shows that both the static and dynamic methods behaved similarly. It was noticeable that as the time frame decreases, the values tend to increase significantly. However, upon examining the boxes containing most of the values between the 1st and 3rd quartile, it was evident that the *Area* method consistently remains close to the *Mean*. This indicated that the selected rooms possess areas of similar sizes and exhibit similar behaviour most of the time. The *Desk* method showed a slightly larger difference compared to the *Area* method. Moreover, the *Area* method yielded to lower GS results while the *Desk* method had the opposite results. In all cases, both results remain within a 1.5-point difference. On a daily timeframe, the difference went up to a 5-point variance. Since the difference between various timeframes for the static methods is neglectable, computing the average may be sufficient to obtain a meaningful result for the building.

For the dynamic methods, a shorter time frame yielded larger differences.

Overall, the interpretation is that the longer the timeframe examined, the more similar the results become. Looking at the complete dataset, the difference is only a distance of five points. Therefore, it is crucial to calculate results over a shorter time frame to reveal any differences or Or the choice of method is mainly important, when the goal is to evaluate performance during a short time frame

## 5 Conclusions

This work investigated six methods, three static and three dynamic, to aggregate the local thermal performance score (LS) in office spaces to a global thermal performance score (GS) at the building or zone level. In the study thermal performance was defined as the ability of the HVAC system to meet the local heating or cooling setpoints specified for each room. Data from six rooms in a campus building of Aalborg University were used.

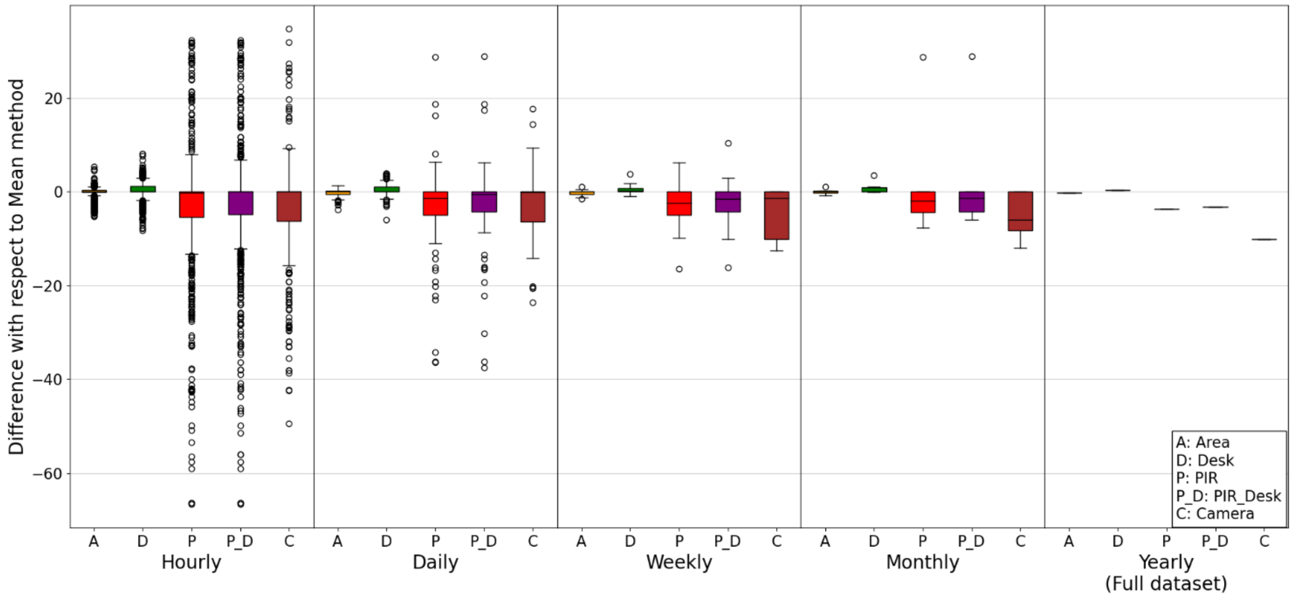

**Fig. 6.** GS difference on various time frame basis.

As anticipated, a notable disparity emerged between static methods, which rely solely on fixed parameters, and dynamic methods, which account for time-varying factors over short timeframes. Dynamic methods consistently yielded lower global scores, irrespective of individual room performance. The difference can be up to 15% monthly. The reason is that the dynamic methods better capture the extreme values as they are not averaged out by non-occupied rooms. The PIR sensors, which are now commonly used in office or education buildings to control artificial lighting are a good indication of the occupancy (only present and not present). The indication of number of occupants at this stage of analysis does not provide significantly better results.

Within the realm of dynamic methods, the *PIR* approach demonstrated adequacy in reflecting actual room occupancy. When compared to the *Camera* method, the PIR method exhibited sufficiently close results, warranting its consideration as a viable occupancy assessment tool. Although the *PIR_Desk* method, which does not necessitate additional information, provided comparable outcomes, it did not enhance the GS precision. Thus, the PIR method appears to suffice, offering a balance between effectiveness and resource efficiency, particularly when contrasted with camera-based alternatives.

This work is a first attempt to calculate a global score of one of the IEQ categories, namely thermal performance, for a zone of entire office building. The next step is to apply these results to a full size building and expand to other IEQ categories.

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