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Spatial distribution of thermal comfort and work performance in a naturally ventilated auditorium

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ABSTRACT

The air temperature, relative humidity, perceived indoor air quality assessed by the occupants, the predicted percentage of dissatisfied, and work performance were examined in a naturally ventilated auditorium. The reliability of air quality assessments, typically conducted at a single location within the premises, has been questioned due to the spatial distribution of the measured parameters. Based on the obtained results, new calculation models for evaluating the acceptability of indoor air quality and relative work performance are proposed.

Keywords: indoor air quality, acceptability, percentage of dissatisfied persons, relative work performance.

INTRODUCTION

Indoor environmental quality (IEQ) is a crucial factor in all types of premises where people spend time, particularly those intended for creative and intellectual activities. Classrooms and auditoria in educational buildings are clear examples of such environments. Their indoor conditions must ensure good air quality as well as thermal, visual, and acoustic comfort to support effective learning for students and efficient work for teachers (Buratti et al., 2018; Astolfi et al., 2020). However, obtaining accurate and comprehensive information about IEQ remains challenging due to its dynamic nature and the complexity of measuring multiple interrelating factors.

Thermal comfort is primarily influenced by physical parameters such as indoor air temperature, radiant temperature, relative humidity, and air velocity, as well as personal factors, including activity level and clothing insulation (Fanger, 1982).

Typically, overall thermal comfort is assessed using the PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) indices, which refer to, respectively, the average thermal sensation of a large group of people and the proportion of individuals likely to express strong dissatisfaction with the thermal conditions – usually feeling either too cool or too warm in a given environment. Discomfort may also result from local thermal effects such as unwanted cooling or heating of specific body parts due to drafts, radiant temperature asymmetry, vertical temperature gradients, or cold and warm floor surfaces (EN ISO 7730, 2005).

Over the past two decades, numerous studies have been conducted to understand the impact of the indoor environment on human well-being, work performance, and learning efficiency. For example, Seppänen et al. (2006), based on literature data, investigated the impact of indoor air temperature on office work performance. They analyzed changes in objective indicators of work performance efficiency as temperature increased. Meanwhile, Sarbu and Pacurar (2015) assessed thermal comfort in air-conditioned lecture rooms based on the PMV and PPD indices, both through subjective evaluations and measurements of the parameters influencing these indices. They also measured CO_2 concentrations and developed a predictive model of academic performance for different indoor environmental conditions. Wargocki et al. (2019) presented a meta-analysis of published evidence on the impact of thermal conditions in classrooms on students' performance. The performance indicators included psychological tests measuring cognitive abilities and skills, mathematical and language tasks, and assessments of learning progress, such as end-of-year examinations. Lan et al. (2022) conducted a study analyzing how thermal comfort conditions, created by adjusting clothing and air velocity in rooms with different indoor air temperatures, affected subjects' cognitive performance. Lin et al. (2025) conducted research to determine optimal temperature values for typical office environments through a systematic review and meta-analysis. They also analyzed temperature set-point selection for heating and cooling in office buildings, which affects both user performance and energy consumption.

To date, no quantitative predictions exist regarding thermal conditions and work efficiency. There is also no universal formula for determining the impact of the assessed acceptability of perceived air quality on productivity or cognitive performance (Kalkis et al., 2024). Both the literature and our research indicate that the method of assessing IAQ is of significant importance. It is commonly evaluated at a single point in the room (ASHRAE, 2021; Cirone et al., 2024). As shown by Sahu and Gurjar (2020), Mahyuddin and Essah (2024), and Qian et al. (2025), air quality varies significantly across different areas of a room and is influenced by multiple factors, such as the presence and activity of occupants. This inhomogeneous distribution of IAQ within a room should be taken into account when controlling ventilation or air conditioning (Polednik and Dudzińska, 2010).

The aim of this study is to evaluate the spatial heterogeneity of indoor environmental parameters and to quantify the acceptability of indoor air quality and relative work performance in a naturally ventilated auditorium. Furthermore, the study proposes a time- and cost-efficient method for assessing IAQ acceptability and predicting cognitive and work-related productivity among room users.

RESEARCH METHODS

Measurements of indoor temperature, relative humidity, and IAQ assessments were carried out in the auditorium of the Faculty of Environmental Engineering at Lublin University of Technology (LUT) in Lublin, Poland. The auditorium has a floor area of 300 m^2, volume of 1200 m^3, and 186 seats. The air-conditioning system was switched off during the measurements. Neither the ventilation conditions nor air distribution were assessed. The auditorium was divided into nine measurement sectors (Polednik and Dudzińska, 2010), with their locations shown in Figure 1. Temperature and relative humidity sensors were placed at a height of 110 cm above the floor. Between 4 and 12 students (with an average of 9) were seated in each sector and asked to assess the IAQ immediately upon taking their seats. The students evaluated the acceptability of indoor air quality using an analog scale ranging from -1 (clearly unacceptable) to +1 (clearly acceptable). Three measurement series were conducted, each involving different groups of students assessing the indoor air quality. A total of

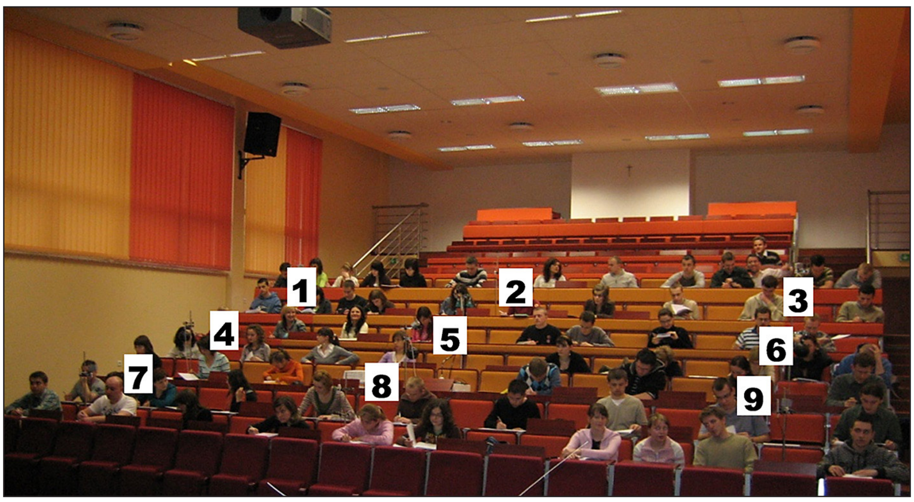

Figure 1. Location of the measurement sectors in the auditorium

162 students participated in the study. The collected data were essential for evaluating relative work performance. The determination of relative work performance (RWP), productivity loss (PL) and the percentage of dissatisfied room users (PD) was presented in a previous study.

The relative work performance affected by IAQ acceptability (RWP_A) was determined using the following formula:

$$RWP_A = 0.0983\,ACC + 0.926 \tag{1}$$

where: ACC is the average value of IAQ at a given temperature, computed from the IAQ(T) regression curve.

Productivity loss which is an associated parameter was calculated as follows:

$$PL = 1 - RWP_A \tag{2}$$

The following equation was used to estimate the relationship between the percentage of dissatisfied room users and the ACC:

$$PD = 100\left(1 + exp(3.15\,ACC + 0.043)\right)^{-1} \tag{3}$$

RESULTS

The indoor air temperature and relative humidity in the individual auditorium sectors, measured at the beginning of the lectures across three measurement series is shown in Figure 2.

The air temperature varied between sectors in each measurement series. Its average values in the three series were 19.9 °C, 21.3°C, and 22.0 °C, respectively. The standard deviation (SD) was approximately 0.4 °C, and the coefficient of variation was 0.02. The indoor air relative humidity (RH) in the three measurement series was 48.5 ± 3.9%, 51.7 ± 3.5%, and 42.6 ± 2.7%, respectively (mean ± SD). The average coefficient of variation was 0.07. Notably, RH systematically decreased across consecutive sectors, with a gradient of 1.2% RH per sector. The average air velocity was 0.08 m/s.

Figure 3 shows acceptability of indoor air quality values obtained in this study, alongside data from Lan et al. (2011), Wargocki et al. (2004), and Liu et al. (2019) at different air temperatures.

The relationship between the acceptability of indoor air quality and indoor air temperature, as established based on these data, can be expressed by the following equation:

$$ACC(T) = -0.0974\,T + 2.593 \tag{4}$$

Figure 4 presents the computed ACC(T), the evaluated ACC, and the PD values in the individual sectors for the three measurement series.

The fluctuations in the assessed ACC values are represented by their standard deviation values. The data indicate that the assessed ACC values exhibited greater fluctuations compared to those computed based on air temperature (ACC(T)). In several auditorium sectors, the obtained ACC results differed significantly from the ACC(T). However, the average values of both were nearly identical within each measurement series (Table 1).

PD in the individual sectors ranged from approximately 5% to 50%, with higher values typically observed in the boundary sectors.

The expected work performance and productivity losses, influenced by the acceptability

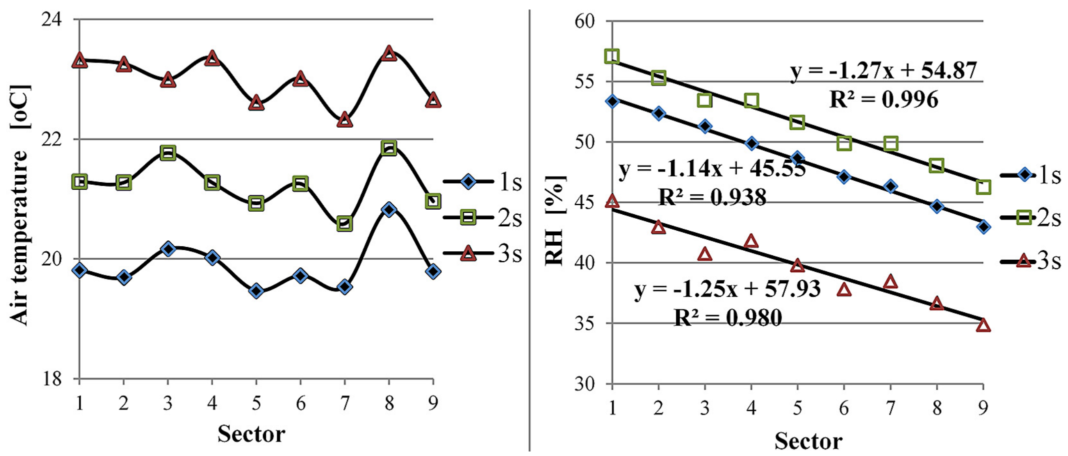

Figure 2. Indoor air temperature and RH in the individual auditorium sectors obtained in three measurement series (1 s, 2 s, 3 s)

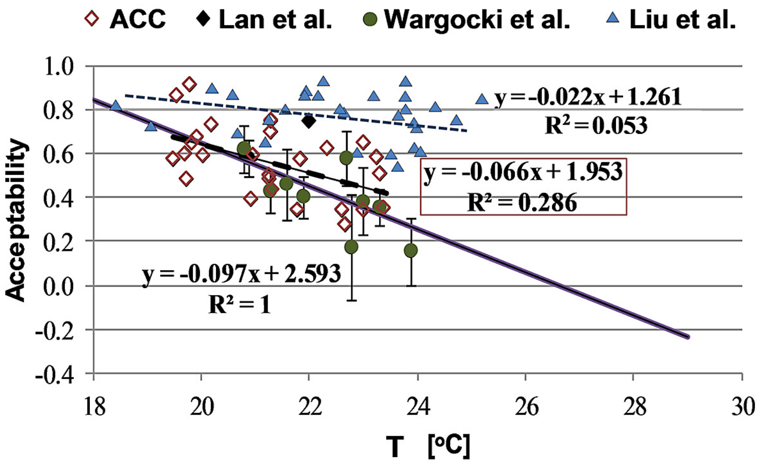

Figure 3. Acceptability of indoor air quality vs. indoor air temperature

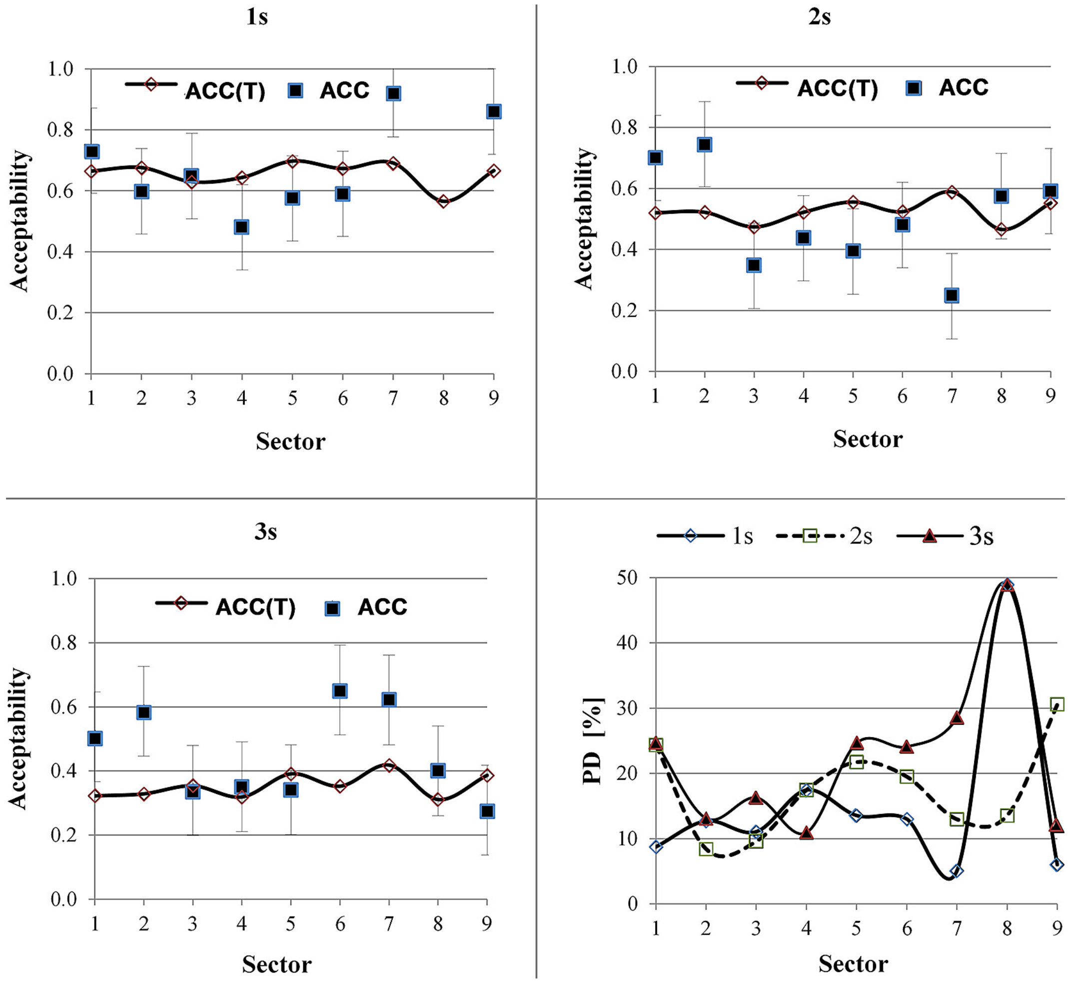

Figure 4. ACC(T), ACC, and PD in the individual auditorium sectors

of indoor air quality in the individual auditorium sectors, are shown in Figure 5.

In accordance with Equation 1, the RWP_A is equal to 1 when the ACC reaches 0.75. The 95% confidence interval for the determined RWP_A values in the individual auditorium sectors was 0.032. The PL variations reached up to approximately 4%, with coefficients of variation ranging from 0.42 (3 s) to 0.7 (1 s). The average PL values were 0.013, 0.015, and 0.017,

Table 1. Average and standard deviation (SD) values of computed ACC(T) and assessed ACC

Measurement series	ACC(T)	SD	ACC	SD
1 s	0.66	0.04	0.68	0.15
2 s	0.52	0.04	0.50	0.16
3 s	0.35	0.04	0.46	0.15

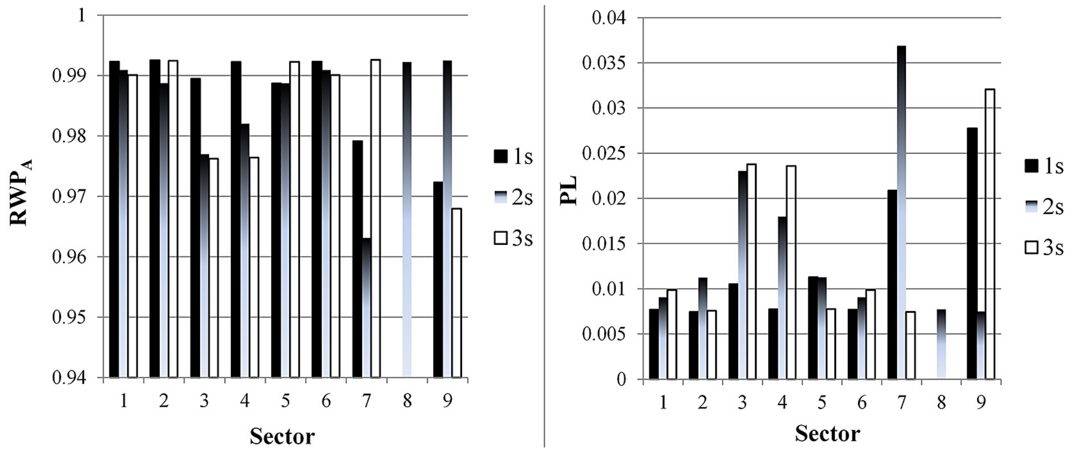

Figure 5. Relative work performance (RWP_A) and productivity losses (PL) affected by the acceptability of indoor air quality in the individual auditorium sectors, obtained in three measurement series (1 s, 2 s, 3 s)

with maximum ranges of 0.02, 0.03, and 0.025 in the first, second, and third measurement series, respectively.

DISCUSSION

The presented results indicate that environmental parameters and IAQ vary across different sectors of the auditorium. Therefore, measuring these parameters and assessing IAQ at a single point cannot provide fully representative results for the entire space (Mui et al., 2006; Khiavi et al., 2025). The method employed in this study allows for the effective determination of ACC, RWP, PL, and PD. The relationship between the acceptability of indoor air quality and temperature ACC(T), as described by Equation 4, is particularly relevant for clean air with no significant chemical pollutants and for RH levels ranging from 34.9% to 57%. These conditions are commonly encountered in typical public spaces, such as classrooms, offices, or cinemas. The calculated ACC(T) values are, for example, consistent within the empirical error (SD) with the ACC values assessed by Wargocki et al. (2004) in six office buildings and a department store. Larger differences between the assessed ACC and the calculated ACC(T) occur when thermal conditions fall outside the specified range. For instance, the results obtained by Lan et al. (2011) in an office room showed differences of up to 0.45, indicating a significant variation in the perception of air quality. However, the air RH in that room was about 22%, and the temperature ranged from 22 °C to 32 °C. Such significant differences could be attributed to the low humidity of the air assessed in the office at that time. The sensitivity of ACC to changes in RH was -0.021/% RH. On the other hand, the results obtained by Liu et al. (2019) in naturally ventilated classrooms indicated no significant correlation between ACC and temperature.

The regression analysis of ACC(T) in this study suggests that the indoor air temperature can be considered as a kind of pollutant. However, this regression can only explain the perception of air quality to a limited extent. The acceptability determined from it does not indicate the required IAQ. RWP and PD are better suited for this purpose. RWP can be calculated based on indoor air temperature using the relationship provided by Seppänen et al. (2006), cited by, e.g. Fisk et al. (2011) and Wargocki et al. (2019). This relationship can be linked to the acceptability of indoor air quality through Equation 4. It is important to note that this approach does not account for the influence of other factors, including the impact of chemical pollutants in the indoor air. Moreover, RWP_A, influenced by the acceptability of indoor air quality according to Equation 1, was determined based on tests measuring text processing speed and simple calculations at acceptability levels of 0.75 and -0.125 (Bako'-Biro et al., 2004; Lan et al., 2011). A change in work performance of 8.9 ± 0.36% can be achieved by increasing the acceptability of clean air through lowering its temperature. In turn, increasing air acceptability by reducing the concentration of chemical pollutants results in an 8.8% change in work performance. The nearly identical values of these changes suggest that the applicability of Equation 1 is independent of the nature of the air pollution.

The relationship between the work performance influenced by the perceived air quality (RWP_A) and the relative work performance influenced by the air temperature (RWP_T) in relation to ACC is shown in Figure 6.

The diagram also presents measurement results from Lan et al. (2011), which align closely with the formula proposed by Seppänen et al. (2006). The RWP_T values between the two marked points are always higher than the RWP_A values. These differences are not noticeable to the room occupants, as they fall within the 95% confidence interval of RWP_A, meaning they are statistically insignificant for occupant perception. To avoid any uncertainties, it is suggested to conduct a test appropriate to the activity of the room occupants. It should also be noted that recent doubts have arisen regarding the Seppänen et al. (2006) model, as well as criticism of its use for predicting the impact of temperature on work performance due to its allegedly low predictive power (Porras-Salazar et al., 2021). Nevertheless, many studies confirm the significance of the relationship between productivity and air temperature. For example, research conducted by Kaushik et al. (2020) confirmed the dependence of office worker productivity on various environmental factors, including indoor air temperature. Geng et al. (2017) showed that, based on research conducted in an office with a controlled environment, optimal productivity was obtained when people felt "neutral" or "slightly cool", and an increase in thermal satisfaction had a positive effect on productivity. Conversely, the results of the Lan et al. (2020) study suggest that elevated temperatures, even when thermal comfort is achieved through appropriate clothing adjustments by room occupants, can lead to a decrease in their performance. Furthermore, the latest research by Lin et al. (2025) showed that in an office with a typical temperature range from 17 °C to 30 °C moderately elevated temperatures above 25 °C had a significantly negative impact on work performance, while moderately lowered temperatures below 21 °C had no significant impact. When it comes to schools, research conducted by Maciejewska and Szczurek (2025) confirmed that monitoring air in classrooms provides information that enables a qualitative assessment of classroom conditions, which in turn allows for the estimation of short-term student work efficiency.

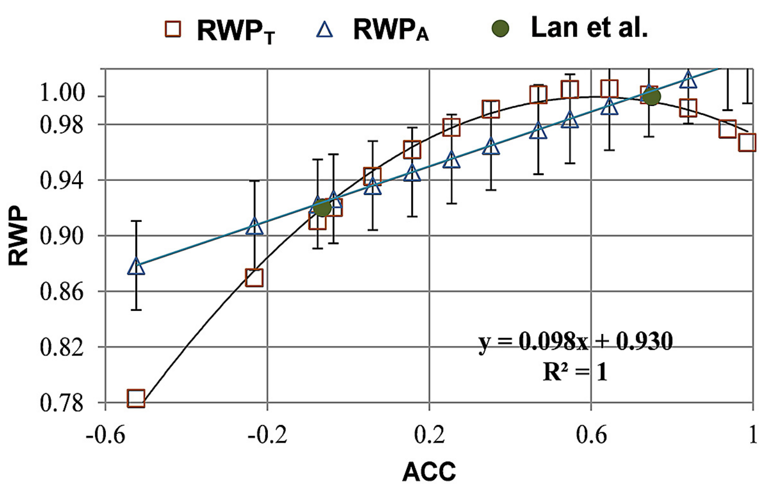

Figure 6. Relative work performance vs. acceptability of indoor air quality. RWP_T is relative work performance influenced by air temperature and RWP_A is relative work performance influenced by the acceptability of the air quality

In summary, the findings presented in this study are expected to enhance the understanding of how thermal comfort affects room users' wellbeing, as well as their cognitive and work performance. The developed predictive model may be implemented by HVAC systems to enable effective indoor air quality control that addresses the needs of room users.

CONCLUSIONS

The presented study revealed that:

1. Indoor air parameters that affect the IAQ and work performance varied across different sectors of the auditorium. The described methods allow for indicating spots with relatively low IAQ, which adversely affect work performance and student comfort. The obtained results indicated that the indoor parameters and the acceptability of the indoor air quality cannot be determined in only one selected spot, as such results would not be representative for the entire room.
2. The similarity between the computed ACC(T) and assessed ACC in two different cases is a strong indication that human perception may be considered objective.
3. The percentage of dissatisfied room users appears to be a useful, direct indicator of perception, which is influenced by indoor air parameters.
4. The significant impact of the acceptability of indoor air quality on relative work performance suggests that tests results adjusted to the activity in a room could serve as a good IAQ indicator.
5. The proposed method for predicting the acceptability of indoor air quality, as well as the cognitive and work performance of room users, can be applied to the selection and effective control of indoor environmental parameters.

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