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# Thermal Comfort in Existing Naturally Ventilated University Classroom: Validation of Measured Values by Simulated Values through BIM

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## ABSTRACT

In today's world, it is necessary to conserve energy while maintaining a comfortable and healthy indoor climate in buildings. In tropical climates, individuals are exposed to longer durations of discomfort and a higher chance of developing health problems in buildings. The indoor thermal settings of a building have a significant impact on inhabitants' health, productivity, and learning abilities. The study sought to validate the measured results of the existing naturally ventilated university classroom through parametric modeling and Computational Fluid Dynamics (CFD) simulation. The study compared the simulated results to the measured or experimental results to validate the accuracy of the building model created in Autodesk Revit. In Ghana's Ashanti Region (Kumasi), experimental measurements were carried out between November and April 2023, during the dry season, and between May and October 2023, during the wet season. Data loggers (Testo data loggers) were used to capture data continuously for 24 hours. The indoor measured data and the indoor simulated results were compared. A comparison of the building model data and the existing building conditions was made to reduce errors. Classrooms $ASB_{GF, FF,}$ and $_{SF}$ recorded a difference of 0.15ºC, -1.52ºC, and -1.77ºC between measured and simulated values with a percentage difference of 0.48%, 5.12%, and 5.82% for the dry season and -1.43ºC, -0.09ºC, and 2.46ºC with a percentage difference of 5.60%, 0.30%, and 8.50% for the wet season. Negative values indicate that the measured data was higher than the simulated data. The dry season values were higher than the wet season values, and this was realized across all the measured and simulated parameters except the air velocity, which recorded higher dry season values for the simulation as compared to the measured values. The study concluded that the indoor space of the studied building was slightly warm, with a 43.66% discomfort level during the dry season, and cool with a 24.89% discomfort level during the wet season. The study recommended that architects should assess the thermal comfort conditions of existing university classrooms to ascertain the building's comfort level for retrofitting. The study recommended that architects should use parametric building models for a whole building simulation to validate the measured thermal comfort of existing buildings for retrofitting.

**Keywords:** Thermal comfort, Natural Ventilation, Simulation Values, Measured Values, Parametric and Classroom.

## INTRODUCTION

In today's world, it is necessary to conserve energy while maintaining a comfortable and healthy indoor climate in buildings (Aflaki et al., 2021; Amin et al., 2015; Lingua et al., 2019). Many countries throughout the world are still dealing with difficulties of internal and external temperature discomfort, which has emerged as a result of constant urbanization, climate change, and other factors (Ahadzie et al., 2021; Koranteng, 2021; Mensah & Ahadzie, 2020). Both the design and evaluation procedures of a building must take into account occupants' perspectives, expectations, and wishes (Ahadzie et al., 2021; Ko et al., 2020). In tropical climates, individuals are exposed to longer durations of discomfort and a higher chance of developing health problems in buildings (Cheng et al., 2022; Johansson et al., 2018; Ochedi & Taki, 2022; Oliveira & Corvacho, 2021). The indoor thermal settings of a building have a significant impact on inhabitants' health, productivity, and learning abilities (Geng et al., 2017; Jastaneyah et al., 2023; Krajcík et al., 2012; Tronchin et al., 2018). Poor air distribution within a building (classroom) can result in a variety of problems, including uncomfortable temperature stratification, airflow short-circuiting, and draft discomfort (Jurelionis et al., 2016; Krajcík et al., 2012; Shao et al., 2017). Thermal discomfort in classrooms can create restlessness, distraction, headaches, and weariness in occupants, all of which can reduce productivity (Ahadzie et al., 2021; Roelofsen, 2002). The indoor thermal conditions of a classroom, according to Ephraim (2020) and Jastaneyah et al. (2023), significantly impact students' learning capacity. High levels of air temperature in classrooms diminish the mental and physical performance of a person, which is an issue in tropical areas (Jastaneyah et al., 2023; Johansson et al., 2018). According to Haddad (2016) and Jastaneyah et al. (2023), classrooms need to be thermally pleasant because occupants spend more time there. During periods of high thermal load, elevated air temperature is a common concern in most school classrooms; nonetheless, it may result in a decrease in students' academic performance (Bayoumi, 2021).

Some studies have proposed suggestions for planning for better thermal conditions (Alghamdi et al., 2023; Mba et al., 2022; Olgyay et al., 2016; Waseem & Talpur, 2021; Widera, 2021; Xu et al., 2021; Zoroğlu Çağlar & Zorer Gedik, 2022). Olgyay et al. (2016) suggested a comfort range for tropical circumstances of 23 $^{o}$C to 29 $^{o}$C with a relative humidity of 30% to 70% for indoor conditions of classrooms. However, Rahadian and Sulistiawan (2020) suggested that the comfortable temperature of buildings in tropical areas ranges between 18 $^{o}$C and 29 $^{o}$C, with a maximum humidity of 80%. Rahadian and Sulistiawan (2020) also recommended that the indoor air velocity of classrooms should not exceed 1.5 m/s. The recommended temperature range for summer comfort in classrooms is 23 $^{o}$C to 26 $^{o}$C according to ANSI/ASHRAE standard 55-2005 (Mora & Bean, 2018). The study, therefore, sought to validate the measured results of the existing naturally ventilated university classroom through parametric modeling and CFD simulation.

## LITERATURE REVIEW

### Thermal Comfort and Natural Ventilation

High humidity will limit the amount of heat that can be absorbed by the skin through evaporation, which will make it uncomfortable and lower the thermal comfort threshold in hot and humid conditions(Cheng et al., 2022; Kajjoba et al., 2022; Mba et al., 2022). However, accelerating the airflow around people can enhance the skin's evaporative heat loss by replacing the humid, saturated air surrounding the skin with fresh, unsaturated air (Singh & Holla, 2021; Zhai et al., 2015). Thus, occupants may benefit from increased airflow speed in terms of thermal comfort (Babaoglu et al., 2022; Cheng et al., 2022; d'Ambrosio Alfano et al., 2020).

### Thermal Comfort Threshold in Hot and Humid Climates

Dankyi and Koranteng (2012) conducted a field investigation on the thermal comfort of instructors and pupils at St. Andrews Junior High School in Madina, Accra. The building was selected because the school was designed and built using sustainable design concepts, such as shape, orientation, and ventilation. A noteworthy finding of the research was that, with a 2°C difference in temperature, classrooms on the first floor had a greater temperature than those on the ground floor. Because there was no ceiling, the temperature in the classrooms on the first floor was higher. Furthermore, even though the vast majority of respondents approved of the overall thermal conditions, some of them continued to vote below the ASHRAE criterion of 80% of occupants voting positively for thermal comfort (Dankyi & Koranteng, 2012). Using Fanger's PMV and PPD models, Barbara et al. (2014) conducted an assessment of thermal comfort in multi-story Accra office buildings that are both naturally and mechanically ventilated. The model is based on ISO 7730 and the American Society of Heating, Refrigerating, and Air Conditioning (ASHRAE) Standard 55, which specifies a 23° to 26°C permissible temperature range. For ten months, the temperature and relative humidity of four multistory office buildings were monitored indoors. The PMV-PPD values were produced by the analysis of the environmental parameters with PMVcalc v2 software. The study found that while mechanically ventilated buildings are within the comfort zone, naturally ventilated buildings have high PMV-PPD values (Barbara et al., 2014).

A study was conducted to determine how much thermal stress exists both indoors and outdoors to develop a four-stage plan to lessen overheating in areas of Ghana that are exposed to the Savannah climate by Koranteng et al. (2021). Based on physiologically equivalent temperature (PET), overheated assessment, residents' subjective thermal responses and evaluations, and a simulated attempt to enhance comfort, a thermal comfort analysis was conducted. On the coolest day, the study discovered "mild to modest cold stress" (28th December). However, the indoor environment saw excessive and severe overheating of at least 56% and 38-degree hours on the warmest day of the year, April 12. The thermal sensation survey found that the research area's building occupants' tolerable comfort temperatures and range were 25.5–33 °C. In the meantime, the simulation demonstrated that an 18% decrease in overheated hours might be produced by a 200% increase in thermal mass, exterior wall insulation, and roof extension and insulation (Koranteng et al., 2021).

## Parametric Modeling for Natural Ventilation

Due to the substantial impact on the environment that buildings' energy consumption has on the environment, designers must pinpoint where improvements can be made in an early design phase to optimize their energy performance. This is, on the other hand, a very complex assignment due to a large number of parameters that are involved in the energy performance of the buildings. Such parameters may be material properties, geometry, weather data, user behaviours, and so forth. In this stage, there is a lack of easy-to-handle tools that can be used by architects and engineers to explore the design alternatives that exist (Mousiadis & Mengana, 2016).

## Natural Ventilation System Analyses and Optimization Using BIM

According to Autodesk (2012), BIM software can be used for the analysis of natural ventilation systems and optimization to reduce building energy use as well as to raise a building's thermal comfort level. Built on the key effects of building occupancy and equipment, BIM software can estimate the potential capacity for natural ventilation to handle the heating and cooling loads of buildings. Lu et al. (2017) observed that BIM software helps users evaluate the feasibility of using natural or mixed modes of ventilation strategies based on the predicted results. Examples include one-sided ventilation, cross-ventilation, whole-building ventilation, chimneys, and opening controls. Such an evaluation of the ventilation strategies can assist users in selecting a reliable mechanical ventilation system for the target project.

## Thermal Comfort Analyses Using BIM

Green buildings are only effective when the occupants in the buildings feel comfortable, which places much emphasis on the high importance of assuring thermal comfort in green buildings (Lu et al., 2017). According to ASHRAE (2013), thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation”. Six primary factors directly affect thermal comfort, including metabolic rate, clothing level, air temperature, mean radiant temperature, airspeed, and humidity. BIM applications can help in the evaluation of occupants' thermal comfort through the above primary factors (Fanger, 1970).

## BIM Data Capturing and Processing for Existing Buildings

BIM for existing buildings can be realized through modelling the data captured with a 3D laser scanner from the existing world. This can be achieved by employing appropriate automated data processing and pattern recognition techniques (Arayici, 2008). As mentioned by Hossain and Yeoh (2018), digital photogrammetry, terrestrial laser scanning, and ground penetration radar are the Current techniques used for as-built data acquisition for BIM creation. These data acquisition technologies have the typical function of capturing the geometric information of the object (building). Deveau (2006) mentioned Topometry as one of the techniques for data collection for the existing building, as far as BIM is concerned. Russhakim et al. (2019), argue that laser scanners may be influenced by several factors, which include: The existence of water and glass windows because the laser cannot penetrate through the water due to different densities; The laser can be refracted when contacted with the glass window; During the processing, skill and knowledge will be very important to ensure the dimension is accurate.

***Digital Photogrammetry:*** This technology converts the still images captured by a camera to generate 3D geometric information. In this technique of data acquisition, at least two cameras are placed away from the object with a known coordinate to create a 3D representation. This creates at least two converging lines to identify a point in space mathematically. This is a technique known as triangulation. The cameras should have coordinates (X, Y, and Z) with their corresponding angles of rotation (ω, ψ, and κ). Control points should also be identified in a real-world coordinate represented in all captured images. This will aid in the recognition of pixels in the images (Hossain & Yeoh, 2018).

***Unmanned Aerial vehicles (UAV or Drones):*** The Capturing of data needs to expand constantly with the incorporation of new technologies. For example, drones can be used to monitor the security and safety of large construction sites and are ideal for precise aerial surveying. Spatial data gathered by drones can be fed into the BIM model (Schober et al., 2017). According to Vacanas et al. (2015) and Hallermann and Morgenthal (2014), Unmanned Aerial Vehicles (UAVs) are pilotless airborne systems, controlled through ground control stations. Drones are a great platform to carry sensors and collect data. UAVs can be the independent eyes of a fully integrated BIM platform, substituting expensive, imprecise, and prolonged manual data collection. The means to collect data with a UAV can be separated into two main categories: laser-based LiDAR and visual, with either a monocular camera or stereo camera. In between these two solutions lies the RGB-D camera, like the famous Microsoft Kinect, providing both depth measurements and images (Dupont et al., 2017). Mutis and Romero (2018) observed that UAV is used in building inspection with infrared thermography. This technique was relied upon for inspecting a facade, determining thermal bridges, and quantifying their magnitude. Mutis and Romero (2018) concluded that, with baseline temperature values, this technique would assist the AEC industry in establishing subsequent retrofitting thresholds.

**CFD Approach in Whole Building Simulation Model**

Despite their complexity, CFD models are getting easier to use thanks to the market's availability of user-friendly solutions and the increasing expansion of computer power (Shirzadi et al., 2018). The basic equations of motion for individual fluid elements are solved by CFD at all points in a given space (Perez, 2017). To conserve the quantities of mass, momentum, energy, and turbulence, a set of partial differential equations is numerically solved.

**Validation of Simulated Building Models**

The process of validation entails modeling the test component, running simulations using measured meteorological data, and comparing the results to the measured test environment to make sure the model's predictions match the data over a realistic range of operating conditions that span a few days to a few weeks (Ramponi & Blocken, 2012). If it works, it assures that the simulation program can accurately represent the properties of the individual parts when included in a large-scale structure (Cheng & Das, 2014). By employing simulation in the experiment design, the procedure can be enhanced, and all significant influencing aspects can be measured. Defining the comparisons to be made, comparing measurements with model predictions, and modifying the model as needed is a more practical method. The simulation program is thought to be able to simulate a component's performance after it has been validated (Enescu, 2019). An absolute truth standard within the bounds of experimental uncertainty is made possible by comparing models to empirical data; nevertheless, using empirical data necessitates costly and time-consuming experimentation (Benzarti Ghedas, 2017). The ability to compare the model to the "actual" metering and auditing data makes empirical data a particularly potent validation tool (Yoon et al., 2020). Therefore, it is necessary to consider both the building's features (such as the HVAC, building materials, and architectural arrangement) and the occupants' behavior (such as the amount of cooling required and the additional power load caused by appliances) (Anand et al., 2017). The goal of the idealized validation studies for building energy models is to verify the engineering assumptions made in the models as well as the linked physics of the models (Piasecki et al., 2019).

Idealized test cells are frequently modeled in this situation. A test cell is normally made up of one room that is well sealed off from the outside world on all but one of its walls (Benzarti Ghedas, 2017). Building models are validated realistically by comparing them with auditing and metering data from real residential and commercial buildings (Chen et al., 2016). Furthermore, the design of structures and building energy models frequently assumes that the building's occupants will utilize it as intended, maintaining temperature setpoints, using passive day lighting controls, etc (Cheng, 2013). In actuality, building occupants are more concerned with their comfort and convenience than with energy conservation (Yoon et al., 2020). Furthermore, the operators of a building are not always as knowledgeable as designers assume them to be and, therefore, do not always operate the building in the way it was designed (Bostley, 2019).

# METHODS

This study presents an analysis of the current state of naturally ventilated university classrooms in Kumasi (Ghana) (hot and humid climate), assessing their current performance on indoor thermal comfort. To do so, on-site monitoring techniques were combined with building modelling through thermal comfort simulation tools and statistical methods for data processing, treatment, and analysis.

## The Studied Building and On-site Monitoring

The Faculty of Allied Sciences Block was selected for the study. The selected building was coded as Classroom ASB, and the individual classrooms that were studied were also coded as $Classroom_{GF}$, $Classroom_{FF}$, and $Classroom_{SF,}$ for the ground floor, first floor, and second floor, respectively. ClassroomASB is a 2-storey block with a North-South orientation. The building is rectangular with a total area of 780.50m². The entrance of the building is located at the end of the ground floor, as shown in Figure 1. The various floors are accessible via a staircase. The exterior fabric is made up of operable glass louver windows with external shading. The building operates natural ventilation. All the floors were monitored for the study, with one classroom per floor. The interior walls have the same dimensions and makeup. Concrete with a tile finish makes up the floors. The ceilings are composed of wood with tongue-and-groove wooden panels. The concrete floors above the last floor serve as the ceiling for all floors below. Aluminum sheets supported by timber trusses make up the roofing. Windows have glass louver blades, while doors and frames are made of wood.

The study compared the simulated results to the measured or experimental results to validate the accuracy of the building model created in Autodesk Revit. In Ghana's Ashanti Region (Kumasi), experimental measurements were carried out between November and April 2023, during the dry season, and between May and October 2023, during the wet season. Data loggers (Testo data loggers) were used to capture data continuously for 24 hours. The indoor measured data and the indoor simulated results were compared. A comparison of the building model data and the existing building conditions was made to reduce errors. The study tested the hypothesis that there are no statistical differences between the measured and simulated indoor thermal comfort of a naturally ventilated university classroom.

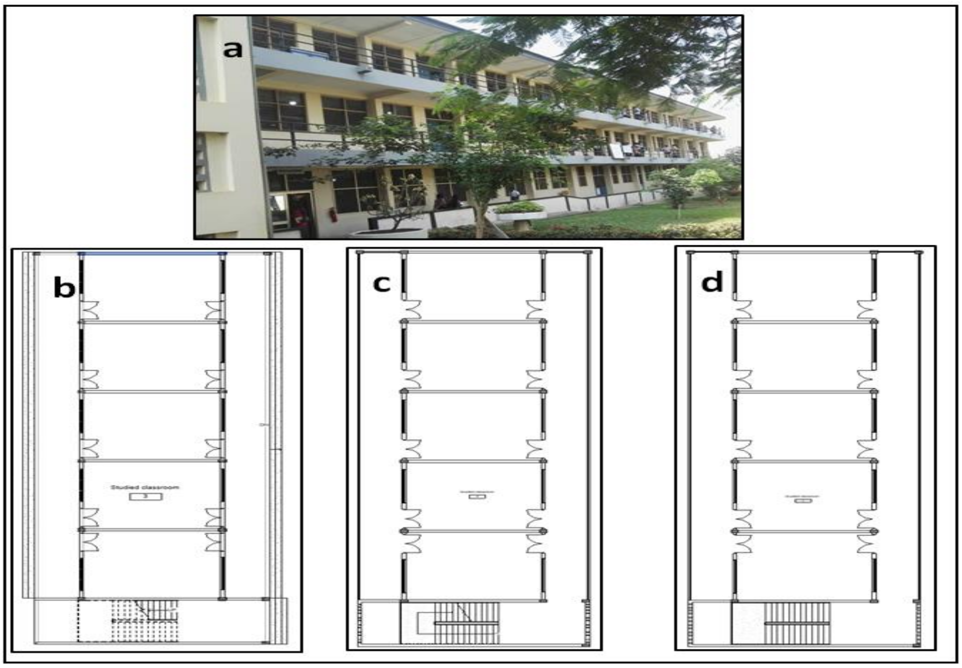


Figure 1 Exterior view (a), Ground floor plan (b), first-floor plan(c), and second-floor plan (d) of the ASB.

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### Building Model Calibration

#### Data Collection

Pertinent data regarding the building's shape, thermal characteristics, and occupancy trends were collected. Measurable data on indoor environmental parameters (temperatures, air velocity, relative humidity, radiant temperature, etc.) were measured using Testo devices.

#### Model Selection and Input

Autodesk Revit and Autodesk Ecotect software applications were selected for building modelling and simulation, respectively. Building geometry, thermal characteristics, and occupancy schedules were added to the model during the building modelling process.

#### Simulation and Comparison

The building model was simulated using Autodesk Ecotect, and the results (temperature and air velocity, relative humidity, and radiant temperature) were compared to the measured data (temperature and air velocity, relative humidity, and radiant temperature).

#### Parameter Adjustment

Important model parameters—such as infiltration rates, shading devices, and u-values were checked to see if they have a major influence on the simulation's outcomes, and necessary adjustments were made.

#### Iteration and Refinement

The study iteratively repeated steps 3 and 4 by modifying the parameters of the model in response to the discrepancy between measured and simulated data, until the model's performance fell within reasonable bounds.

#### Validation

To make sure the building model generalizes effectively and makes accurate predictions scenario, it is verified using a different set of data that was not used for the calibration.

## RESULTS

### Results on Measured Indoor Thermal Comfort

Four university classrooms with natural ventilation from two universities in Kumasi, Ghana, were studied. Table 1 summarizes the survey dates for the dry and wet seasons, classroom type, and ventilation type.  In each of the selected four buildings, three classrooms were selected based on levels (ground floor, first floor, and second floor). The thermal behavior of these three selected classrooms was studied. The ground floor, first floor, and second floor were coded as $\text{Classroom}_{GF}$, $\text{Classroom}_{FF}$, and $\text{Classroom}_{SF,}$ respectively, in the study.

Table 1 Summary of the Survey Dates for the Dry and Wet Season.

| Classroom type | Ventilation type | Survey date (2023) | Season |
|---|---|---|---|
| ASB | NV | November 10-23 (13 days) | Dry |
| | NV | May 24- June 8 (14 days) | Wet |

NV- Natural Ventilation

### Comparative analysis of environmental parameters within the ASB

As shown in Figure 2, indoor environmental parameters were assessed for the various classrooms under study within the ASB. With indoor air temperature, the Classroom $ASB_{SF}$ recorded the highest mean value of 32.20 ºC, which occurred on January 5th, 2023, during the dry season, and the Classroom $ASB_{SF}$ had the lowest mean value of 30.85 ºC, which was recorded on December 28th, 2023, during the dry season. Classroom $ASB_{FF}$ had the highest indoor air velocity of 0.39m/s during the wet season. The lowest mean value for indoor air velocity was obtained during the dry season. Classroom $ASB_{GF}$ obtained the lowest mean value (0.05m/s) during the dry season. The highest indoor relative humidity occurred during the wet season. The highest mean value (74.68%) was recorded in the Classroom $ASB_{SF}$. The dry season recorded the lowest mean value of 64.73% obtained in the Classroom $ASB_{SF}$. The dry season had the highest indoor radiant temperature with a mean value of 16.99 ºC obtained from the Classroom $ASB_{SF}$. The lowest mean value (14.12) was obtained in the Classroom $ASB_{GF}$ during the wet season. Relative humidity recorded the highest and lowest mean values of 74.68% and 72.11% for the Classroom $ASB_{SF}$ and Classroom $ASB_{GF}$, respectively, for the wet season. Indoor air temperature also recorded mean values of 26.85 ºC and 26.55 ºC as the highest and lowest in the Classroom $ASB_{FF}$ and Classroom $ASB_{SF}$, respectively, during the wet season. On the 6th of August 2023, the lowest air temperature was obtained, and the highest was recorded on July 20th, 2023. The highest variation in indoor air temperature of 5.65 ºC occurred in the Classroom $ASB_{SF}$, with the lowest variation of 4.02 ºC occurring at the Classroom $ASB_{GF}$.

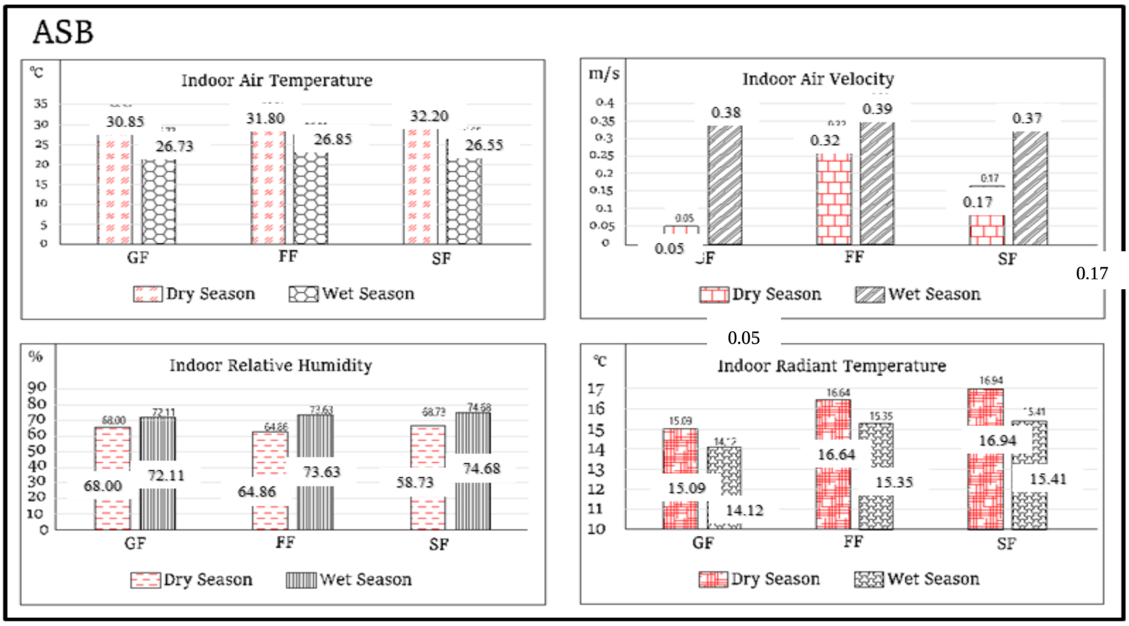


Figure 2 (a) Indoor air temperature, (b) indoor air velocity, (c) indoor relative humidity, and (d) indoor radiant temperature for the Classroom $ASB_{GF}$, Classroom $ASB_{FF}$, and Classroom $ASB_{SF}$.

### Validating the Measured values with Simulation values

Digital photographs of the buildings under study were converted to a 3D point cloud using the software application called Meshroom. After exporting as a DWG file, the wireframe model or 3D point cloud was used to help create a parametric 3D model of the building using the BIM program, Autodesk Revit. The data gathered from the Meshroom software was also verified using traditional measuring techniques. The selected buildings were simulated, and the results are presented as follows.

### Simulation results from the ASB for all Levels (classroom $ASB_{GF}$, classroom $ASB_{FF}$, and classroom $ASB_{SF}$) and the two Seasons (Dry and Wet).

#### Classroom $ASB_{GF}$

The simulated results from the Classroom $ASB_{GF}$ are presented in Table 2, including indoor air temperature, air velocity (m/s), MRT (°C), solar gain (W), PMV, and PPD (%). The simulation results from the Classroom $ASB_{GF}$ indicated that the indoor air temperature for the dry season was 31.00 °C and 25.40 °C for the wet season. The indoor air velocities recorded from the simulation were 1.75 m/s for the dry season and 1.58 m/s for the wet season, respectively. An MRT of 30.95 °C was recorded for the dry season and 25.69 °C for the wet season. The solar gain by the building was 0.17 W for the dry season and 0.01 W for the wet season. A PMV of 2.00 and 0.32 was recorded for the dry and wet seasons, respectively. The PPD was 80.17% for the dry season and 29.31% for the wet season.

Table 2 Simulated Results of the Indoor Conditions in the Classroom $ASB_{GF}$.

| **Environmental Parameters** | **Dry season** | **Wet season** |
|---|---|---|
| Air Temperature(°C) | 31.00 | 25.40 |
| Air velocity (m/s) | 1.75 | 1.58 |
| Mean Radiant Temperature (°C) | 30.95 | 25.69 |
| Relative Humidity | 64.12 | 70.34 |
| Solar gain (W) | 0.17 | 0.01 |
| **Thermal comfort scale** | | |
| Predicted Mean Vote | 2.00 | 0.32 |
| Predicted Percentage Dissatisfied (%) | 80.17 | 29.31 |

**Classroom $ASB_{FF}$**

Concerning the Classroom $ASB_{FF}$, air temperatures for the dry and wet seasons were 29.67 °C and 26.76 °C, respectively, with air velocities of 1.61 m/s and 1.58 m/s for both seasons. The study recorded MRT of 33.60 °C in the dry season and 25.37 °C in the wet season. Solar gains of 1.10 W and 0.06 W for the dry and wet seasons were recorded, respectively. For the dry and wet seasons, respectively, a PMV of 2.85 and 0.25 was obtained. During the dry season, the PPD was 87.34%, and during the wet season, it was 31.72%. Table 3 shows the simulated results of the indoor condition of Classroom $ASB_{FF}$.

Table 3 Simulated Results of the Indoor Conditions in Classroom $ASB_{FF}$.

| **Environmental Parameters** | **Dry season** | **Wet season** |
|---|---|---|
| Air Temperature(°C) | 29.67 | 26.76 |
| Air velocity (m/s) | 1.61 | 1.58 |
| Relative humidity | 62.03 | 70.11 |
| Mean Radiant Temperature (°C) | 33.60 | 25.37 |
| Solar gain (W) | 1.10 | 0.06 |
| **Thermal comfort scale** | | |
| Predicted Mean Vote | 2.85 | 0.25 |
| Predicted Percentage Dissatisfied (%) | 87.34 | 31.72 |

**Classroom $ASB_{SF}$**

Table 4 shows the simulated results of the indoor condition of Classroom $ASB_{SF}$. In the dry and wet seasons, the air temperature recorded on the Classroom $ASB_{SF}$ was 30.43 °C and 29.01 °C, respectively, with

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corresponding air velocities of 1.59m/s and 1.58m/s. MRT recorded 30.51 ºC and 25.15 ºC for the dry and wet seasons, respectively. During the dry season, solar gain was 0.29 W, and during the rainy season, it was 0.08 W. The PPD was 87.34% for the dry season and 31.72% for the wet season, with PMV of 2.85 and 0.25 recorded for the dry and wet seasons, respectively.

Table 4 Simulated results of the indoor condition of Classroom $ASB_{SF}$.

| **Environmental Parameters** | **Dry season** | **Wet season** |
|---|---|---|
| Air Temperature(ºC) | 30.43 | 29.01 |
| Air velocity (m/s) | 1.59 | 1.58 |
| Relative humidity | 65.03 | 71.11 |
| Mean Radiant Temperature (ºC) | 30.51 | 25.15 |
| Solar gain (W) | 0.29 | 0.08 |
| **Thermal comfort scale** | | |
| Predicted Mean Vote | 1.92 | 0.19 |
| Predicted Percentage Dissatisfied (%) | 85.81 | 34.12 |

**Comparison of Data from Measured and Developed Existing Building Models (ASB)**

The study compared the simulated results to the measured or experimental results to validate the accuracy of the building model created in Autodesk Revit. The verified simulation models' predictions and the measured values agreed quite well. Measured versus simulated indoor environmental variables are shown in Figure 3. Table 5 shows the differences between measured and simulated values of the environmental variables. According to the differences between measured and simulated values of the environmental variables obtained, a negative (-) value means the measured value was higher than the simulated value.

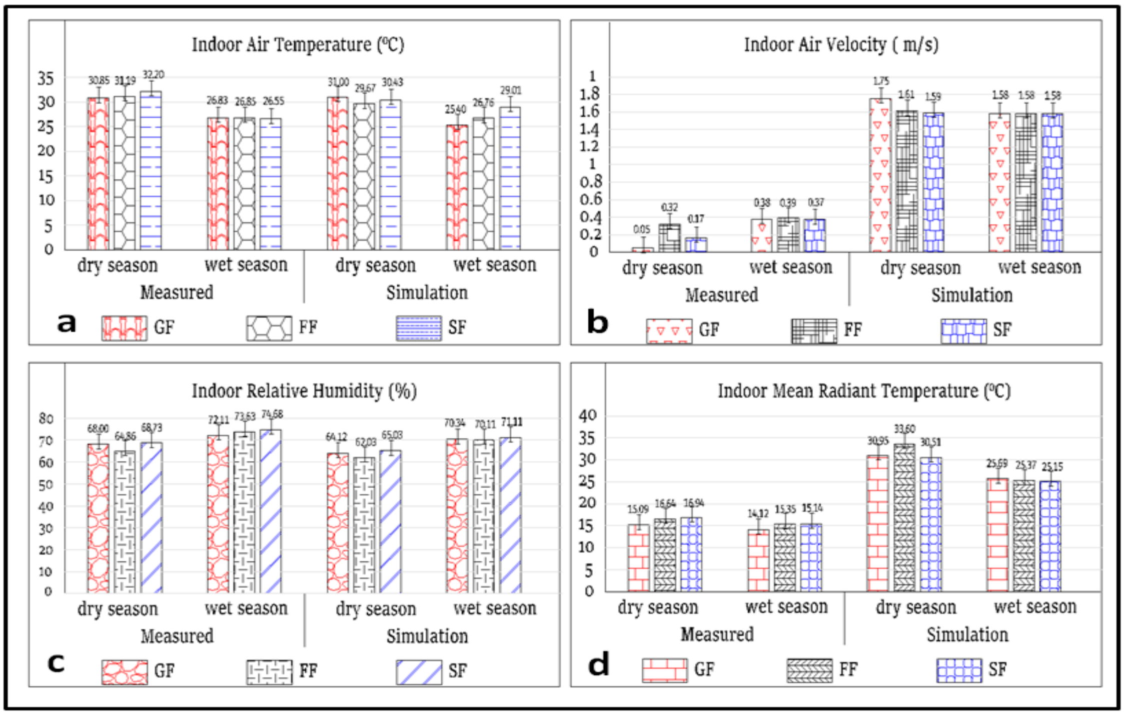


Figure 3 (a) Indoor air temperature, (b) indoor air velocity, (c) indoor relative humidity, and (d) indoor radiant temperature for ASB.

Table 5 Differences between measured and simulated values of the environmental variables

| Environmental Parameters | Floor Level | Diff. between measured & simulated | |
|---|---|---|---|
| | | *Dry season* | *Wet season* |
| Indoor air Temperature ($^oC$) | GF | 0.15 | -1.43 |
| | FF | -1.52 | -0.09 |
| | SF | -1.77 | 2.46 |
| Indoor Air Velocity (m/s) | GF | 1.7 | 1.2 |
| | FF | 1.29 | 1.19 |
| | SF | 1.42 | 1.21 |
| Indoor Relative Humidity (%) | GF | -3.88 | -1.77 |
| | FF | -2.83 | -3.52 |
| | SF | -3.7 | -3.57 |
| Indoor Mean Radiant Temp. ($^oC$) | GF | 15.86 | 11.57 |
| | FF | 16.96 | 10.02 |
| | SF | 13.57 | 9.74 |

A negative (-) value means the measured value is higher than the simulated value.

**Validation of Developed Existing Building Model Using Measured and Simulated Values**

The study compared the simulated results to the measured or experimental results to validate the accuracy of the building model created in Autodesk Revit. In Ghana's Ashanti area, experimental measurements were carried out between November and April during the dry season and between May and October 2023 during the wet season. Data loggers were used to capture data continuously for 24 hours (Testo). The indoor simulated results and the measured indoor results are shown in Figure 4. The patterns observed in the simulated and measured data were comparable. The air temperature recorded simulated values of 30.00 $^oC$ and 25.40 $^oC$ for dry and wet seasons, respectively. These values were lower than the measured values, which were 30.85 for the dry season and 26.83 for the wet season. The simulated values for the air velocity were 1.75m/s for the dry season and 1.58m/s for the wet season. The measured values were 1.38m/s for the dry season and 1.05m/s for the wet season. With the MRT, the simulation recorded 28.45 $^oC$ during the dry season and 25.69 $^oC$ for the wet season. Dry and wet seasons recorded 26.95 $^oC$ and 24.37 $^oC$, respectively, for the measured experimentation. The RH recorded a simulated value of 64.12% for the dry season and 70.34% for the wet season. The measured recorded values were 68.00% and 72.11% for dry and wet seasons, respectively. The dry season values were higher than the wet season values, and this was realized across all the measured and simulated parameters except the air velocity, which recorded higher dry season values for the simulation as compared to the measured values. The recorded PMV for the dry and wet seasons were 2.00 and 0.32, respectively. In the dry season, the PPD was 80.17%, and in the rainy season, it was 29.31 %. These results indicate that the indoor space of the studied building was warm, with 80.17% discomfort level during the dry season and slightly warm with 29.31% during the wet season.

A linear regression assessment on both simulated and measured data was performed using the coefficient of determination ($R^2$) and root mean square error (RMSE) to quantify the level of agreement between simulated and measured values to validate the simulated model created, as shown in Figure 5. For a dependable model, the $R^2$ value should approach 1, and the RMSE value should approach 0 (Chicco et al., 2021; Jamil & Akhtar, 2017; Lin et al., 2024). Simulated and measured values were used to validate the model results using indoor air temperature values. The $R^2$ of the indoor air temperature was 0.9047, and RMSE was 0.6344. Validating the two model scenarios with an $R^2$ value of 0.99 and a low RMSE value (Dyvia1 & Arif, 2021). The simulations generally depict good agreement among the suite of observed indoor temperatures, exhibiting $R^2$ value of 0.9047, which is greater than 0.8, with RMSE value of 0.4430. Overall, the level of agreement between the suite of simulated and observed variables was considered sufficient and reliable in the dry season. With $R^2$ value of 0.9352, which is higher than 0.8, the simulations often show strong agreement among the suite of reported indoor temperatures during the wet season. All things considered, the degree of agreement between the set of simulated and observed variables was deemed adequate and trustworthy during the wet season, as shown in Figure 6.

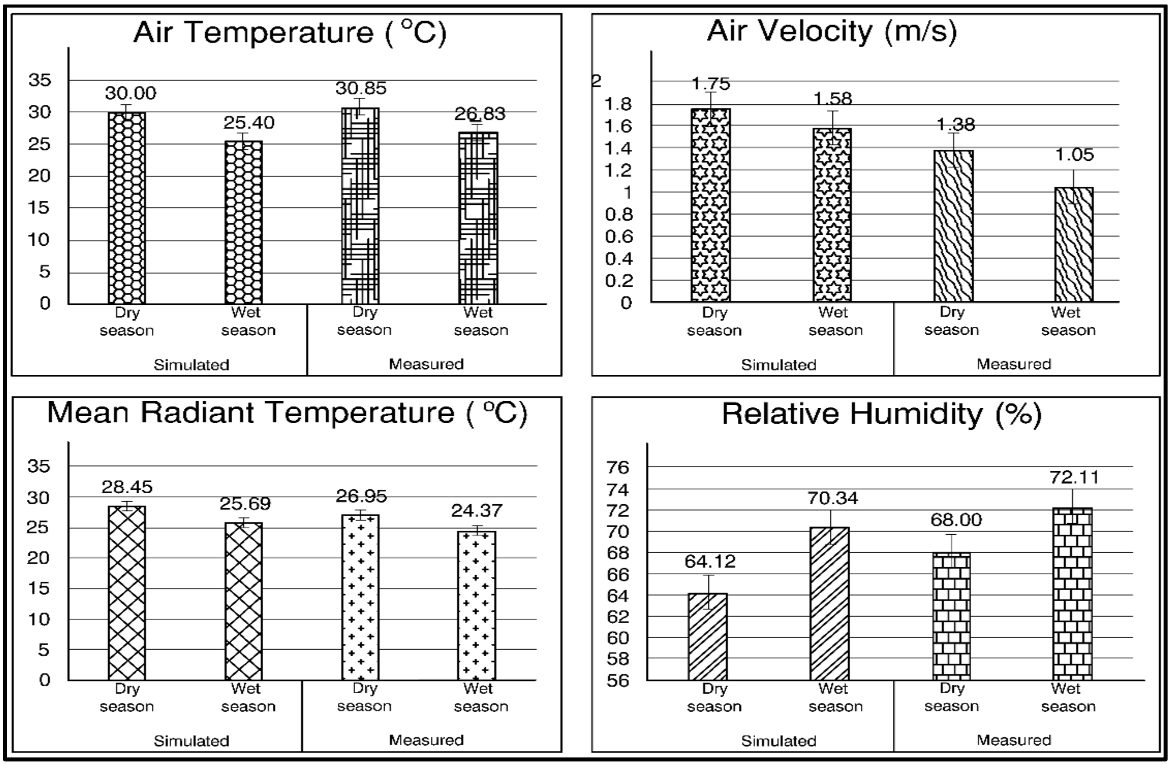


Figure 4 Comparison of measured and simulated results for air temperature, mean radiant temperature, air velocity, and relative humidity

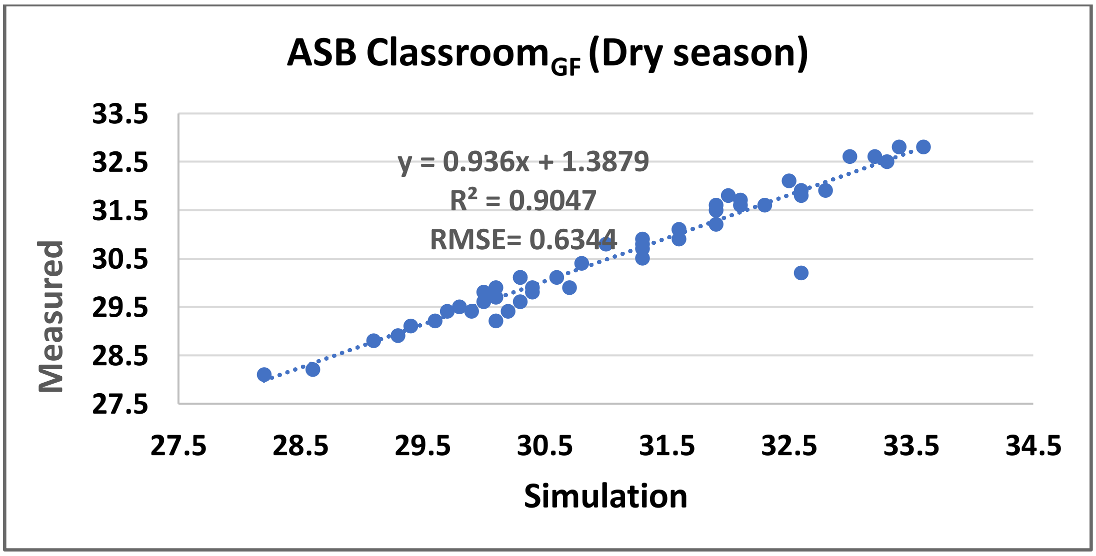


Figure 5 Statistical analysis (regression) of simulated and measured indoor air temperature during the dry season for the ASB classrooms

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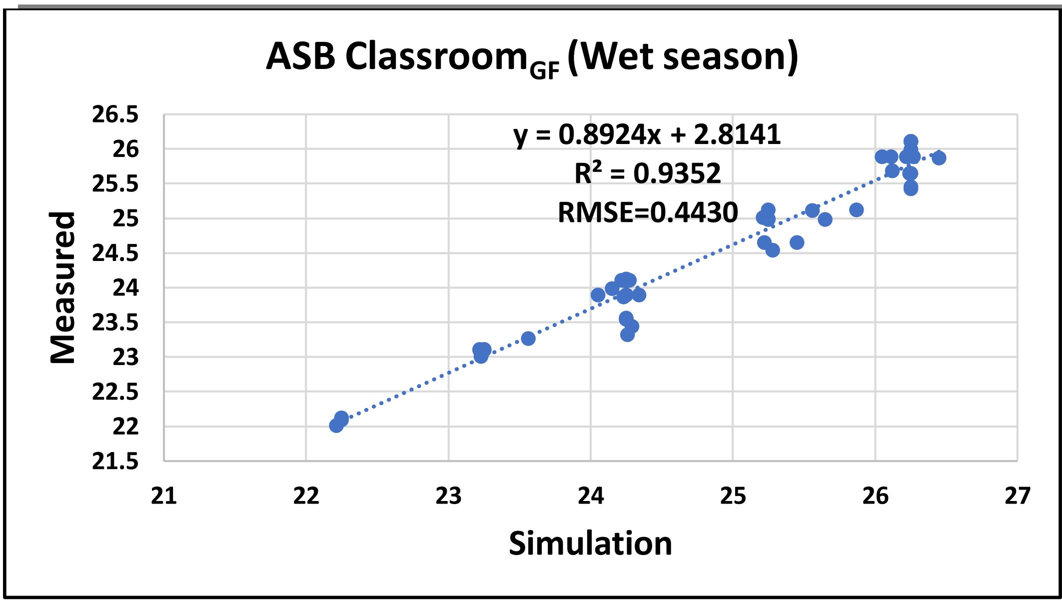


Figure 6 Linear regression of simulated and measured indoor air temperature for ASB Classroom (Wet season).

## DISCUSSION OF RESULTS

The study confirmed the accuracy of the building model created in Autodesk Revit by comparing the simulated results with the experimental measurements. The measured values and the predictions from the validated simulation models aligned closely. The correlation coefficient values demonstrate strong agreement between the measured and simulated values. The simulated results from the Classroom $ASB_{GF}$ for indoor air temperature, Air velocity (m/s), MRT (°C), Solar gain (W), PMV, and PPD (%). The results from the simulated classroom $ASB_{GF}$ indicated that the indoor air temperature for the dry season was 31.00 °C, and 25.40 °C for the wet season. The indoor air velocities recorded from the simulation were 1.75 m/s and 1.58 m/s for dry and wet seasons, respectively. MRT of 30.95 °C, was recorded for the dry season and 25.69 °C, for the wet season. The solar gain by the building was 0.17 W for the dry season and 0.01 W for the wet season. A PMV of 2.00 and 0.32 was recorded for dry and wet seasons, respectively. The PPD was 80.17% for the dry season and 29.31% for the wet season, the differences between measured and simulated values of the environmental variables. Relative humidity had negative values for all the building types and the studied classrooms. Negative values indicate that the measured data was higher than the simulated data. Classrooms $ASB_{GF,\ FF,}$ and $_{SF}$ recorded a difference of 0.15 °C, -1.52 °C, and -1.77°C between measured and simulated values with a percentage difference of 0.48%, 5.12%, and 5.82% for the dry season and -1.43 °C, -0.09 °C, and 2.46 °C with a percentage difference of 5.60%, 0.30%, and 8.50% for the wet season.

Englund et al. (2020) state that negative values (-%) represent higher measured than simulated values. Englund et al. (2020) found slightly higher measured values compared to simulated values. According to the ASHRAE Guideline (2002), the difference between measured and simulated data should not be higher than ±10% for MBE and ±30% for CV(RMSE). These findings were in line with the findings of the study, where negative values were obtained, indicating higher measured values. The percentage difference between the measured and simulated values for all the classrooms was less than ±30%.

The $R^2$ value of 0.9047 indicates that the independent variable (measured values) accounts for around 90.47% of the variance in the dependent variable (simulated values). This shows that the variables have a strong association with one another and that the model fits the data well (during the dry season). With $R^2$ value of 0.9352, which is higher than 0.8, the simulations often show strong agreement among the suite of reported indoor temperatures during the wet season. All things considered, the degree of agreement between the set of simulated and observed variables was deemed adequate and trustworthy during the wet season. The independent variable (measured values) explains 93.52% of the variance in the dependent variable (simulated values), according to the $R^2$ value of 0.9352. This demonstrates how well the model fits the data and how strongly the variables are related to one another (during the dry season).

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The $R^2$ values of 0.9047 and 0.9352 (90.47% and 93.52%) for dry and wet seasons, respectively, show a strong association between measured and simulation values. The RMSE value should approach 0 (Chicco et al., 2021; Jamil & Akhtar, 2017; Lin et al., 2024). The RMSE values for dry and wet seasons were 0.6344 and 0.4430, respectively. These values, which were close to zero (0), also indicate a strong association between measured and simulated values. Based on this, the hypothesis that there are no statistical differences between the measured and simulated indoor thermal comfort of a naturally ventilated university classroom is accepted.

The study validates real-world thermal comfort data using BIM-based simulations. It demonstrates that BIM is not just a design tool but can be effectively used for post-occupancy evaluation and operational analysis. This contributes to the growing integration of BIM with Building Performance Simulation (BPS) for ongoing facility management. It adds empirical evidence about thermal comfort in naturally ventilated classrooms, where conditions are more variable and harder to control. Provides real data on how such spaces perform in terms of thermal comfort, which is often underrepresented in simulation studies that focus on mechanically controlled environments.

The study likely outlines a systematic approach to model calibration, comparing simulated values (temperature, humidity, etc.) with measured data. This methodology can serve as a replicable framework for other researchers or practitioners to validate their building models.

Findings from a university classroom in a specific climatic or regional context (e.g., tropical or subtropical) help fill geographical gaps in thermal comfort literature. This is crucial because thermal comfort models (like PMV/PPD) are often developed in controlled Western contexts and may not be fully applicable elsewhere. By emphasizing actual occupant comfort rather than just code compliance or energy efficiency, it supports the shift toward human-centric building performance evaluation.

## CONCLUSIONS

The objective of the study was to validate the measured results of the existing naturally ventilated university classroom through parametric modeling and CFD simulation.

The dry season values were higher than the wet season values, and this was realized across all the measured and simulated parameters except the air velocity, which recorded higher dry season values for the simulation as compared to the measured values. The study concluded that the indoor space of the studied building was slightly warm, with a 43.66% discomfort level during the dry season, and cool with a 24.89% discomfort level during the wet season. This study evaluated the thermal comfort conditions in a naturally ventilated university classroom by comparing field-measured environmental data with simulated values generated through Building Information Modeling (BIM)-based energy modeling tools. The results demonstrated a reasonably good agreement between measured and simulated values, confirming the reliability of simulation models when properly calibrated with real data. The classroom experienced temperature and humidity levels that occasionally exceeded thermal comfort thresholds, particularly during peak occupancy and warmer hours. Simulation models calibrated using real-world data can effectively predict indoor thermal conditions, supporting their use in performance diagnostics. The PMV and PPD indices indicated moderate levels of thermal discomfort, suggesting room for improvement in passive design strategies or ventilation effectiveness. This research confirms that BIM-based simulations, when validated against actual measurements, are valuable tools for assessing and improving thermal comfort in educational buildings.

## RECOMMENDATIONS

- The study recommended that architects should assess the thermal comfort conditions of existing university classrooms to ascertain the building's comfort level for retrofitting.
- The study recommended that architects should use parametric building models for a whole building simulation to validate the measured thermal comfort of existing buildings for retrofitting.
- Redesign or adjust openings (e.g., windows, vents) to enhance cross-ventilation and air exchange in existing buildings.
- Shading devices, reflective coatings, or light-colored finishes should be used to reduce indoor heat gain.

- Night flushing or thermal mass should be utilized for better indoor temperature regulation.
- Further research should be conducted in the cold climate zone using calibrated simulation models for seasonal evaluations.
- Integrate Internet of Things (IoT) sensors for real-time monitoring to support dynamic building management.
- The study recommends that architects and facility planners adopt BIM-integrated thermal analysis early in the design of naturally ventilated spaces.
- The study recommends the development of university-specific thermal comfort guidelines based on localized data.

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