Occupants’ comfort and stress indices in a structural timber school building in the Northeast US in different seasons

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Short biographical notes on the contributor

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Abstract: The study examines stress indices and occupants’ comfort in a cross-laminated timber school building in the Northeast US in different seasons. The case study has won different awards for its sustainability credentials and use of structural timber for the construction. The environmental parameters were measured in the cold and warm periods. Thermal comfort models were applied to evaluate the occupants’ comfort. The stress indices were computed using the Wet-Bulb Globe Temperature and Universal Thermal Climate Index models. The average internal temperatures of 20.2°C and 22.5°C were measured in the cold and warm periods. In the cold and warm seasons, the mean relative humidity values were 43.6% and 58.3% respectively. The average carbon-dioxideconcentration falls within the acceptable band for a comfortable environment. The classrooms were much warmer than the hall and office. Lower and higher temperatures were noted during the occupied and non-occupied hours, which can cause warm and cold discomfort. The proposed Wet-Bulb Globe Temperature and Universal Thermal Climate Index in the warm period are 3.4°C and 3.0°C higher than the values computed for the cold season. The overall results showed that no thermal stress is predicted in the spaces. However, moderate thermal stress is predicted in the classrooms during the warmest months. The temperatures exceeded 28.0°C for about 5% of the time in one of the classrooms during the warm period. The study recommends that designers should consider thorough assessments before recommending interventions in buildings. The study also suggests that occupants should be enabled to adjust the thermal environment of buildings outside the occupied hours.

Keywords: occupants’ comfort, stress indices, field study, cross-laminated timber (CLT) school buildings, warm and cold periods, WBGT (Wet-Bulb Globe Temperature) and UTCI (Universal Thermal Climate Index) models.

# Introduction

Timber is a building material commonly used for the construction of different buildings in the US and other parts of the world. The material is being considered for various structures in many regions of the world due to its availability, low-carbon footprint, lightweight, speed of erection, workability, less number of equipment and labour required to handle the construction. In North America, particularly in the US, timber is also well researched, and various regulatory bodies such as the American Wood Council are set-up to maintain the high quality of the material for various purposes (AWC, 2018). In the US, residential and office buildings account for a significant percentage of buildings built with timber (AWC, 2018). Other structures such as commercial, schools, industrial buildings are also constructed with the material. In terms of the construction method, most of the timber buildings in this region are timber-framed while structural timber products are being used for the construction of new and refurbished buildings. Over the past few years, structural timber buildings such as cross-laminated timber (CLT) developments are being developed in the US (Mallo & Espinoza, 2015). While the region is increasing its effort on the innovative building technology to advance the development of structural timber buildings (Mallo & Espinoza, 2015; Adekunle, 2014; AWC, 2018), it is important to understand the indoor environmental conditions of structural timber buildings. As a result, this study is developed to evaluate the thermal environment of structural timber school buildings in the region.

The research examines occupants’ comfort and stress indices in a structural timber school building constructed with cross-laminated timber (CLT) materials in the Northeast US in different seasons. The paper assesses occupants’ comfort by considering indoor monitoring of variables in the development in cold and warm periods. Since existing studies have examined thermal comfort in school buildings in the region (Simons et al., 2010; Mendell et al., 2013; Haverinen-Shaughnessy & Shaughnessy, 2015) and outside the region (Pereira et al., 2014; Mishra et al., 2017), this study aims to provide the first set of data on thermal comfort and stress indices in CLT school buildings in different seasons. The research also utilizes the applicable thermal comfort standards and mathematical models to investigate the comfort temperatures and stress indices in the school buildings. The investigation intends to provide additional contributions to the body of knowledge by examining occupants’ comfort and stress indices concurrently in CLT school buildings in cold and warm periods. The research also intends to add to the existing studies on thermal comfort (Rijal Stevenson, 2010; Teli et al., 2013; Morgan et al., 2017; Adekunle & Nikolopoulou, 2016) and stress indices (Lemke & Kjellstrom, 2012; Vatani et al., 2016; Adekunle, 2019; Adekunle & Nikolopoulou, 2019) in structural timber school buildings. The paper also aims to offer an additional set of data on summertime temperatures (Rijal & Stevenson, 2010; Adekunle and Nikolopoulou, 2016; Morgan et al., 2017), and wintertime performance and occupants’ comfort in structural timber buildings (Rijal & Stevenson, 2010; Adekunle & Nikolopoulou, 2019). The main objective of the study includes to investigate thermal comfort of occupants in CLT school buildings in different periods and seasons. The objectives also include to examine the possibility of cold and heat stress in such buildings, identify different interventions that can be considered or introduced to reduce the vulnerability of occupants to heat and cold stress in school buildings, and understand the performance of CLT school buildings in the study area.

# Literature review

A research project on the performance of low-carbon prefabricated timber buildings stated that structural timber products such cross-laminated timber (CLT), glued laminated timber (GLULAM), and structural insulated panels (SIPs) are steadily used for the construction of different buildings in various locations across the world (Adekunle, 2014). Existing studies on thermal comfort in buildings explained that occupants of structural timber buildings are vulnerable to rising temperatures in warm periods, especially in summer (Adekunle & Nikolopoulou, 2016; Morgan et al., 2017). Occupants of structural timber buildings are also susceptible to lower temperatures in winter, and users may be predisposed to cold discomfort during cold seasons. Therefore, additional studies are required to understand the performance of structural timber buildings in different regions.

***Review of thermal comfort in school buildings***

Zomorodian et al. (2016) considered a detailed review of thermal comfort in educational buildings in the last five decades. Zomorodian et al. (2016) also stated that ventilation is a major factor to improve indoor air quality and thermal comfort of occupants in buildings. The study maintained that there is a noticeable difference in thermal neutralities, and further research should be considered on thermal comfort at micro-level in educational buildings (Zomorodian et al., 2016). Related results are also obtained in the research that evaluated the perception of thermal comfort of 384 students during the class session in a learning environment of a university in the cold period (Mishra et al., 2017). The research revealed that on the one hand, votes on thermal sensation differed significantly throughout the class period and; on the other hand, perception differs based on the external temperature, gender, operative temperature, and the background in terms of the geographical location of the participant (Mishra et al., 2017).

Occupants’ comfort and the effect of age groups are evaluated in the existing investigations (Hussein & Rahman, 2009; Teli et al., 2013). The existing research has studied thermal comfort of occupants in naturally ventilated school buildings located in the hot, humid region (Hussein & Rahman, 2009), and tropical region (Nematchoua et al. 2018). The investigations identified that the thermal environment was acceptable to over 80% of the respondents (Hussein & Rahman, 2009; Nematchoua et al. 2018). Equally, the respondents noted that the thermal environment was acceptable and right for them, even when their responses on the scale showed ‘warm’ or ‘no change.’ The mean votes on thermal sensation also surpassed the ASHRAE Standard 55 threshold (ASHRAE, 2017).

Also, Hussein & Rahman (2009) stated that the occupants of school buildings in the hot and humid region are likely to adapt to increasing temperatures in such buildings. Similarly, the existing research examined and discussed the applicability of the adaptive thermal comfort standard in naturally ventilated school buildings in different regions (Hwang et al., 2009; Teli, 2013; Jindal, 2018; Nematchoua et al. 2018). Hwang et al. (2009) applied the adaptive thermal comfort standard to determine the rate of acceptability and comfort range. The study (Hwang et al., 20090 found out that the acceptability rate has a wider band while the comfort range has a smaller band. Nematchoua et al., (2018) examined the adaptive thermal comfort model and relationship between experimental data and computational model in some naturally ventilated traditional and school buildings in the hot, humid island of the Indian Ocean. The study (Nematchoua et al. 2018) revealed that comfort temperatures differed from one season to another, and the traditional buildings are more comfortable than the school buildings.

On-site monitoring of environmental variables was carried out within the indoor environment of educational buildings in different periods (Jindal, 2018; Nematchoua et al. 2018). The studies (Jindal, 2018; Nematchoua et al. 2018) reported that the occupants prefer lower temperatures at a reduced rate. Bluyssen et al. (2018) examined associations between features of classroom, comfort, and well-being of the users in 54 classrooms of 21 school buildings in the Netherlands. The research (Bluyssen et al., 2018) considered the on-site monitoring of environmental parameters like temperature, CO2 level, humidity, and it explained that the respondents were concerned about noise, sunlight, smells, as well as decreasing or increasing temperatures within the thermal environment. Pereira et al. (2014) also noted that people are likely to accept and adjust to temperatures that exceed the comfort range. Montazami & Nicol (2013) proposed that further updates should be made to the current overheating guidelines for school buildings due to the outcomes and recommendations from existing research in the field.

Equally, Liang et al. (2012) noted that the building fabric energy regulation has a significant effect on thermal comfort of occupants in educational buildings. Katafygiotou & Serghides (2014) explained that an association is found between the energy efficiency of buildings and air quality, and humidity tends to have a less noticeable impact on the thermal sensation of users in educational buildings. Likewise, Zhang et al. (2013) stated that the occupants of school buildings in the hot, humid climate are likely to adjust to rising temperatures and humidity much better than the occupants of such buildings in the temperate region. Zhang et al., (2013) mentioned that occupants in the temperate climate are susceptible to elevated heat and temperatures as a result of their less tolerance to extreme temperatures and humidity. Therefore, further research is needed to evaluate the susceptibility of occupants to elevated and lower temperatures in school buildings.

Correlating occupants’ comfort in naturally ventilated and non-naturally ventilated buildings, Zhang et al. (2013) highlighted that occupants in non-naturally ventilated buildings make necessary modifications to regulate the thermal environment and make it more thermally comfortable than occupants in naturally ventilated buildings. Zhang et al. (2013) further stated that occupants make changes at the early stage to adjust the thermal environment while the occupants in non-naturally ventilated buildings tend to have a better perception of the thermal environment than the occupants in naturally ventilated buildings. Katafygiotou & Serghides (2014) also noted the excessive utilization of energy for cooling and heating during different periods in school buildings. The finding on the unnecessary use of energy in school buildings indicates that the uncontrolled energy usage could cause warm and cold discomfort of occupants in the buildings.

***Review of thermal comfort in US school buildings***

In the US, numerous studies have examined thermal comfort in educational buildings such as elementary schools (Mendell et al., 2013) and classrooms (Simons et al., 2010; Haverinen-Shaughnessy et al., 2015; Haverinen-Shaughnessy and Shaughnessy, 2015). Some of the studies investigated the relationship between school building conditions, classroom ventilation rate, and attendance rates (Simons et al., 2010; Mendell et al., 2013). Haverinen-Shaughnessy et al. (2015) and Haverinen-Shaughnessy and Shaughnessy (2015) assessed indoor environmental quality in US schools and the relationship with health and student performance. However, the existing studies on thermal comfort in school buildings in the region did not consider thermal comfort in CLT school buildings.

Similarly, NIOSH (2015) evaluated different variables using on-site monitoring of environmental variables to understand the parameters that influence the perception of comfort within the thermal environment. The research (NIOSH, 2015) showed that the perception of comfort is strongly related to physiological changes, the heat flow from the body to the surrounding, and the body temperature. NIOSH (2015) further explained that environmental variables, personal factors, as well as clothing insulation, affect the heat flow from the body to the immediate environment. According to ASHRAE Standard 55 (ASHRAE, 2017), the operative temperatures that ranged from 19.5°C to 27.8°C and 20.3°C to 23.9°C are suggested for warm and cold periods correspondingly. ASHRAE Standard 55 also stated that both environmental, personal, and other parameters affect the comfort temperatures range within the thermal environment. Equally, EPA (2012) recommended humidity band between 30% and 60% for healthy indoor environment to avoid the mold development; while ASHRAE (2013) explained that humidity level that surpasses 65% could lead to the development of microbes.

Usually, buildings are anticipated to be naturally ventilated in warm seasons and non-naturally ventilated in cold seasons; while heating and cooling systems to regulate the thermal environment could be turned on or off depending on the external temperatures (Nicol & Humphreys, 2007). Buildings are expected to provide a comfortable thermal environment for occupants even in time of extreme temperatures (NHS, 2011). According to DOE (2015), to provide and maintain a comfortable indoor climate for building users, HVAC systems are installed to regulate the thermal environment of buildings. Therefore, the current research evaluates thermal comfort in CLT school buildings. The research applies the thermal comfort models (BSEN15251, 2008; CIBSE, 2015; ASHRAE 2017) to evaluate occupants’ comfort in the school buildings during warm and cold periods.

***Review of heat indices***

Heat stress is described as a situation when a human body cannot easily dissipate excess heat, and it usually happens when the core temperature of the human body and the heart rate increase (NIOSH, 2018). Existing studies have propounded mathematical models for the computation of stress indices in different thermal environments (Stull, 2011; Lemke & Kjellstrom, 2012). Regarding the calculation of the stress indices in the case study, the research applies the Wet Bulb Globe Temperature Heat (WBGT) and the Universal Thermal Climate Index (UTCI) mathematical models to determine the stress indices in the spaces. The research also explores the computation models for comparison of the stress indices in different thermal environments. The paper compares the outcomes of the current study with the existing studies in the field to investigate if the calculated temperatures exceed the thresholds recommended by the applicable thermal comfort models. The study also recommends possible design interventions and suggestions that can improve the overall thermal comfort, health, and well-being of occupants in school buildings.

# Method – environmental monitoring and mathematical models

The research used different methods, such as on-site monitoring of environmental variables and mathematical models for the collection of data. The on-site monitoring was considered to measure environmental variables which can be used to understand and assess the thermal environment. The mathematical models were applied to compute the stress indices and understand if occupants are prone to heat or cold stress within the thermal environment in different seasons. The study also explored the applicability and categories of various thermal standards (BSEN15251, 2008; CIBSE, 2015; and ASHRAE 2017) to evaluate the thermal comfort of users and the performance of the case study. The thermal comfort models were used to evaluate if occupants are subject to warm or cold discomfort. The thermal comfort models were also considered to examine if indoor temperatures were within the acceptable limits for occupants’ comfort within the building. The applicability, thresholds, and characteristics of the thermal comfort models and related variables for defining the thermal environment of buildings have been considered and presented in the existing research.

The CIBSE thermal comfort standard (2015) recommends the appropriate building range for determining maximum acceptable temperature (Tmax). The CIBSE comfort standard states that buildings should be planned and developed to be within the Category II (suggested acceptable range is 3K) bands. The CIBSE TM52 further stresses that the Category II upper band should be evaluated by using Equation 1. The equation (Equation 1) also indicates the maximum acceptable temperature for the Category II TM52, and it specifies the running mean temperature (Trm).

𝑇𝑚𝑎𝑥 = 0.33 𝑇𝑟𝑚 + 21.8 (Equation 1)

On the one hand, the BSEN15251 thermal comfort model considers a naturally-ventilated thermal environment with physically controlled openings such as door, windows, etc., and mechanical ventilation. On the other hand, the BSEN15251 standard specifies that the thermal environment should not be regulated or adjusted using air-conditioning systems. The BSEN1525 thermal comfort model states that the Category II thermal envelope refers to the thermal environment occupied by users with ‘normal level of expectations.’ Spaces such as office spaces, laboratories, learning spaces including classrooms, lecture halls, etc. fall within the Category II thermal envelopes. The BSEN15251 thermal comfort model considers and recommends the calculation of the running mean temperature. Similarly, the ASHRAE thermal comfort standard (ASHRAE, 2017) also follows a similar approach that other thermal comfort standards considered in this study for evaluating the thermal comfort of occupants and the performance of buildings. The thermal comfort models are applied to assess thermal comfort of occupants during the total period of the on-site measurements, occupied hours (8am-5pm), non-occupied hours (6pm-7am), and extended occupied hours (8am-10pm).

***On-site monitoring of environmental parameters***

Environmental parameters (such as temperature, relative humidity, dew-point, air velocity, and CO2 level) were measured at 60-minute intervals in the selected spaces of the school buildings. The sensors were mounted on the internal walls at 1.1 m height above the floor level to measure and log the parameters. The data recorded during the warm and cold periods were downloaded, checked, and analysed. In the warm period, the on-site monitoring was carried out from June to September 2017. For the cold season, the on-site measurements were done from October 2017 to February 2018.

***Computation of environmental variables not measured during the on-site monitoring***

During the surveys, two of the data loggers used for the on-site monitoring did not record relative humidity; however, the sensors measured and logged temperature, dew-point, and other variables. Mathematical models were considered in this study to calculate the values of the environmental variables that were not measured during the on-site monitoring of the case study building. The mathematical models were also used to check and validate the calculated data. Equation 2, outlined by Wanielista et al. (1997), was used for the computation of relative humidity at 60-minute intervals. In the equation (Equation 2), *f* stands for relative humidity, TD is defined as dew-point temperature, and T is known as temperature. Wanielista et al. (1997) also mentioned that if other applicable variables are known, Equation 3 can be used to compute dew-point temperature. Likewise, other relevant mathematical expressions that can be applied to compute temperature, relative humidity, and dew-point are outlined and discussed in the existing research (Alduchov & Eskridge, 1996).

 (Equation 2)

 (Equation 3)

Equally, Vaisala (2013) explained that when relative humidity has been determined, saturation vapour pressure can also be calculated using Equation 4, while vapour pressure can be computed by applying Equation 5. In the equations, Pws stands for saturation vapor pressure (hPa), T is defined as temperature (°C), Pw is vapour pressure (kPa), and RH is relative humidity (%). In Equation 4, A, m, n are constants, and the values are defined in the existing study (Vaisala, 2013).

 (Equation 4)

 (Equation 5)

***Wet Bulb Globe Temperature (WBGT) and Universal Thermal Climate Index (UTCI)***

The current research also assessed the Wet Bulb Globe Temperature (WBGT) and the Universal Thermal Climate Index (UTCI) by using the applicable mathematical models to determine the stress indices in warm and cold periods. The mathematical expressions have been considered for determining heat stress and cold stress in different operational spaces of workplaces (NEHC, 2007; Lemke & Kjellstrom, 2012), industrial places (Vatani et al., 2016), and residences (Adekunle & Nikolopoulou, 2019; Adekunle, 2019). An in-depth discussion of the WBGT model has been presented in the existing papers (Stull, 2011; Lemke & Kjellstrom, 2012). Similarly, the full account of the UTCI, including the background information, has been provided in the existing research (Lemke & Kjellstrom, 2012). Table 1 and Table 2 outline the temperature bands and classes of thermal stresses for the WBGT and the UTCI.

Table 1. Temperature limits and classes of thermal stress for the WBGT.

|  |  |
| --- | --- |
| **The WBGT stress index classification** | **Time scale** |
| Temperature below 28.6°C | Below 60 minutes/hour |
| Temperature at 29.3°C | Below 45 minutes/hour |
| Temperature at 30.6°C | Below 30 minutes/hour |
| Temperature at 31.8°C | Below 15 minutes/hour |
| Temperature over 38°C | Below 0 minute/hour |

Table 2. UTCI Evaluation scale to classify thermal stress within the thermal environment (Glossary of Terms for Thermal Physiology, 2003).

|  |  |
| --- | --- |
| Band of UTCI (°C) | UTCI Stress Category |
| Temperature more +46°C | Extreme heat stress |
| Temperature from +38°C to +46°C | Very strong heat stress |
| Temperature from +32°C to +38°C | Strong heat stress |
| Temperature from +26°C to +32°C | Moderate heat stress |
| Temperature from +9°C to +26°C | No thermal stress |
| Temperature from +9°C to 0°C | Slight cold stress |
| Temperature from 0°C to -13°C | Moderate cold stress |
| Temperature from -13°C to -27°C | Strong cold stress |
| Temperature from -27°C to -40°C | Very strong cold stress |
| Temperature below -40°C | Extreme cold stress |

For the WBGT, Stull (2011) recommended that the psychrometric wet bulb temperature can be computed by applying Equation 6. The research (Stull, 2011) outlined that the psychrometric wet bulb temperature (Tpwp°C) can also be expressed as the wet-bulb temperature (Tw). Based on the parameters considered in Equation 6, Stull (2011) further stated that the arctangent (atan) function in the equation considers the values that are defined in radians. From the equation, Tw is defined as the combined effect of Ta (°C) and RH (%) at an average atmospheric pressure of approximately 101.325 kPa.

Tw = Taatan[0.151977(RH% + 8.313659)1/2] + atan(Ta + RH%) – atan(RH% - 1.676331) + 0.00391838(RH%)3/2 atan(0.023101 × RH%) – 4.686035 (Equation 6)

The UTCI model is created on the conceptual idea of the similar temperature with an associating thermal environment of RH (about 50%), temperature above 29°C, and a vapour pressure under 2 kPa (Blazejckzy et al., 2013). Equally, Osczevski & Bluestein (2005) stated that a wind velocity that exceeds 3m/s would have a noticeable effect on the UTCI during the cold period when external temperatures exceed 38°C; while occupants tend to be susceptible to a high degree of heat stress within the thermal environment. The computational model to calculate the UTCI using Equation 7 is presented in the existing research (Błażejczyk, 2011). In Equation 7, T is defined as temperature, Tmrt is described as mean radiant temperature, RH stands for relative humidity, and V is described as wind speed at roughly 10m higher than the ground level. The WBGT and UTCI models have been used in many applications in various schemes (Climate Chip, 2016). The UTCI model discussed in this study is computed using the methodological approach in the existing work (Jendritzky et al., 2002; UTCI, 2005). Both models are applied to compute the warm and cold stress indices during the occupied hours (8am-5pm), non-occupied hours (6pm-7am), and extended occupied hours (8am-10pm).

UTCI = 3.21 + 0.872T + 0.2459Tmrt + (-2.5078V) – 0.0176RH (Equation 7)

# Description of the case study

The case study is built with cross-laminated timber (CLT) panels. The case study is considered for the research because it is the first school building in the US to use CLT panels as a “stressed skin” assembly. The development is a mixed-use project that is built on almost 20 acres of inner-city park area at the lower part of one of the State-owned Parks in the Northeast of the United States (Figure 1). The case study comprises of upper grades school, an urban farm area, and a resource facility for the public, informative, and recreational activities. The school also offers a state-of-the-art curriculum in inner-city agriculture and sustainable land-management practices. The case study has an overall floor area of about 1300m2. It consists of different spaces like classrooms, offices, art/drawing studio, preparatory space, storage, and the main hall for different activities (Figures 2-3). The case study is developed to accommodate about 200 students and staff.



Figure 1. The geographical map showing the Northeast region of the United States

Concerning the design and arrangement of the spaces, the entrance foyer, main hall, central office, storage, mechanical rooms, kitchen, restrooms, are on the lower floor (Figure 2). The staff offices, prep space, break out space, classrooms, and laboratories, art/drawing studio, are on the upper floor. The tension surface, ceiling finishes are done with CLT panels while bearing, and shear walls are built with vertical CLT panels. The project also considered glued laminated timber (Glulam) panels to span the main hall and for the erection of the rafters. The development has won many awards and received recognition in terms of its green rating and use of natural materials for the construction of the building. The development has also been recognised by the Leadership in Energy and Environmental Design (LEED) due to its cost-efficiency in terms of energy usage and other sustainability credentials. The LEED is the US green building rating framework, and it is the most widely used green building rating methodology in most regions across the world. The U-values of the internal and walls of the case study are estimated to be between 0.13 W/m2K and 0.20W/m2K.

On the lower floor, the on-site measurements of environmental parameters were considered in the central office, and the main hall (Figure 2). The on-site monitoring was carried out in the classrooms on the upper floor. The selected spaces were also measured in both periods (warm and cold). The spaces are chosen based on the research goal, availability, orientation, space usage, and other factors. During warm periods, the case study is naturally ventilated. However, it is supplemented with mechanical heating and ventilation systems in different periods. Ground source heat pumps are also installed in the development for heating and cooling purposes. The selected spaces are chosen from various orientations to improve the quality of the data gathered and discussed in this study.



Figure 2. The plan of the lower floor showing the main hall, and general office.



Figure 3. The external view of the case study showing the classrooms and other spaces on the upper floor.

# Data analysis

# *Analysis of outdoor weather data*

In the warm period, the average external temperature (daily) was between 12.0°C and 27.0°C. The mean external temperature (daily) in the cold period ranged from -12.0°C to -22.0°C. The total mean external temperature in the warm season was 21.0°C. The total average external temperature during the cold period was 4.8°C. The average maximum external temperature of 25.9°C and minimum external temperature of 16.8°C were reported during the on-site monitoring in the warm period. In the cold period, the mean maximum temperature of 9.2°C and minimum external temperatures of 0.7°C were measured. The mean external dew-point temperatures of 15.7°C and -0.6°C were observed during the warm and cold periods, respectively. The average external RH (daily) was between 99.9% and 31.0% in the warm period. In the cold period, the mean values for outdoor external RH (daily) ranged from 99.9% to 18.0%. The total average external RH in the warm period was 71.3%, and the mean RH value was 67.2% in the cold period. The average vapour pressure in the warm period was 1015.0mb, and a mean value of 1019.0mb was reported in the cold period.

 In the warm period, the mean outdoor temperature during the occupied hours (8am-5pm) was reasonably higher than the mean external temperature during the non-occupied hours (6pm-7am). A similar result was also obtained in the cold season. On the one hand, the mean outdoor temperature (daily) during the occupied hours (8am-5pm) was at least 2.1°C higher than the average external temperature during non-occupied hours (6pm-7am) in both seasons. On the other hand, the mean outdoor RH (daily) during the occupied hours (8am-5pm) was less than the average external RH (daily) during the non-occupied hours (6pm-7am), especially in the cold period. The mean dew-point temperatures were also higher during the occupied hours (8am-5pm) than the mean values during the non-occupied hours (6pm-7pm) in the warm and cold periods.

# *Analysis of outdoor stress indices*

About the stress indices in the outdoor environment during the warm period, the average outdoor WBGT `of 18.7°C and the average outdoor UTCI of 21.6°C are calculated for the location of the case study. Similarly, in the cold period, the mean outdoor WBGT of 3.3°C and the mean outdoor UTCI of 4.8°C are computed as the outdoor stress indices for the site. The features of the external weather data in the warm and cold periods are summarised in Table 3. The breakdown of the external weather data observed at the location of the case study showed that high maximum temperatures surpassed the critical comfort indicator of 28.0°C. However, the mean temperature reported for the warm season did not exceed the limit. The average outdoor temperature observed in the cold period is below the comfort baseline specified by ASHRAE for the period. The breakdown of the data also showed that outdoor occupants might be susceptible to reasonable heat stress in the warm period. Equally, the analysis revealed the tendency of slight cold stress for outdoor occupants in the cold period.

Table 3. Features of the external weather data for the warm and cold periods at the location of the study.

|  |  |  |
| --- | --- | --- |
| **Variables** | **Warm Period**  | **Cold Period** |
| **High**  | **Average** | **Low**  | **High**  | **Average**  | **Low**  |
| Maximum temperature (°C) | 32.0 | 25.9 | 13.0 | 27.0 | 9.2 | -10.0 |
| Minimum temperature (°C) | 23.0 | 16.8 | 8.0 | 22.0 | 0.7 | -17.0 |
| Mean temperature (°C) | 27.0 | 21.0 | 12.0 | 22.0 | 4.8 | -12.0 |
| Maximum dew-point (°C) | 24.0 | 18.1 | 7.0 | 22.0 | 3.6 | -22.0 |
| Minimum dew-point (°C) | 21.0 | 13.0 | 2.0 | 21.0 | -5.1 | -25.0 |
| Mean dew-point (°C) | 23.0 | 15.7 | 4.0 | 21.0 | -0.6 | -23.0 |
| Relative Humidity (%) | 99.9 | 71.3 | 31.0 | 99.9 | 67.2 | 18.0 |
| Wind speed (m/s) | 17.4 | 5.0 | 0 | 22.4 | 5.6 | 0 |
| Vapour pressure (Millibars) | 1028.0 | 1015.0 | 1006.0 | 1044.0 | 1019.0 | 982 |
| Precipitation (mm) | 612.1 | 35.6 | 0  | 1948.2 | 73.7 | 0.0 |
| WBGT | 25.1 | 18.7 | 9.4 | 21.5 | 3.3 | -13.1 |
| UTCI | 29.2 | 21.6 | 11.8 | 24.2 | 4.8 | -14.0 |

# *Relationship between the external environmental parameters*

The study revealed that strong connections are found between the external temperatures and external dew-point in both periods (Figure 4). The investigation showed that the external dew-point temperatures have a noticeable effect on the external temperatures in the cold period than the warm season. The analysis revealed that, usually, dew-point could influence stress indices at an increasing rate in the cold period than warm period.



Figure 4. The association between the external maximum, minimum, mean temperatures, and external dew-point during cold and warm periods.

# Findings

# *Indoor environmental variables during the monitoring periods*

The results showed that the average internal temperature measured in the central office on the lower floor was 22.5°C in the warm period, and the mean temperature was 21.0°C within the same space in the cold period. The average indoor temperatures of 20.6°C and 19.2°C were recorded in the main hall on the lower floor in the warm and cold period in that order. The investigation showed that lower mean temperatures were recorded in the main hall than the central office in both warm and cold periods. The bigger area of the floor, capacity, operational use, different activities carrying out in the main hall, location, and frequent use of openings might have contributed to the main hall being cooler than the central office, even though both spaces are on the lower floor.

For the whole period of the on-site measurements, the average temperatures were between 22.2°C and 24.1°C in the teaching spaces (i.e., classrooms) in the warm period. In the cold period, the mean temperatures varied from 20.2°C to 20.4°C in the teaching spaces. The study noted that Classroom 2 (Southeast orientation) is found to be the warmest teaching space in the warm period. In the cold season, higher maximum and average temperatures were recorded in Classroom 1 (Northwest orientation) than the other spaces. The orientation might contribute to the increasing temperatures observed in Classroom 2 than other learning spaces in the warm period.

# *Warm period*

Similarly, in the warm period, the mean dew-point temperatures of 13.7°C and 15.3°C were measured in the central office and the main hall correspondingly. The average dew-point of 9.2°C and 11.0°C were observed in the central office and main hall respectively in the cold period. The average mean RH across the spaces ranged from 52.8% to 71.9% in the warm period, and the mean value varied from 31.8% to 59.6% in the cold period. The temperatures recorded in the classrooms were higher than the values reported in the other spaces in the warm period. The classrooms are on the upper floor, and this design feature may have contributed to the higher temperatures measured in the learning spaces than the central office and main hall. Similar results were obtained in the spaces during the occupied hours (8am-5pm) and non-occupied hours (6pm-7am) in the warm season, as shown in Table 4. The findings revealed the tendency of the occupants to be reasonably comfortable in the offices and main hall than the learning spaces during the occupied hours (8am-5pm) in the warm period.

# *Cold period*

In the cold season, higher mean temperatures were recorded in the central office than the other spaces during occupied hours (8am-5pm) and non-occupied hours (6pm-7am) in the cold period (Table 4). The study found out that factors such as longer hours of administrative activities, frequent heating of the space, orientation may contribute to higher temperatures reported in the central office than the other spaces during these periods. Also, the total CO2 level range was less than 1000ppm (that is, from 48.2-496.3ppm in the warm period, and 56.8-494.7ppm in the warm period) for most of the duration of the on-site monitoring. The average CO2 value was within the recommended band of 350ppm to 1000ppm specified for healthy and comfortable indoor spaces. The natural ventilation strategy supplemented with mechanical heating and ventilation systems as well as the materials used may have helped in improving the indoor air quality of the building. Table 4 summarises the mean, maximum, and minimum values of the environmental variables within the spaces in both periods.

Table 4. Maximum, minimum and mean values of temperature, dew-point, RH and CO2 value range in the selected spaces for different occupied and non-occupied hours in the warm and cold periods

|  |  |  |
| --- | --- | --- |
| **Spaces** | **Warm Period** | **Cold Period** |
| **Temperature (°C)** | **Mean dew-point (°C)** | **Mean RH (%)** | **CO2****value range (ppm)** | **Temperature (°C)** | **Mean dew-point (°C)** | **Mean RH (%)** | **CO2****value range (ppm)** |
| **Max.**  | **Min.**  | **Mean**  | **Max.**  | **Min.**  | **Mean**  |
| Central office (lower floor) | 26.6 | 18.2 | 22.5 | 13.7 | 57.7 | 48.2 – 496.3 | 23.0 | 18.4 | 21.0 | 9.2 | 46.7 | 56.8 – 494.7 |
| Main hall (lower floor) | 28.2 | 17.7 | 20.6 | 15.3 | 71.9 | 26.4 | 17.6 | 19.2 | 11.0 | 59.6 |
| Classroom 1 (upper floor) | 28.1 | 18.2 | 22.2 | 12.5 | 55.2 | 30.4 | 12.4 | 20.4 | 3.1 | 31.8 |
| Classroom 2 (upper floor) | 28.9 | 20.7 | 24.1 | 13.8 | 52.8 | 24.2 | 12.3 | 20.3 | 6.7 | 42.9 |
| Classroom 3 (upper floor) | 28.5 | 19.5 | 23.1 | 13.1 | 54.1 | 26.8 | 12.2 | 20.2 | 4.2 | 37.4 |
| Central office (8am-5pm) | 26.6 | 18.6 | 22.6 | 13.5 | 55.6 | 48.5-496.3 | 23.0 | 18.5 | 21.2 | 9.6 | 47.5 | 59.2-494.7 |
| Main hall (8am-5pm) | 28.2 | 17.7 | 21.0 | 15.4 | 70.7 | 26.6 | 17.8 | 19.8 | 11.4 | 58.4 |
| Classroom 1 (8am-5pm) | 28.1 | 18.9 | 22.2 | 12.0 | 53.1 | 30.4 | 13.3 | 20.9 | 3.1 | 31.0 |
| Classroom 2 (8am-5pm) | 28.9 | 21.0 | 23.9 | 12.9 | 50.5 | 24.2 | 12.5 | 20.7 | 6.9 | 43.1 |
| Classroom 3 (8am-5pm) | 28.5 | 19.9 | 23.0 | 12.4 | 51.8 | 26.8 | 12.3 | 20.8 | 4.3 | 37.1 |
| Central office (6pm-7am) | 26.5 | 18.2 | 22.5 | 14.1 | 59.2 | 48.2-490.6 | 22.9 | 18.4 | 20.9 | 10.4 | 51.2 | 56.8-492.4 |
| Main hall (6pm-7am) | 25.2 | 17.6 | 20.3 | 15.2 | 72.7 | 20.7 | 17.6 | 18.7 | 10.8 | 60.5 |
| Classroom 1 (6pm-7am) | 28.0 | 18.2 | 22.0 | 12.8 | 56.7 | 24.9 | 12.4 | 20.0 | 3.0 | 32.4 |
| Classroom 2 (6pm-7am) | 28.8 | 20.7 | 24.2 | 14.4 | 54.5 | 24.0 | 12.3 | 19.8 | 7.1 | 43.7 |
| Classroom 3 (6pm-7am) | 28.4 | 19.4 | 23.0 | 13.6 | 55.6 | 24.5 | 12.2 | 19.9 | 5.2 | 38.1 |

# *Occupied, non-occupied, and extended occupied periods*

During the on-site measurements in warm and cold periods, the study found out that the case study users also use the spaces for various events (such as evening classes, sports, meetings, etc.) outside the normal occupied hours (8am-5pm). As a result, the thermal environment of the case study was also assessed over the extended occupied hours (8am-10pm). The outcomes revealed the mean internal temperatures varied between 20.9°C and 24.0°C in the warm period. The average internal temperatures ranged from 19.6°C to 21.1°C in the cold period. The results showed that on the one hand, higher mean, maximum, and minimum temperatures were reported in the learning spaces than the other spaces in the warm period. Location of the learning spaces on the upper floors may have contributed to the higher temperatures reported in the spaces than the other spaces. On the other hand, higher mean temperature (at least 0.3°C) was recorded in the central office than the other spaces in the cold period (Table 5). The results showed that the classrooms are warmer than the central office and main hall in the warm period; while the central office tends to be warmer than the remaining spaces in the cold period.

Table 5. Maximum, minimum and mean values of temperature, dew-point, and RH in the selected spaces for extended occupied hours in the warm and cold periods

|  |  |  |
| --- | --- | --- |
| **Spaces** | **Warm Period** | **Cold Period** |
| **Temperature (°C)** | **Mean dew-point (°C)** | **Mean RH (%)** | **Temperature (°C)** | **Mean dew-point (°C)** | **Mean RH (%)** |
| **Max.**  | **Min.**  | **Mean**  | **Max.**  | **Min.**  | **Mean**  |
| Central office (8am-10pm) | 26.6 | 18.2 | 22.6 | 13.4 | 55.9 | 23.0 | 18.5 | 21.1 | 9.6 | 47.8 |
| Main hall (8am-10pm) | 28.2 | 17.6 | 20.9 | 15.4 | 71.1 | 26.6 | 17.8 | 19.6 | 11.5 | 59.9 |
| Classroom 1 (8am-10pm) | 28.1 | 18.9 | 22.1 | 12.1 | 53.4 | 30.4 | 13.3 | 20.8 | 3.2 | 31.3 |
| Classroom 2 (8am-10pm) | 28.9 | 20.7 | 24.0 | 13.1 | 50.9 | 24.2 | 12.5 | 20.7 | 8.1 | 44.3 |
| Classroom 3 (8am-10pm) | 28.5 | 19.4 | 23.1 | 12.6 | 52.2 | 26.8 | 12.4 | 20.5 | 5.7 | 37.9 |

# Discussion

# *Relationship between the external and indoor environmental parameters*

The associations between the mean internal and external temperatures within the spaces were also evaluated (Figure 5). In the warm period, the relationships are found between the variables in all the selected spaces. A lower level of relationship was reported in the classrooms (R2 = 0.3804) than the main hall (R2 = 0.6653) and central office (R2 = 0.6720) in the warm period. Factors such as space volume, floor-to-ceiling height, location of the spaces on the ground floor which may have helped to reduce changes in temperatures are likely to contribute to a higher level of relationship reported in the main hall and central office than the level of association obtained in the learning spaces. The study revealed that the external and internal temperatures are strongly interrelated in the two spaces (main hall and central office) in the warm period. The internal temperatures are within the similar band (approximately 2.0°C) in the selected spaces with higher internal temperatures in the learning spaces (classrooms) and the central office than the main hall. In the cold period, the research revealed linked are reported between the variables in the main hall (R2 = 0.5781) and the central office (R2 = 0.3602), while no connection is found between the variables in the classrooms (R2 = 0.0410) as shown in Figure 5. The investigation found out that other variables like occupation hours could determine users' comfort in the learning spaces, users’ behavioural actions, layout and orientation, availability and use of regulators to adjust the thermal environment, physiological adjustments, and activities taken place in the spaces, etc.



Figure 5. The association between the mean internal and external temperatures in the warm and cold periods.

# *Relationship between the indoor environmental parameters, WBGT and UTCI*

Also, air velocity was recorded in the selected spaces during the on-site measurements. The average air velocity ranged from 0.1m/s to 0.2m/s in the spaces. The computational models presented in Equation 6 and Equation 7 were also introduced to determine the stress indices within the spaces. The mean values of air velocity observed in the spaces were applied for the calculation. The results showed that on the one hand, higher values of the WBGT and UTCI were calculated in the central office than the values computed for the main hall and classrooms in the cold period.

On the other hand, higher WBGT and UTCI values were computed in Classroom 2 (Southeast facing) than the other spaces in the warm period. The results revealed that changes in temperatures and other variables, as well as seasonal change, could influence the WBGT and UTCI values. The study also showed that the higher the temperatures within the spaces, the higher the WBGT and UTCI values computed for the spaces.

For the total duration of the on-site measurements, the results showed that no thermal stress is predicted in the spaces in the warm period (Table 6). However, further analyses that focused on the warmest months (July-August) in the warm period revealed the possibility of moderate heat stress in the classrooms, especially in Classroom 2. The study showed that some factors such as the location of the space, size, and location of openings, use of high-level windows, space usage and circulation, as well as orientation might contribute to moderate thermal stress predicted in Classroom 2. The UTCI values during the warm period exceed 26.0°C in Classrooms 2 and 3. The research highlights the possibility of the users to be vulnerable to heat stress during a heat wave in warm period and cold stress during an extremely cold weather condition.

The total average values of the WBGT (18.8°C) and UTCI (22.4°C) were calculated in the selected spaces in the warm period. In the cold period, the average values of 15.4°C and 19.4°C were computed as the WBGT and UTCI correspondingly. The investigation revealed that for the warm period, lower stress indices are calculated in the current research than the existing papers on heat stress in different thermal environments (Vatani et al., 2016). For the cold period, higher stress indices are computed in this paper than the existing research on cold stress in buildings (Adekunle & Nikolopoulou, 2019). The investigation showed that elevated temperatures could lead to warm discomfort and make occupants vulnerable to heat stress during warm periods; while decreasing temperatures can cause cold discomfort and cold stress in cold seasons.

The research also evaluated the percentage of hours of temperatures that exceed the comfort limit of 28°C for more than 5% of the time in the spaces (Table 6). The outcomes revealed that the temperatures surpassed 5% of the time above 28°C in Classroom 2 during different occupied and non-occupied hours in the warm period. The study revealed the possibility of warm discomfort in the classrooms, especially in Classroom 2 during the warm period. The investigation showed that orientation of the space, floor level, and other variables could influence temperatures and thus affect occupants’ comfort and stress indices within the thermal environment. The temperatures did not exceed the comfort limit for more than 5% of the time in the other spaces. Table 6 provides a summary of the average values of the internal temperatures, WBGT, and UTCI in the spaces in the warm and cold periods.

Table 6. Average values of the parameters within the spaces in the warm and cold periods compared with the comfort model, WBGT, and UTCI heat indices

|  |  |  |
| --- | --- | --- |
| **Spaces** | **Warm Period** | **Cold Period** |
| **Mean temperature (°C)** | **Mean WBGT (°C)** | **Mean UTCI (°C)** | **Percentage of hours of temperature that exceeds 25°C/28°C** | **Mean temperature (°C)** | **Mean WBGT (°C)** | **Mean UTCI (°C)** | **Percentage of hours of temperature that exceeds 25°C/28°C** |
| Central office (lower floor) | 22.5 | 18.9 | 22.4 | 4.1/0 | 21.0 | 16.4 | 20.3 | 0/0 |
| Main hall (upper floor) | 20.6 | 18.4 | 21.2 | 0.5/0.1 | 19.2 | 16.0 | 19.0 | 0.6/0 |
| Classroom 1 (upper floor) | 22.2 | 18.2 | 21.9 | 8.0/0.1 | 20.4 | 14.4 | 19.1 | 0.1/0.1 |
| Classroom 2 (upper floor) | 24.1 | 19.7 | 23.8 | 29.2/5.0 | 20.3 | 15.4 | 19.4 | 0/0 |
| Classroom 3 (upper floor) | 23.1 | 19.0 | 22.8 | 18.5/2.6 | 20.2 | 14.8 | 19.1 | 2.3/0 |
| Combined - all spaces (total duration) | 22.5 | 18.8 | 22.4 | 12.1/1.6 | 20.2 | 15.4 | 19.4 | 0.6/0 |
| Central office (8am-5pm) | 22.6 | 18.7 | 22.4 | 4.1/0 | 21.2 | 16.7 | 20.5 | 0/0 |
| Main hall (8am-5pm) | 21.0 | 18.6 | 21.5 | 1.0/0 | 19.8 | 16.4 | 19.6 | 1.5/0 |
| Classroom 1 (8am-5pm) | 22.2 | 18.1 | 21.8 | 7.0/0.1 | 20.9 | 14.7 | 19.5 | 0.1/0.1 |
| Classroom 2 (8am-5pm) | 23.9 | 19.4 | 23.5 | 24.3/4.2 | 20.7 | 15.8 | 19.8 | 0/0 |
| Classroom 3 (8am-5pm) | 23.0 | 18.6 | 22.6 | 15.5/2.3 | 20.8 | 15.3 | 19.7 | 2.5/0 |
| Combined - all spaces (8am-5pm) | 22.5 | 18.7 | 22.4 | 10.4/1.3 | 20.7 | 15.8 | 19.8 | 0.8/0 |
| Central office (6pm-7am) | 22.5 | 19.0 | 22.5 | 4.1/0 | 20.9 | 16.8 | 20.4 | 0/0 |
| Main hall (6pm-7am) | 20.3 | 18.2 | 20.9 | 0.1/0 | 18.7 | 15.6 | 18.6 | 0/0 |
| Classroom 1 (6pm-7am) | 22.0 | 18.3 | 21.8 | 8.7/0.1 | 20.0 | 14.2 | 18.7 | 0/0 |
| Classroom 2 (6pm-7am) | 24.2 | 20.0 | 24.0 | 32.6/5.4 | 19.8 | 15.1 | 18.9 | 0/0 |
| Classroom 3 (6pm-7am) | 23.0 | 19.1 | 22.8 | 19.1/2.6 | 19.9 | 14.7 | 18.8 | 0/0 |
| Combined - all spaces (6pm-7am) | 22.4 | 18.9 | 22.4 | 12.9/1.6 | 19.9 | 15.3 | 19.1 | 0/0 |
| Central office (8am-10pm) | 22.6 | 18.8 | 22.4 | 4.6/0 | 21.1 | 16.6 | 20.4 | 0/0 |
| Main hall (8am-10m) | 20.9 | 18.5 | 21.4 | 0.8/0 | 19.6 | 16.3 | 19.5 | 1.0/0 |
| Classroom 1 (8am-10pm) | 22.1 | 18.1 | 21.7 | 8.3/0.1 | 20.8 | 14.7 | 19.4 | 0.1/0.1 |
| Classroom 2 (8am-10pm) | 24.0 | 19.5 | 23.6 | 25.4/6.4 | 20.7 | 16.0 | 19.8 | 0/0 |
| Classroom 3 (8am-10pm) | 23.1 | 18.8 | 22.7 | 16.5/3.5 | 20.5 | 15.1 | 19.4 | 1.2/0 |
| Combined - all spaces (8am-10pm) | 22.5 | 18.7 | 22.4 | 11.1/2.0 | 20.5 | 15.7 | 19.7 | 0.5/0 |

The research also examined if relationships are found between the average internal temperatures, RH, air velocity, WBGT, and UTCI values. The results showed that strong links are found between the variables, especially in the warm period. Stronger relationships exist between the parameters in the main hall and the central office than the classrooms in the cold period. A weak relationship exists between the average internal temperatures and RH in the spaces in the cold period. Also, Figure 6 and Figure 7 illustrate the level of relationships that are found between the variables in the central office in the warm and cold periods. Similar outcomes were also found in the other spaces. The investigation revealed that higher values of air velocity at increasing temperature do not have a noticeable impact on the UTCI values in the cold period (Figure 7).



Figure 6. The association between the average internal temperature, WBGT, UTCI, and RH in the central office during the warm and cold periods.

Figure **7**. The association between the average internal temperature, WBGT, UTCI, and air velocity within the central office during the warm and cold periods.

# *Relationship between the mean WBGT and UTCI*

The results also showed that strong links exist between the mean values of WBGT and UTCI in the warm and cold periods (Figure 8). The study noted that a combination of various personal and environmental factors could influence stress indices within the thermal environment. For instance, behavioural actions of users such as taking cold drinks during the elevated summertime temperatures or heat wave, regular intake of hot drinks during the cold period, physiological modifications, clothing insulation adjustments can reduce the risk of people to heat stress and cold stress within the thermal environment in various periods. The overall outcomes showed that an increase or decrease in the WBGT values has a significant effect on the UTCI values. The research highlighted the applicability of the WBGT and UTCI models for assessment of stress indices in different thermal conditions and periods.



Figure 8. The association between the average WBGT and UTCI during the warm and cold periods.

# *Comparison of findings from this study with findings from existing research*

 The research also compared the findings on the overall mean of WBGT and UTCI values with the findings presented in the existing papers in the field, as shown in Figure 9. The outcomes showed that higher average temperatures are reported in some of the existing research (Vatani et al., 2016) than the mean temperatures observed in the current research. The outcomes also showed that higher relationships exist between the parameters in some of the existing papers than the level of relationships reported in the current research in both periods. However, higher relationships and average temperatures are reported in the current research than the values reported in the existing paper (Lemke & Kjellstrom, 2012). The outcomes revealed the possible risk of heat stress and cold stress in different periods.



Figure 9. Comparison of the outcomes of the current research in the warm and cold periods with the existing papers on the association between the mean values of the WBGT and UTCI

# *Comparison of findings from this study with the thermal comfort standards*

The study also compared the internal temperatures measured in the selected spaces (central office, main hall, and classrooms) with the ASHRAE, the BSEN15251, and the CIBSE thermal comfort models to assess the thermal environment of the development. The spaces are expected to be naturally ventilated in summer, but they are not naturally ventilated in the cold period. Therefore, the study only considered the comparative results for the warm period. The outcomes showed that the internal temperatures are between the appropriate Category II upper and Category II lower thermal comfort bands for most of the time (Figure 10). The internal temperatures did not exceed the bands for over 5% of the time. However, different results were reported when the temperatures observed during the occupied hours (8am-5pm), non-occupied hours (6pm-7am), and extended occupied hours (8am-10pm) within the spaces are compared with the thermal comfort models. The results showed that the internal temperatures slightly exceed the Category II upper limits of most of the thermal comfort categories for about 5% of the time in Classroom 2 when the temperatures measured during the extended occupied hours (8am-10pm) were evaluated. In general, the investigation noted that regular use of regulators (like fans, openings such as large doors in the main hall), and more extended occupied hours as a result of different activities at the School might have contributed to lower temperatures observed during the on-site measurements in the spaces.



Figure 10. Average internal temperatures measured in the selected spaces of the development compared to the ASHRAE, BSEN15251, CIBSE thermal comfort categories.

# Conclusions

The research revealed that the internal temperatures of the spaces are within the appropriate thermal comfort categories (ASHRAE, BSEN15251, and CIBSE) evaluated in this study. However, the internal temperatures exceeded the applicable thermal comfort categories when the temperatures recorded in the classrooms (especially Classroom 2) during the extended occupied hours (8am-10pm). The applicability of the mathematical models to evaluate the stress indices showed the average WBGTs of 15.4°C and 18.8°C were computed for the cold and warm periods respectively. Similarly, the average UTCIs of 19.4°C and 22.4°C were computed for the cold and warm periods. The overall results revealed that no thermal stress was reported in the spaces. However, there is a possibility of moderate thermal stress when the temperatures recorded during the warmest months were evaluated in the classrooms. Also, a different outcome may be obtained if CLT school buildings in other regions are examined due to factors such as weather conditions. The research highlights that higher values of air velocity at warm temperatures do not have a noticeable effect on the UTCI values in the cold period but have a considerable effect on the parameter in the warm period.

The internal temperatures exceeded the 28.0°C comfort limit for about 5% of the time in one of the classrooms during occupied and non-occupied hours in the warm period. The research revealed that users of the case study might be prone to cold stress and heat stress during extreme cold and warm periods. The study also showed the occupants are susceptible to moderate thermal stress within the outdoor thermal environment of the development.

Since limited or no studies have examined thermal comfort, and stress indices in CLT school buildings, a comparative analysis of the findings obtained from this study with the findings from existing research on CLT school buildings in the region and other regions of the world could not be considered. Moreover, due to the location of the case study and weather conditions (mild summer and cold winter) during the field measurements, the investigation could not capture data that would help understand thermal comfort and stress indices in CLT school buildings under the extreme weather conditions. As a result, further research will be considered to address these limitations.

The practical implications of the study include the awareness of the importance of stress indices in school buildings and some design variables as well as other factors which may help in reducing the vulnerability of users to heat or cold stress within the thermal environment. The outcomes of the study showed occupants might be prone to heat or cold stress even in mild weather conditions, and more attention should be paid to the health and overall well-being of people in schools, especially in extreme weather conditions. Further studies should be considered by researchers to understand the thermal environments of schools built with different materials in extreme weather conditions and possible interventions and adaptive measures to improve occupants’ comfort. Designers should consider a thorough analysis to examine possible design strategies that could reduce discomfort and stress in buildings. School owners should ensure building regulations and codes are followed while regular assessments of schools should be considered to understand the thermal environment. Policy makers should work together with designers and researchers to make informed decisions and develop a reliable approach to improve thermal comfort in schools.

Finally, the study recommends that designers should consider thorough investigations on the possibility of cold and warm discomfort before recommending or introducing different interventions which might affect occupants’ comfort in buildings. The study also recommends that occupants should be able to regulate the indoor thermal environment in buildings that may be occupied outside the regulated occupied hours. Thus, limiting the users’ susceptibility to heat stress and cold stress in the warm period and cold period respectively.

# Acknowledgement

The author appreciates the authority for the permission to carry out on-site measurements at the development. The author declares no conflict of interest regarding this work.

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