Hygrothermal exposure in a nearly zero-energy school during heat waves

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Abstract

This study aims to inform the building designers about hygrothermal exposure risks in nearly zero-energy schools and the importance of evaluating these risks during short-term extreme heat events. The hygrothermal exposure in the reference school was evaluated using a metric called heat index [°C], which calculates the level of hygrothermal risks using air temperature [°C] and relative humidity [%]. Using DesignBuilder, a calibrated nearly zero-energy school energy model was created by Attia et al. (2020a) and then simulated using EnergyPlus. The building model was simulated for a 7-day heat wave. The study results confirm that the reference nearly zero-energy school from Brussels is highly susceptible to hygrothermal exposure with a risk level of caution for 98% of the occupied time during the heat wave. The study findings highlight the need to enhance the Belgian Energy Performance of Buildings Directive (EPBD) calculation methods and incorporate hygrothermal discomfort indicators to accurately depict the exposure risks due to the impacts of climate change.

Highlights

- Investigated the hygrothermal risks in a reference school during heat waves.
- The hygrothermal performance evaluation used a heat stress metric called heat index.
- Study findings indicate a risk level of caution in the reference school during heat waves.
- This can result in possible fatigue of students with physical activities and/or prolonged exposure.

Introduction

Due to the high occupancy rate and occupant vulnerability, indoor environmental quality in schools is important. Improper indoor environmental quality can have a long-term negative effect on health, according to Bluyssen (2016). These symptoms include headaches, coughing, and detrimental stress levels and mental clarity in students from Pulimeno et al. (2020). Furthermore, the ability to recuperate from the effects of outdoor heat stress will be inhibited by high indoor temperatures, as to Kovats and Hajat (2008) and Hamdy and Hensen (2015a). The predicted increase in average and extreme temperatures caused by global warming will make schools more uncomfortable and likely dangerous to students due to the high interior temperatures, as per studies from Hamdy and Hensen (2015b) and Hamdy et al. (2017) on dwellings. Hence, the building sector needs to go beyond the minimum standard performance requirements, as Mirzabeigi et al. (2022) suggested.

Studies like Singh et al. (2020) and Zomorodian et al. (2016) examined hygrothermal comfort in schools, and the findings concluded that students of various ages feel more comfortable in cooler temperatures on a thermal sensation scale. Furthermore, according to Zomorodian et al. (2016), the significance of creating comfortable indoor thermal conditions in these schools is highlighted by students spending more time at school than at any other place besides their homes. As productivity, well-being, and energy saving in schools are all related to thermal comfort, it has become more significant in recent years.

This study aims to look into the vulnerability of Belgian schools to hygrothermal exposure risks during heat waves. The objective is to perform a hygrothermal simulation for a real-world nearly zero-energy school from Brussels and to evaluate the risks of that case study using the heat index metric. This study adds to existing knowledge on the hygrothermal performance of schools from Figueroa-Lopez et al. (2023) and Almeida and de Freitas (2010). This study evaluated the hygrothermal performance of nearly zero-energy schools during heat waves, and this is relevant since:

1. The study identified the areas prone to hygrothermal exposure in the reference school and made practical recommendations to improve comfort.
2. This study identified potential hygrothermal issues that can disrupt building operations and made practical suggestions to avert significant damage.
3. It can improve future building designs to make them more resistant to hygrothermal exposure risks during heat waves.

The study's main aim was to investigate the impacts of short-term heat events, as in Attia (2021a), on the building performance of a benchmark model for nearly zero-energy schools in Brussels in a mixed humid climate (4A) as per ASHRAE standard 169 (2013). This was realized by evaluating hygrothermal risks at the reference school's building and zone levels. A foundation for integrating hygrothermal calculation methods into the existing EPBD tools in Belgium and other EU members is provided for practical implementation.

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The originality of this paper is that the study used an innovative climate change-sensitive selection and sizing approach using ISO 15927-2, and this approach accounted for the effects of climate change. Furthermore, the heatwave identification method was based on temperature distribution thresholds over several years and accepted in IEA EBC Annex 80 - Resilient Cooling of Buildings. The existing methodology from Royal Meteorology Institute in Belgium defines heat waves as a period of 5 consecutive days with maximum daily temperatures of 25 °C or more (summer days), which includes 3 days of 30 °C or higher (tropical days) as given by Brits et al. (2009). This definition based on absolute values does not consider climate variability around different locations in Belgium and thus is not considered.

Methods

The study conceptual framework that provides an overview of the methodology is shown in Figure 1. The study workflow is as follows:

1. Firstly, a dataset of monitored weather is prepared for the hottest period of the year in Brussels from July 11, 2022, to August 21, 2022.
2. Secondly, a heat wave identification method using the average daily air temperature distribution is used to identify heat waves.
3. Finally, the hygrothermal exposure in the reference nearly zero-energy school was evaluated using heat index [°C] for the detected heat wave.

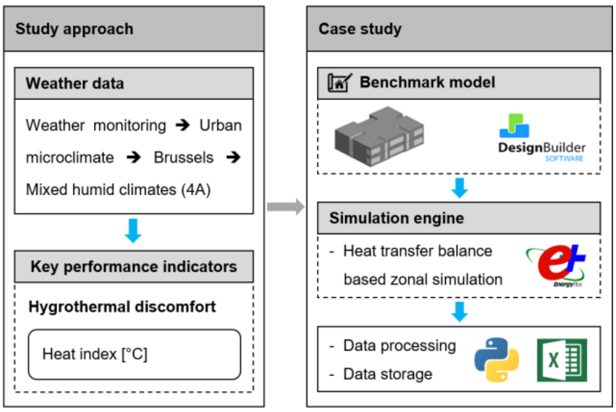


Figure 1: Proposed workflow of the study.

Heat wave identification

The heat wave identification approach used in this study was based on the percentiles of daily mean temperature distribution from the past several years according to the methodology from Ouzeau et al. (2016). This is an acknowledged method for identifying heat waves from IEA EBC Annex 80 – Resilient Cooling of Buildings. This approach was based on three thresholds with air temperature as an operational parameter, converted from absolute values to percentiles of the daily mean temperature distribution over several years.

The thresholds used for identifying heat waves are: (i) Sint (95 percentile) is the interruption threshold, which enables the merging of two consecutive heat waves without a significant drop in temperature, (ii) Spic (99.5 percentile) is the threshold beyond which a heat wave is detected, (iii) Sdeb (97.5 percentile) is the threshold that determines when a heat wave begins and ends. The heat waves in Brussels for the monitored period were identified using an in-house python developed by Joshi et al. (2022) based on Machard (2022). A heat wave from August 10, 2022, to August 16, 2022, with a global intensity of 6.8 °C.days, a maximum temperature of 27.2 °C, and a duration of 7 days was identified.

Key performance indicator

A hygrothermal discomfort metric called the heat index from National Weather Service (NWS) from the United States is used in the study to analyze the indoor environment in the reference building. NWS also calls it apparent temperature and measures how it feels when considering relative humidity [%] and air temperature [°C]. Hygrothermal discomfort is significant since sweating assists the body in cooling down and regulating its internal temperature. When the relative humidity is high, the evaporation process is less efficient, the human body cannot cool off as effectively, and the temperature will seem considerably hotter to the human body, as mentioned by Amaripadath et al. (2023a). This study examines the indoor heat index during the identified heat wave. The formula for heat index according to Weather Prediction Center (WPC) is given below in (1):

$$HI = -42.379 + 2.04901523 \cdot T_a + 10.14333127 \cdot RH - 0.22475541 \cdot T_a \cdot RH - 6.83783 \cdot 10^{-3} \cdot {T_a}^2 - 5.481717 \cdot 10^{-2} \cdot RH^2 + 1.22874 \cdot 10^{-3} \cdot {T_a}^2 \cdot RH + 8.5282 \cdot 10^{-4} \cdot T_a \cdot RH^2 - 1.99 \cdot 10^{-6} \cdot {T_a}^2 \cdot RH^2 \quad (1)$$

where T_a is air temperature [°C], and RH is relative humidity [%]. According to the air temperature [°C] and relative humidity [%] levels, different correction factors are applied to (1), and these factors are explained by National Weather Service (NWS). Heat index gives a more accurate description of how it feels and thresholds for how much heat the human body can take before it becomes unsafe. The following criteria describe the heat index risks: a. safe below 27 °C, b. maintain caution between 27 and 32 °C, c. maintain severe caution between 32 and 41 °C, d. under danger from 41 to 54 °C, and e. under extreme danger over 54 °C. The number of hours that fall into each heat index risk category by total occupied hours is the percentage of heat index hours, as in Luo et al. (2021).

Case study

A reference nearly zero-energy school representative for Belgium from Attia et al. (2020a) is used in this study to assess hygrothermal discomfort during heat waves. The General Data Protection Regulation (GDPR) of the European Union was followed in the data collection and analysis during the creation of the building model, as in Voigt and Von dem Bussche (2017). The chosen reference school was placed on level ground, far from any trees or other obstacles that would shadow the building's mass. Reinforced concrete posts and columns with 65 cm concrete hollow block walls, with insulation made of rigid polystyrene panels measuring 30 cm, make up the fundamental building structure. Windows has a solar heat gain coefficient as low as 0.5 and are triple-glazed, coated, and transparent with a conductivity of 0.8 W/m^{2}K. Between 25% and 45% of the total wall area comprises glazed surfaces in the northeast and southwest facades. The facades have no solar protection, and most windows have interior blinds. The average area and the number of students per classroom were used to calculate the average occupancy density for the chosen school.

The number of classrooms in the reference school was 10, with an average class area of 60.4 m^2. The occupancy density and schedules were 7.2 m^2/student, from 07h00 to 18h00 on weekdays and unoccupied during the weekend. The lighting load was estimated to be 6 W/m^2. A centrally located daylight sensor is connected to a daylight management system to control the lighting. EN 12464-1 (2011) shows the required level of illuminance in classrooms. Considering the clothing insulation and metabolic rate, the internal equipment load intensity was calculated based on EN 16798-1 (2019) and ter Mors et al. (2011). The equipment heat gains were estimated to be 1 W/m^2, while the occupant internal heat gains were 80 W/pers. With a plug load density of 5 W/m^2, all classrooms were modeled without computers, assuming only teachers can access computers, making it a negligible load. The cooling energy use intensity was estimated at 4 kWh/m^2/year.

The reference school has mechanical ventilation with heat recovery installed. According to the occupancy schedule for the school day, the HVAC system is coupled to an air handling unit in the technical rooms with a Constant Air Volume (CAV) system to deliver a minimal amount of fresh air per person of 20 m^3/h, based on the average Flemish and Walloon EPBD requirements for the occupant's age and degree of activity as per EN 13779 (2007). The CAV system modulates the volume of air that feeds a classroom while also providing a supply air stream with changing temperatures. The chosen school has mechanical cooling systems modeled using a variable refrigerant flow (VRF) system. The reference benchmark school model used in this study is illustrated in Figure 2.

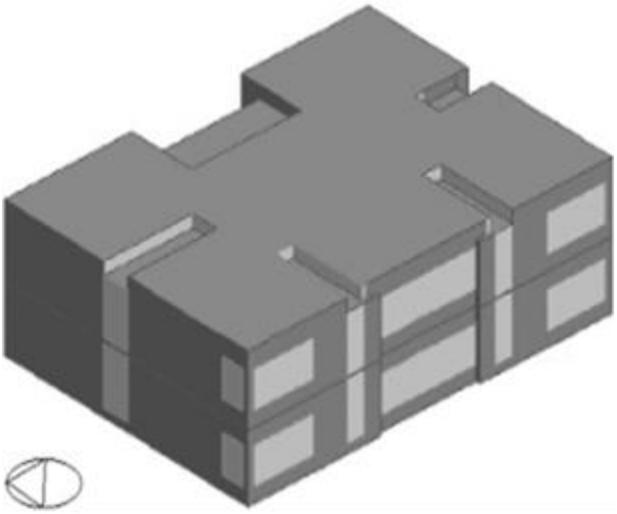


Figure 2: Benchmark nearly zero-energy school in Brussels, Belgium.

To ensure the quality of numerical simulations, the benchmark model was calibrated according to ASHRAE Guideline 14 (2014). The Mean Bias Error (MBE) and Coefficient of the Variation of the Root Mean Square Error (CV(RMSE)) for monthly electricity use for 2018 were determined. The calculated MBE and CV(RMSE) for electricity use were 4% and 2%, which were within the permissible ranges of ± 5% and ± 15%, respectively. More information on the reference nearly zero-energy schools can be found in Attia et al. (2020a). The reference benchmark nearly zero-energy school with the rendered view and model data is shown in Figure 3.

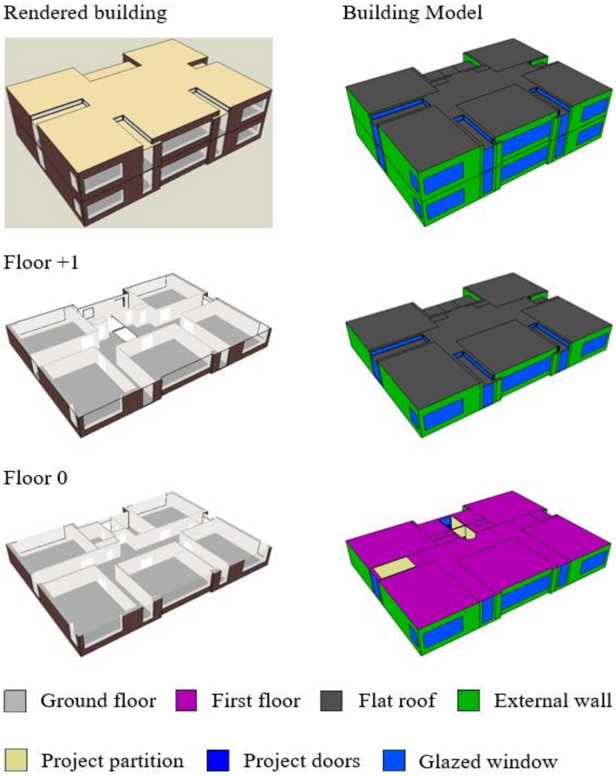
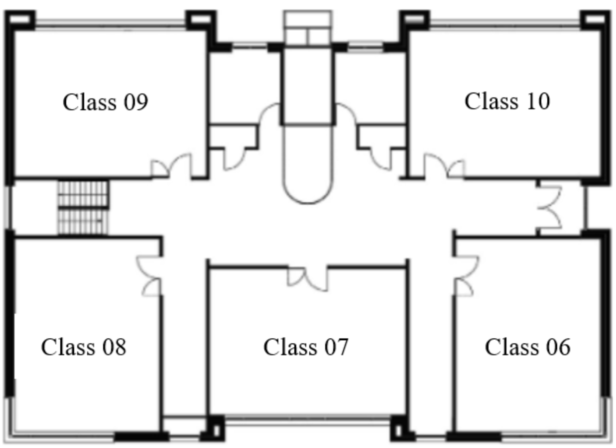


Figure 3: DesignBuilder model data for the benchmark nearly zero-energy school.

The floor plans of the reference nearly zero-energy school are shown in Figure 4. The building zones from Class 01 to Class 10 are evaluated for hygrothermal exposure risk in this study. Hourly air temperature [°C] and relative humidity [%] values are used for the evaluation.

Floor +1



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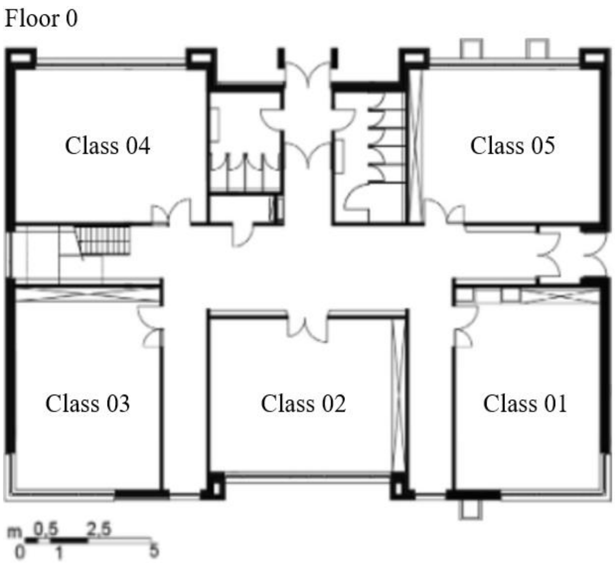

Figure 4: Benchmark nearly zero-energy school plans.

The maximum dry-bulb temperature, coincident wet-bulb temperature from Żuławińska (2022) and Vecellio et al. (2022), and minimum dry-bulb temperature according to climate change-sensitive sizing as per Amaripadath et al. (2023b) was set at 39 °C, 19.3 °C, and 22 °C.

Results

The characterization of hourly heat index [°C] calculated from air temperature [°C] and relative humidity [%] in the reference nearly zero-energy school is shown in Figure 5. The study results indicate that the heat index [°C] remained between 27 °C and 32 °C during the analysis period. This was evident for zone-level and building-level characterization. This puts the reference school at risk level of caution during the heat wave.

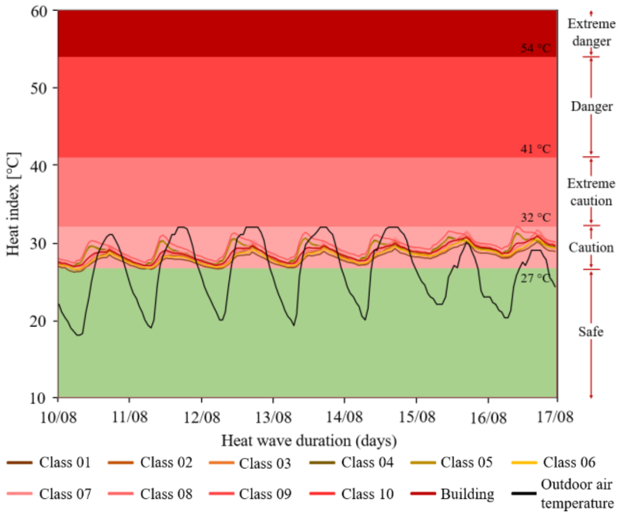

Figure 5: Characterization of hourly heat index [°C]in the reference school during the heat wave.

Further analysis with the percentage of heat index hours [%], which is the percentage of hours within each risk level by the total number of occupied hours during the analysis period, is illustrated in Figure 6. Here, the hygrothermal exposure risk is quantified using the reference school's air temperature [°C] and relative humidity [%]. The investigated case study suffers from a hygrothermal risk under caution for up to 98% of occupied hours on the building level during the heat wave. This indicates that heat index levels are consistently between 27 °C and 32 °C in the reference school. Even the relatively safer zones like Class 01, 02, and 03 were under caution for 83% of occupied hours. Consequently, the students will be exposed to fatigue with physical activities and/or prolonged exposure, indicating that the reference school could not suppress hygrothermal risks.

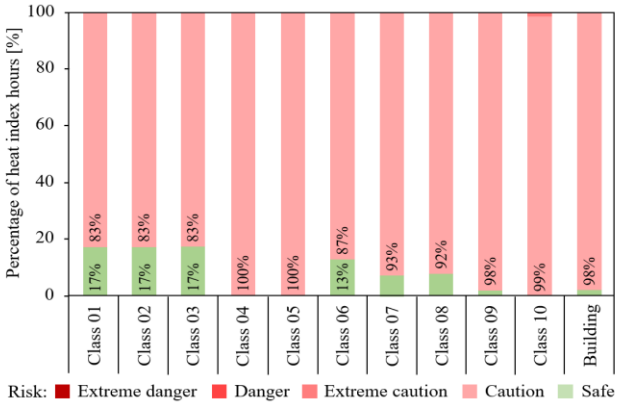

Figure 6: Percentage of heat index hours [%] with risk levels in the reference school during the heat wave.

Discussion

The main findings from the study are that many primary schools in Belgium will be exposed to hygrothermal risks, creating health effects like fatigue in the students. The current passive and active cooling strategies implemented in the reference nearly zero-energy school alone will not be able to suppress the heat stress. It will require further mitigation strategies against short-term extreme heat events. Even the relatively less affected classrooms are still under caution for most of the occupied period. So based on current building configurations, the school should not be occupied during heat waves to avoid detrimental impacts on student health. The observed classrooms' heat index varies slightly, according to Figure 5. This seems plausible given the relatively small size of the reference school and the nearly identical size of the classrooms. Figure 6 also suggests that Classrooms 04, 05, 09, and 10 have the greatest risk of heat exposure.

The main recommendations are that building designers should look into passive measures like solar shading and active cooling systems to mitigate hygrothermal exposure safely in the reference school. In addition to the building scale cooling measures, implementation of neighborhood scale measures like increased vegetation was found to drop the temperature in humid and arid areas by 0.14 °C to 0.20 °C for a 1% increase in urban tree cover as per Middel et al. (2012) and Skelhorn et al. (2014). A post-occupancy study and long-term field monitoring are critical to evaluate the occupant sensation and perception towards hygrothermal discomfort and their capacity for adaptation, as in Attia (2020b). Adaptive and static hygrothermal comfort models should also be developed using quantitative measurements and qualitative surveys.

The study's main strength is that a calibrated model for nearly zero-energy schools in Belgium was used.

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Buildings Performance Institute Europe (BPIE) experts have identified using validated benchmark models to evaluate building performance as being of significant importance, according to Atanasiu (2011). The regional EPBD experts' design decisions for effective building operations will be greatly influenced by benchmark models, according to Attia et al. (2020a). The main limitation of the study methodology is that it was performed for the most recent heat wave in Brussels with an intensity of 6.8 °C.days. However, findings from Sakka et al. (2012) predict that longer and more intense heat waves will become the norm in the future. With a predicted increase in outdoor air temperature in the future, this will only exacerbate hygrothermal exposure.

The main implication of practice and research is that the Passive House and EPBD require significant changes in hygrothermal discomfort analysis. It must include other metrics like cooling and dehumidification energy use and accompanying carbon emissions, as Attia et al. (2021) suggested. The effectiveness of the heat index metric should be further investigated to more accurately represent the effects of urban heat islands, outdoor solar radiation, and sky conditions and adjust them to the Belgian climate. The study findings can be universally applied to develop a standardized methodology for assessing hygrothermal risks in Europe. Future studies should address factors affecting occupant well-being, like the impact of adaptive facades Attia et al. (2019), envelope u-values, ventilation, infiltration, internal equipment gains, solar gains, and proximity to adjacent structures. A sensitivity analysis using building energy performance simulations would be recommended, as in Mahar et al. (2020), to find the influence of these parameters on hygrothermal exposure.

Conclusion

A multi-story nearly zero-energy school model, which represents primary schools in Belgium, was used for the study. The study used a heat index metric for hygrothermal performance evaluation of the reference school during a heat wave. Heat waves will significantly negatively impact the building's performance, and building owners and operators should be aware of possible heat-related issues. The occupant's comfort and needs should take precedence during heat waves. The Passive House Standard does not include hygrothermal performance in its calculation methods. Under the current climate change conditions, primary schools in Belgium face a major hygrothermal exposure risk during heat waves, according to the performance evaluation of the reference school from Belgium. Based on the findings, the study provides a set of suggestions to the policymakers and building professionals to update the existing EPBD norms and standardize the hygrothermal risk estimation and calculation in Belgium and, to a larger extent, Europe. In addition, the study highlights the hygrothermal exposure risks in primary schools.

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References

Almeida R. and de Freitas V. P. (2010). Hygrothermal performance of Portuguese classrooms: Measurement and computer simulation. *Proceedings from 1st Central European Symposium on Building Physics*. Krakow (Poland), 13–15 September 2021.

Amaripadath D., et al. (2023a). A systematic review on role of humidity as an indoor thermal comfort parameter in humid climates. *Journal of Building Engineering 68*, p. 106039.

Amaripadath D., et al. (2023b). Climate change sensitive sizing and design for nearly zero-energy office building systems in Brussels. *Energy and Buildings 286*, p. 112971.

ANSI/ASHRAE (2013): *Climatic data for building design standards (ASHRAE Standard 169)*.

ANSI/ASHRAE (2014): *Measurement of energy, demand, and water savings (ASHRAE Guideline 14)*.

Atanasiu B. (2011). Principles for nearly Zero-energy Buildings: Paving the way for effective implementation of policy requirements. *Buildings Performance Institute Europe*, p. 124.

Attia S., Rahif R., Fani A., and Amer M. (2021). Comparison of overheating risk in nearly zero energy dwelling based on three different overheating calculation methods. *Proceedings from IBPSA Building Simulation Conference*. Bruges (Belgium), 01–03 September 2021.

Attia S., Shadmanfar N., and Ricci F. (2020a). Developing two benchmark models for nearly zero energy schools. *Applied Energy 263*, p. 114614.

Attia, S. (2020b). Spatial and behavioral thermal adaptation in net zero energy buildings: An exploratory investigation. *Sustainability 12*, p. 7961.

Attia S., Garat S., and Cools M. (2019). Development and validation of a survey for well-being and interaction assessment by occupants in office buildings with adaptive facades. *Building and Environment 157*, pp. 268-276.

Bluyssen P. M. (2017). Health, comfort and performance of children in classrooms – New directions for research. *Indoor and Built Environment 26(8)*.

Brits E., et al. (2009). Climate change and health - Set-up of monitoring of potential effects of climate change on human health and on the health of animals in Belgium. *Scientific Institute of Public Health*.

https://doi.org/10.26868/25222708.2023.1160

European Committee for Standardization (2011): *Light and lighting - Lighting of work places - Part 1: Indoor work places (EN 12464-1)*.

European Committee for Standardization (2007): *Ventilation for non-residential buildings – performance requirements for ventilation and room-conditioning systems (EN 13779)*.

European Committee for Standardization (2019): *Energy performance of buildings – Ventilation for buildings – Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (EN 16798-1)*.

Figueroa-Lopez A., Oregi X., Almeida M., and Hernández-Minguillón R. J. (2023). Evaluation of hygrothermal comfort in educational centres by monitoring three case studies with different ventilation systems in Vitoria, Spain. *Journal of Building Engineering 65*, p. 105591.

Hamdy M. and Hensen J. L. M. (2015a). Ranking of dwelling types in terms of overheating risk and sensitivity to climate change. *Proceedings from IBPSA Building Simulation Conference*. Hyderabad (India), 07–09 December 2015.

Hamdy M. and Hensen J. L. M. (2015b). Assessment of overheating risk in dwellings. *Proceedings from Healthy Buildings Europe*. Eindhoven (The Netherlands), 18–20 May 2015.

Hamdy, M., et al. (2017). The impact of climate change on the overheating risk in dwellings – A Dutch case study. *Building and Environment 122*, pp. 307–323.

Joshi M. Y., Amaripadath D., Machard A., and Attia S. (2022). Heatwaves identification classification and visualisation with python. *Zenodo*.

Kovats S., and Hajat S. (2008). Heat Stress and Public Health: A Critical Review. *Public and Environmental Health Research Unit 29(9)*. pp. 1–9.

Luo X., Hong T., and Sun K. (2021). Simulating thermal resilience of buildings and their influence by urban microclimate using EnergyPlus. *Proceedings from IBPSA Building Simulation Conference*. Bruges (Belgium), 01–03 September 2021.

Machard A. (2022). AMachard/Assembling-future-weather-files-including-heatwaves. *Zenodo*.

Mahar W. A., Verbeeck G., Reiter S., & Attia S. (2020). Sensitivity analysis of passive design strategies for residential buildings in cold semi-arid climates. *Sustainability 12(3)*, p. 1091.

Middel A., Chhetri N., and Quay R. (2015). Urban forestry and cool roofs: Assessment of heat mitigation strategies in Phoenix residential neighborhoods. *Urban Forestry & Urban Greening 14(1)*, pp. 178–186.

Mirzabeigi S., Homaei S., Razkenari M., and Hamdy M. (2022). The impact of building retrofitting on thermal resilience against power failure: A case of air-conditioned house. *Proceedings from Conference on Building Energy and Environment*. Montreal (Canada), 26–29 July 2022.

NWS. What is the heat index? *National Weather Service*.

Ouzeau G., et al. (2016). Heat waves analysis over France in present and future climate: Application of a new method on the EURO-CORDEX ensemble. *Climate Services 4*, pp. 1–12.

PHPP (2010). Passive house certificate.

Pulimeno M., Piscitelli P., Colazzo S., Colao A., and Miani A. (2020). Indoor air quality at school and students' performance: Recommendations of the UNESCO Chair on Health Education and Sustainable Development & the Italian Society of Environmental Medicine (SIMA). *Health Promotion Perspectives 10(3)*, pp. 169–174.

Sakka A., Santamouris M., Livada I., Nicol F., and Wilson M. (2012). On the thermal performance of low income housing during heat waves. *Energy and Buildings 49*, pp. 69–77.

Singh M. K., et al. (2019). Progress in thermal comfort studies in classrooms over last 50 years and way forward. *Energy and Buildings* 188–189, pp. 149–174.

Skelhorn C., Lindley S., and Levermore G. (2014). The impact of vegetation types on air and surface temperatures in a temperate city: A fine scale assessment in Manchester, UK. *Landscape and Urban Planning 121*, pp. 129–140.

ter Mors S., Hensen J. L. M., Loomans M. G. L. C., and Boerstra A. C. (2011). Adaptive thermal comfort in primary school classrooms: Creating and validating PMV-based comfort charts. *Building and Environment 46(12)*, pp. 2454–2461.

Vecellio D. J., Wolf S. T., Cottle R. M., and Kenney W. L. (2022). Evaluating the 35°C wet-bulb temperature adaptability threshold for young, healthy subjects (PSU HEAT Project). *Journal of Applied Physiology 132(2)*, pp. 340–345.

Voigt P, Von dem Bussche A. (2017). The EU general data protection regulation (GDPR). Practical guide 1st ed, *Springer International Publishing AG*.

WPC. The heat index equation. *National Weather Service*.

Zomorodian Z. S., Tahsildoost M., and Hafezi M. (2016). Thermal comfort in educational buildings: A review article," Renewable and Sustainable Energy Reviews 59, pp. 895–906.

Żuławińska J. "Wet bulb calculator," *Omni Calculator*.

https://doi.org/10.26868/25222708.2023.1160