Evaluation of thermal resilience to overheating for an educational building in future heatwave scenarios

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ABSTRACT

Airtight and highly insulated buildings are subjected to overheating risks, even in moderate climates, due to unforeseeable events like frequent heatwaves and power outages. Educational buildings share a major portion of building stocks and a large percentage of the energy is expended in maintaining thermal comfort in these buildings. Overheating risks in educational buildings can lead to heat-stress and negatively impact the health conditions and also cognitive performance of the occupants. In the light of increasing severity and longevity of heat waves in future climate scenarios, and associated power outages occurring during the heatwaves, measures to reduce overheating risk while limiting the cooling energy is gaining importance. Since the performance of existing buildings are not guaranteed during events like heatwaves, power outages, it is crucial for these buildings to be resilient to overheating. (Building) resilience is a method to deal with these uncertainties and is stated as "an ability of the building to withstand disruptions; and to maintain the capacity to adapt, learn and transform." The focus of this paper is to evaluate thermal resilience for two test lecture equipped with low-energy cooling strategies like natural night ventilation (NNV) and indirect evaporative cooling (IEC) rooms, by dynamic Building Energy Simulations (BES). To assess the thermal resilience to overheating three different heatwaves (HW) files (intense, severe, and longest) for 3 future scenarios (1) Historical (2010-2020), (2) mid-term (2041 -2060) and (3) long-term (2081-2100) and a 24h power outage (PO)scenario was simulated. Benchmarking was done with a base case- Typical Meteorological year(TMY) with no power outage. The heatwave files were developed adopting the methodology proposed by the 'Weather Data Task Force' of International Energy Agency Energy in Buildings and Communities Programme (IEA EBC) Annex 80 "Resilient Cooling of Buildings". This study shows, IEC has high to moderate recovery capacity in TMY period and low recovery capacity in HW period, for a power outage of 24 h. Recovery capacity is low during HW period, especially during an intense and longer HW period when outdoor temperature influences the cooling capacity of the IEC. The results also demonstrates the impact of the thermal mass on the resilience to overheating. Passive survivability assessment indicates, the lecture room with lighter thermal mass does not violate 30°C threshold during a power outage in TMY period and additionally,. recovers faster (11% times faster) from peak temperature compared to lecture room with heavy thermal mass. There is a steep increase in unmet degree hours (occupied hours above24°C threshold) during HW compared to TMY period. This paper gives a directive towards assessment of resilience to overheating and also points out the gap in the existing indicators to assess the resilience.

KEYWORDS
Overheating, Thermal Resilience, Educational Buildings, Heatwaves, Power Outages

1 INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC)s 2022 report warns about the severity of the climate change impacts (stronger storms, frequent heatwaves, droughts etc.) in future climate scenarios and also stresses on adaptation and mitigation plans[1]. In Europe, the last two decades have witnessed 18 of the warmest years on record, and an increase in the frequency and intensity of extreme weather events [2]. Warmer summers and frequent heatwaves will lead to higher outdoor temperature which in turn will surge the overheating risk in buildings. Overheating in buildings is expected to increase as global warming continues [3]. Buildings in even moderate climate like Belgium are subjected to climate change and frequent heatwaves, increasing the overheating risk and cooling energy need in buildings[4][5]. Heatwaves are often associated with power outages due to pressure in the grid for peak electricity demand[6]. Educational buildings accounts for a large share of building stocks and are responsible for high energy consumption due to high occupant density with intermittent use, increased airtightness, and high glazing ratio. A major portion of this energy use is expended to provide thermal comfort in the classrooms. The thermal environment in the educational buildings impacts the health of the occupant's well-being and the cognitive performances[7]. Since the occupants spends a large share of time in the classrooms and in educational buildings, it is also fundamental to ensure thermal comfort in classrooms.. Currently, these educational buildings, have implemented energy efficient technologies and practices (e.g., high-insulation, airtight envelopes, improved glazing, natural ventilation, passive cooling strategies to mitigate climate change through reducing carbon emissions. However, overheating has become a recurring problem in these buildings proving that "excessive striving for energy efficiency" could compromise a building's ability to maintain comfortable thermal conditions during heatwaves[3][8]. Thus, to avoid any health risks due to overheating in these educational buildings, these buildings need to assess and improve the resilience to overheating apart from its energy performances.

Building Resilience can be defined as "An ability of the building to withstand disruptions; and to maintain capacity to adapt, learn and transform" [9][10]. Thus, apart from energy performance, resilience is gaining importance to assess building performance [11] [12] and can be considered as a primary function of the building [13]. Thermal Resilience can be assessed by existing indicators like Thermal Autonomy[14],Passive survivability [15] and Recovery Capacity [16]. Thermal autonomy (TA) is the percentage of occupied hours when indoor operative temperature is inside limits of thermal comfort without intervention of active systems. Passive survivability (summer) refers to the time (in hours) from when cooling is shut off to when the indoor operative temperature reaches 30 °C from original cooling set-point of 24 °C. Recovery capacity is the rapidity of the restoration of the normal functions, i.e., the time taken by the building and the system to get back thermal comfort temperature from the peak temperature in the building.

The objective of this paper is to evaluate the thermal resilience of two test lecture rooms in Technology Campus Ghent, KU Leuven. For this a base case scenario during a TMY file with no shock or power outage (PO) is compared to 3 types of heatwave (HW) (intense, severe, and longest) for historical (2001-2020),future mid-term (2041-2060) and future long-term (2081-2100) scenarios. Additionally, the impact of a 24-hour power outage on the hottest day of the TMY and HW scenario was also assessed. Performance of the test lecture rooms and the passive cooling technologies like -indirect evaporative cooling (IEC) and the natural night ventilation (NNV) will be evaluated by thermal comfort indices like degree hours and thermal resilience indicators like the passive survivability and recovery capacity.

2 MATERIAL AND METHOD

2.1 Case Study Building

The case study building is a nZEB educational building consisting of two test lecture rooms built on top of an existing university building at the Technology Campus Ghent, KU Leuven. The building consists of four zones: two test lecture rooms (E120-first floor and E220-second floor), a staircase and a technical room. The floor area and the volume of each test lecture rooms are 140 m^2 and 380 m^3 respectively. The test lecture rooms are identical in design with different thermal mass. E120 has external insulation with a brick external wall, whereas E220 has a lightweight timber frame external wall with the same U-value. Both the rooms have concrete slab floor. Thus, E220 has a light and E120 has a medium thermal mass according to the EN ISO 13790[6].

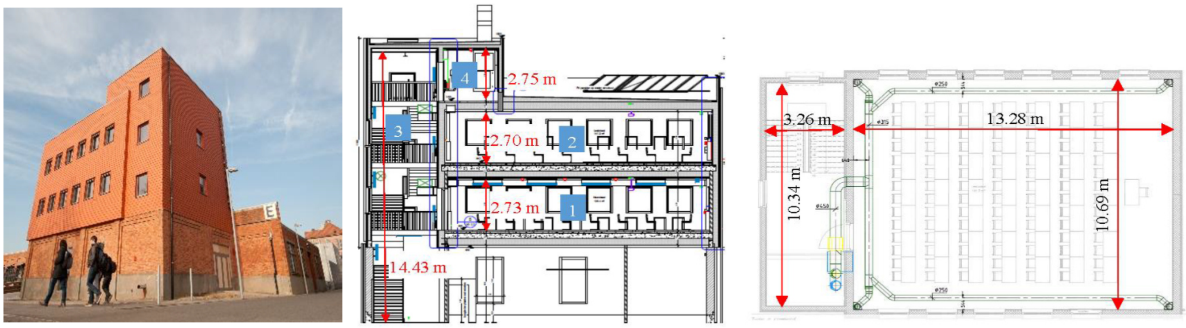


Figure 1. Section (left) and floor plan with sensors(right) of the case study building

Figure 1 shows the actual photograph, section and plan of the test lecture rooms. **Error! Reference source not found.** indicates the U-values indicating the building properties. The educational building is designed and constructed according to the Passive House Standard, meaning that the air tightness n_{50} is lower than 0.6 h^{-1} and the u-values of the building envelope are lower than 0.15 W/m^2K. The air tightness n50 value of E120 and E220 are 0.41 h^{-1} and 0.29 h^{-1} respectively. There are triple glazed windows (u-value: 0.65 W/m^2K, g-value: 0.52) on the south-west facade and 4 windows in the north-east façade. The window-to-wall ratio is 26.5% on both facades. The window-to-floor ratio is 13%. The windows on the South-West façade are equipped with internal and external solar shading. Movable screens on the southwest façade acts as the external shading, which are controlled automatically (shading is ON when the radiation on the windows is above 250 W/m^2). The shading control is also provided with manual overrule. The net energy demand for heating the test lecture rooms are calculated in [17]. The annul net demand is 11 kWh/(m2.a), achieving the requirements of Passive House standard in school buildings[18].

Table 1. Construction packages and u-values

Construction package	u-value
External Wall (E120 and E220)	0.15 (W/m^2K)
Roof	0.14 (W/m^2K)
Floor	0.15 (W/m^2K)

2.2 HVAC and control strategies

The building is equipped with an all-air system with balanced mechanical ventilation with a total supply airflow of 4400 m3/h. 4 Variable Air Volume (VAV) boxes control the airflow of the demand-controlled ventilation system. The airflows are based on CO2 concentrations and temperature in the rooms. For heating, the air is pre-heated by air-to-air heat recovery with heat exchangers with an efficiency of 78%. Additionally, heating coils of 7.9 kW each are integrated in the supply ducts for each lecture rooms. A condensing wood pellet boiler with an internal storage of 600l is the heat source. The maximum heating power is 8kW and the maximum efficiency is 95%. The two lecture rooms are passively cooled by –(a) natural night ventilation and (2) indirect evaporative cooling at the air handling unit that cools the supply air by controlling the modular bypass. Natural night ventilation relies on the 10 motorized windows with chain actuators (6 on the South-west facade and 4 in the North-east façade), located 1 m height from the bottom of the floor heights. The design of the ventilative cooling system is described in [17]. The total effective operable area of these windows is 4% of the floor area. For the IEC operation- both the modular bypass and the IEC are part of the Air Handling Unit (AHU). When the IEC is operation, the AHU supplies the maximum flowrate of 4400m^3/h. The maximum capacity of the IEC is 13.1 kW.

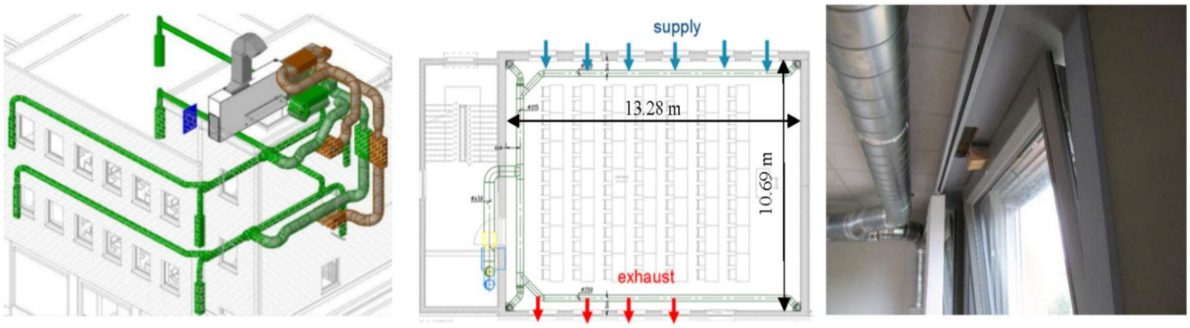


Figure 2. Ventilation system(supply in green, return in brown)(left) of the test lecture rooms and principle of natural night ventilation (middle) and detail of motorized window(1.29 x 1.38 m^2, maximum opening angle 8.8°) (right)[19]

Control strategy for the IEC and the natural night ventilation depends on the internal and external conditions. For the IEC operation, the valves in the supply side of the AHU regulates the air flow either through the IEC or through the modular bypass depending on the external conditions. For natural night cooling strategy regulates the opening of the window on both sides of the room if the internal and external conditions for the control strategy are met. Control strategy of the operation of IEC and the modular bypass is based on the internal and external temperature. This strategy actuates the supply air temperature and the air flow rate. When the room air temperature exceeds the cooling setpoint by +4°C, IEC is activated. IEC is deactivated when the room temperature reaches setpoint -0.5°C. [19]. Control strategy of the natural night ventilation is based on internal temperature and relative humidity, and external conditions like outdoor temperature, wind velocity, precipitation. Once open, the window will remain open for at least 15 min. The windows are open between 10 pm to 6 am from 1st April to 31st October if the following conditions are met:

- Room temperature exceeds both the heating set point (=22°C) and the external temperature +2°C
- Maximum room temperature of the previous day exceeds 23°C
- External temperature is higher than 12°C
- Internal relative humidity is smaller than 70%
- There is no rainfall and the wind velocity on site is smaller than 10 m/s

2.3 Occupancy schedules

Typical occupancy for both E120 and E220 are shown in Figure 3.

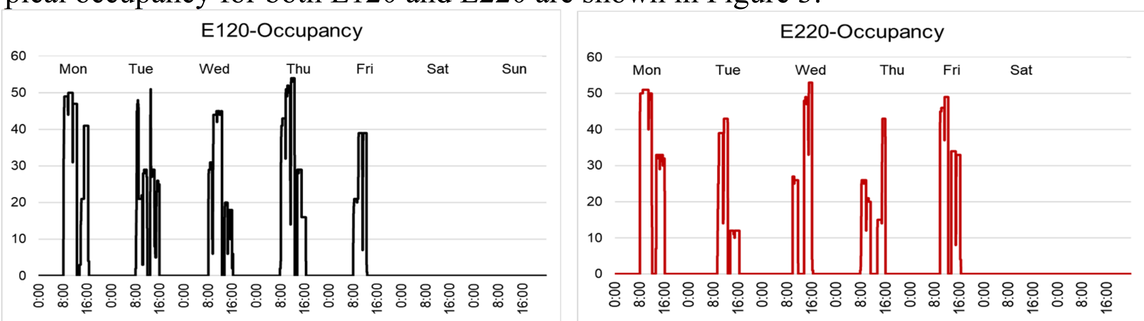


Figure 3. Occupancy schedule of E120 and E220 from Monday to Friday. The classes are scheduled between 8:15 am to 18:00 pm

The occupancy level in the building depends on the academic year, which consists of 124 days with courses and 63 days with examinations (in January, June, and August-September. Holiday periods are in April (2 weeks), July and the first half of August (6 weeks) and December–January (2 weeks). The lecture rooms are in use from Monday to Friday between 8 h15 and 18 h with a maximum occupancy of 80 persons or 1.78 m2/pers.

3 Methodology

3.1 Weather Data

Two types of weather data sets- (a) observational weather data from the weather station of the Ghent Technology campus, KU Leuven, and (b) Typical meteorological year and heat wave data for 3 period -historical (2010s), mid-term (2050s) and long-term(2100s) formulated adapting the method adopted by the Weather data task force of IEA Annex 80 was used for the model validation and dynamic simulations. A TMY weather data for Ghent was used as base case scenario. For historic and future heatwaves, only 3 types of heatwaves for each 7of the 3 periods- intense, severe, and longest was chosen for the simulations. Figure 4 shows all the heatwaves for all 3 periods and indicates the heatwaves chosen for the simulations. The diameter of the circle represents the severity of each heatwave. The centre of the circle on x axis is the duration(days)of each heatwave and on y axis is the intensity(°C) of the heatwave.

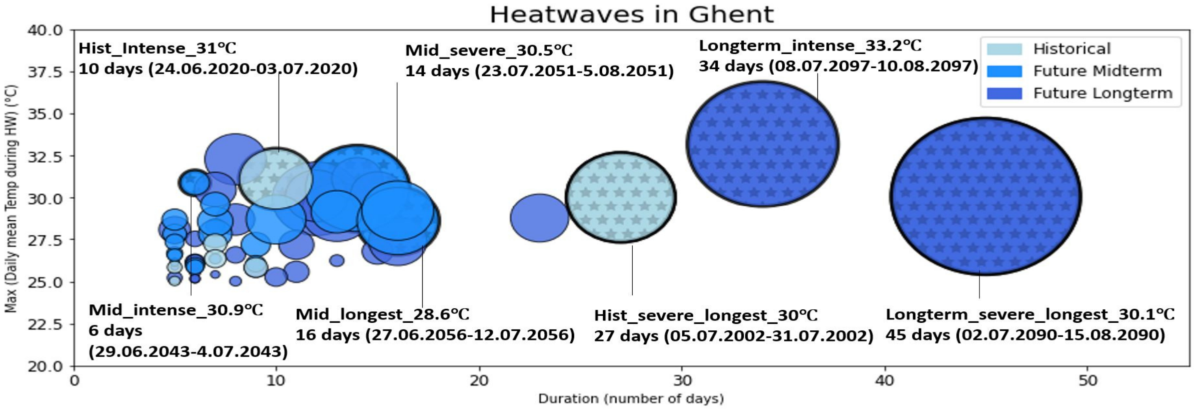


Figure 4. Heatwaves in Ghent for 3 period -Historical (2000-2020), mid-term (2041-2060) and long-term (2081-2100)

Table 2. Weather data used for simulations and the duration and occurrence period for heatwaves

Data	Duration of HW (days)	Data TMY	PO during TMY	Data HW	PO during HW
Historical Intense	10	TMY 1A	PO TMY1A	HW 1A	PO HW 1A
Historical Severe and Longest	27	TMY1B	PO TMY 1B	HW 1B	PO HW 1B
Mid-term Intense	6	TMY2A	PO TMY 2A	HW 2A	PO HW 2A
Mid-term Severe	14	TMY2B	PO TMY 2B	HW 2B	PO HW 2B
Mid-term Longest	16	TMY2C	PO TMY 2C	HW 2C	PO HW 2C
Long-term Intense	34	TMY3A	PO TMY 3A	HW3A	PO HW 3A
Long-term Severe and Longest	45	TMY3B	PO TMY3B	HW 3B	PO HW 3B

3.2. Evaluation of thermal comfort and thermal resilience

For thermal comfort assessment, Unmet degree hour (UDH) is used as the key performance indicator[20]. The concept of UDH is comparable to that of temperature-weighted exceedance hours, a metric defined in ASHRAE Standard 55–2017[21]. The UDH metric weighs each hour that the temperature of a conditioned zone exceeds a certain threshold (calculated once for each- 24°C, 25°C and 28°C) by the number of degrees Celsius by which it surpasses that threshold. UDH are calculated as follows:

$$UDH=\int_{t1}^{t2}[T(t) - T_{threshold}]^{+}dt \quad (1)$$

where T is the indoor air temperature [°C]; $T_{threshold}$ is the temperature threshold [°C]; t is time [h]; and x + = x if x>0, or 0 otherwise.

For thermal resilience assessment two indicators-(1) Passive Survivability and (2) Recovery capacity was used. For passive survivability assessment, the time taken for lecture rooms to reach 30 ℃, once the power outage occurs, and the time taken for each lecture rooms to return below 30 ℃ once the power restored is calculated. Similarly for recovery capacity, the time taken for lecture rooms to reach 24℃ from the highest temperature reached in that period is calculated. The recovery capacity is considered high if the zone is gets back below 24℃ in less than 1-hour, medium if the time taken is below 24 hour and low if the time is more than 24 hours.

3.3.Building Energy Simulations (BES)

The two test lecture rooms and HVAC system are modeled in Modelica[22]. The output of these simulations are the operative indoor temperatures of E120 and E220 and operation of IEC and the operable windows for natural night ventilation. To assess the thermal comfort during summer, simulations are conducted for each heat wave period and the corresponding same period in a typical year data with typical occupancy (see Figure 3). The thermal resilience assessment is done during the heat wave period and the period after a 24-hour power outage is implemented on the hottest day of the heat wave and the corresponding hottest day in the TMY period. The objective is to determine the performance of the two test lecture rooms in terms of thermal comfort and thermal resilience, i.e., number of hours after the power outage temperature remains below 30℃ and the number of hours it takes for the building to drop the temperature below 30℃ again when the power is turned back on.

3.4. Validation of the simulation model

Before the thermal comfort and thermal resilience indicators can be evaluated, the simulation model needs to be validated. Long term measurements of parameters like temperature, CO2, relative humidity, and AHU are conducted for both the rooms[19].

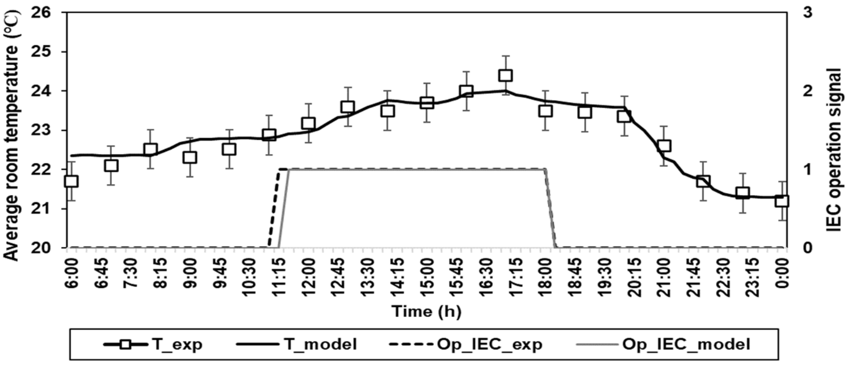


Figure 5. Comparison of the indoor operative temperature of the simulation result with the monitored data in E120

Comparison of the measured data on-site with simulated indoor operative temperatures for test lecture E120 has been done for the 17.09.2021. Figure 5 shows the comparison of indoor operative temperature for the monitored and simulated data. Method adopted in [23] is used to validate the simulation model. The mean absolute error between the simulated model temperatures and the monitored temperature is 0.75℃ and this is a good agreement between the monitored and simulated data. This simulation model can now be further used to analyze the thermal resilience of the building.

4 Results and discussion

4.1 Thermal comfort assessment

Degree hours for each E120 and E220 are calculated based on method described in section 3.2. For both the lecture rooms, during the TMY period, the degree hours above 25℃ and 28℃ are zero(see Figure 6 and 7). This means, there are no occupied hours when the temperature are above 25 ℃ and 28℃. However, if there is a power outage of 24 hours in the TMY period, for E120, there is a an average 413%, 187% and 15% increase in the degree hours above 24℃, 25℃ and 28℃ respectively compared to no power outage scenario. For E220, there is an average increase of 620% in the degree hours above 24℃ in TMY period without and with power outage. There are no occupied hours above 25°C and 28°C for E220, in both TMY without and with power outage.

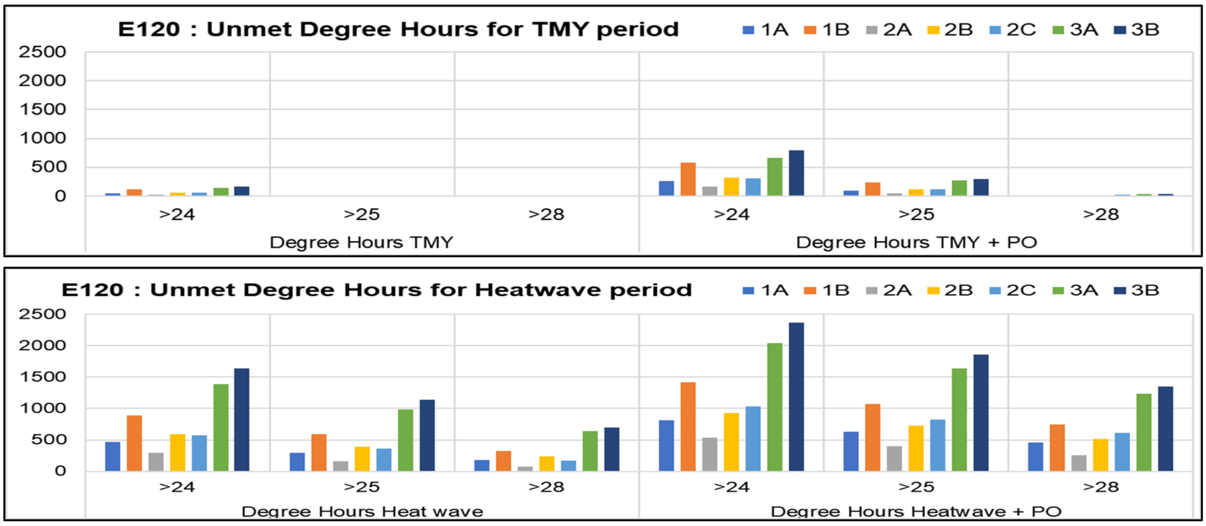


Figure 6. Unmet degree hours for TMY and Heatwave periods, with and without power outage in E120

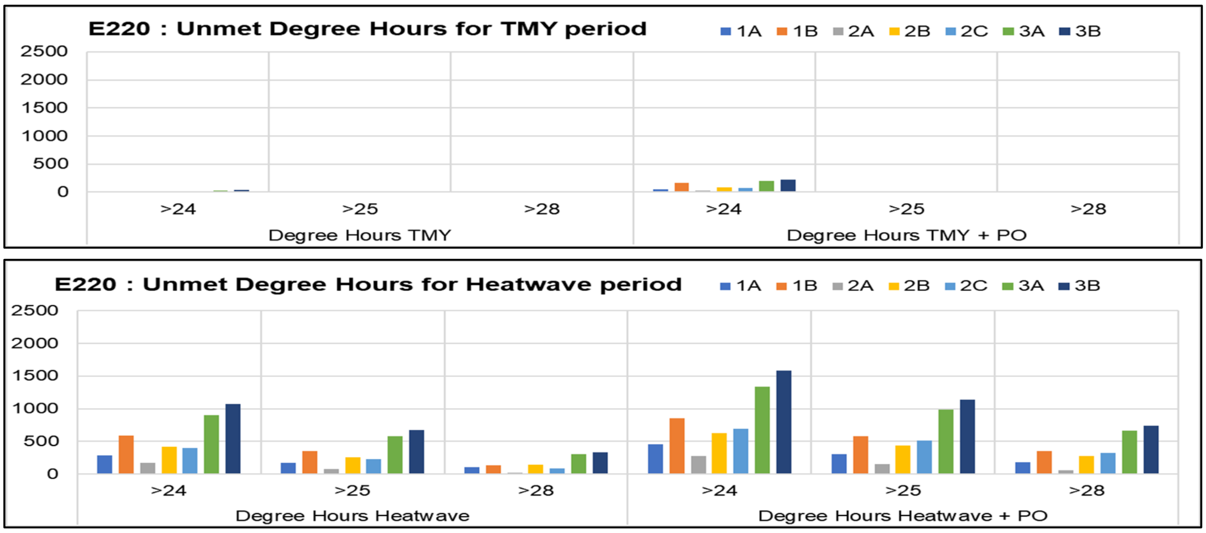
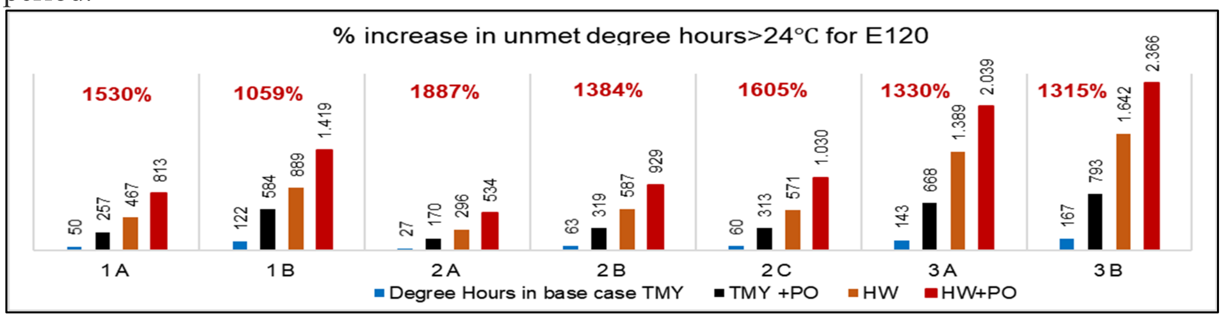


Figure 7. Unmet degree hours for TMY and Heatwave periods, with and without power outage in E220

In both test lecture rooms there is a considerable increase in unmet degree hours above 24°C,25°C and 28°C during the heatwave scenario. The increase in unmet hours from a TMY period to a heat wave period with power outage above 24°C for E120 is shown in Figure 7. Mid-term severe heatwave with a power failure has the most severe impact in the indoor temperature in E120. The indoor thermal comfort in E220 is good in TMY period, even with a 24 hour power outage. However, there is an average increase of 3400% and 5500% unmet hours above 24°C during heatwave period and heatwave period with power outage compared to TMY period.



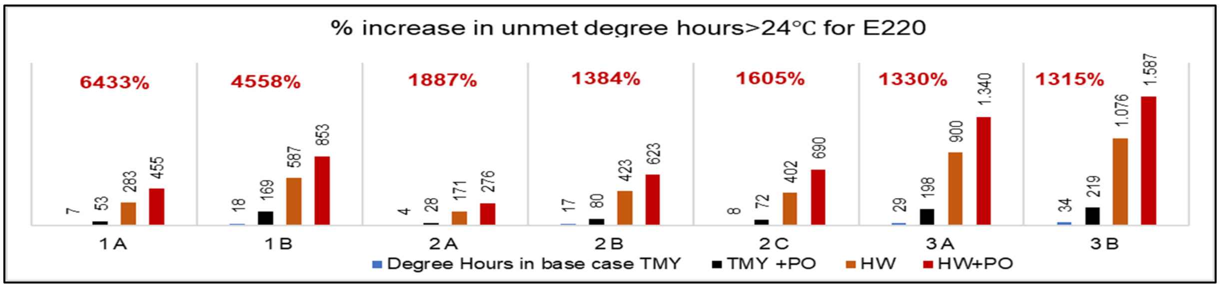


Figure 8. Increase in % of unmet degree hours above 24℃ threshold for E120 and E220 compared between base case TMY scenario and final Heatwave with power outage scenario

4.2. Passive survivability Assessment

. 24-hour power outage (No operation of the AHU, natural night cooling and shading) is imposed on the hottest day for each weather scenario. The power outage in the building will take place from 7:30 am (usually when the AHU starts operating) and occur for 24 hours. The solar shading is no longer automatically controlled during the power outage but is assumed to be all the way up (OFF). The power will be turned on again at 7:30 am the next day.

During the TMY period, lecture room E120 takes 11.5 hours to reach 30℃ (E120 reaches a maximum of 30.5℃ and E220 reaches a maximum of 27.8℃), whereas for E220 the temperature never reaches 30℃ when the power outage occurs. And for E120, once the power is restored after 24 hours, the temperature gets back below 30℃ within 30 min. However, during the Heatwave period, for room E120, the temperature of the room is already above 30 ℃, before the power outage occurs. This is due to high outdoor temperature where the passive cooling technologies cannot guarantee thermal comfort. The conditions become even severe when a 24 hour heat wave is implemented. The indoor temperature reaches a maximum of 38.01 ℃ and takes 101.3 hours to drop below 30℃ , once the AHU is turned on. Figure 9 shows the trend of the outdoor and indoor temperature evolution for the weather data 1A (Heat wave historical intense and the corresponding TMY period) in the event of a 24 hour power outage.

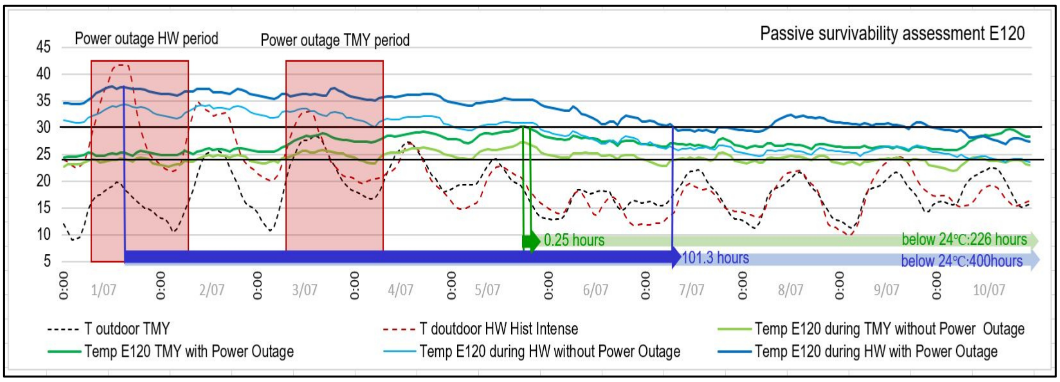


Figure 9. Passive survivability and recovery time assessment

Results shows the outdoor temperature has the highest influence i.e., during the TMY period, when there is a power outage of 24 hours, the temperature of Zone E120 reaches 30℃ after 11.5 hours whereas in E220 indoor temperature never reaches 30 ℃. However, during the heatwave period, a power outage has severe impact in both the rooms as indoor temperature are already high during heat wave period, a power outage of 24h causes temperature to rise above 30℃ with 30 min. The time taken to reach below 30℃ is 101.3 hours compared to the 0.25 hours in TMY period. The passive survivability is low during the heat wave period as the passive cooling strategies cannot guarantee thermal comfort during warm periods and a power outage thus escalates the severity of the condition. From this it can be concluded that when a power failure occurs, the thermal resilience of the building is low. The building maintains temperature below 30°C for 11.4 hours without the passive cooling strategies like IEC and natural night ventilation during the typical weather period but fails to guarantee the 30°C threshold during the heat wave period. After switching back the power, it takes about less than 30 min during TMY period but more than 4 days to reach below 30°C threshold. The passive survivability is better for E220 than the E120 due to its lighter thermal mass which helps to flush out the stored heat.

4.3. Recovery capacity

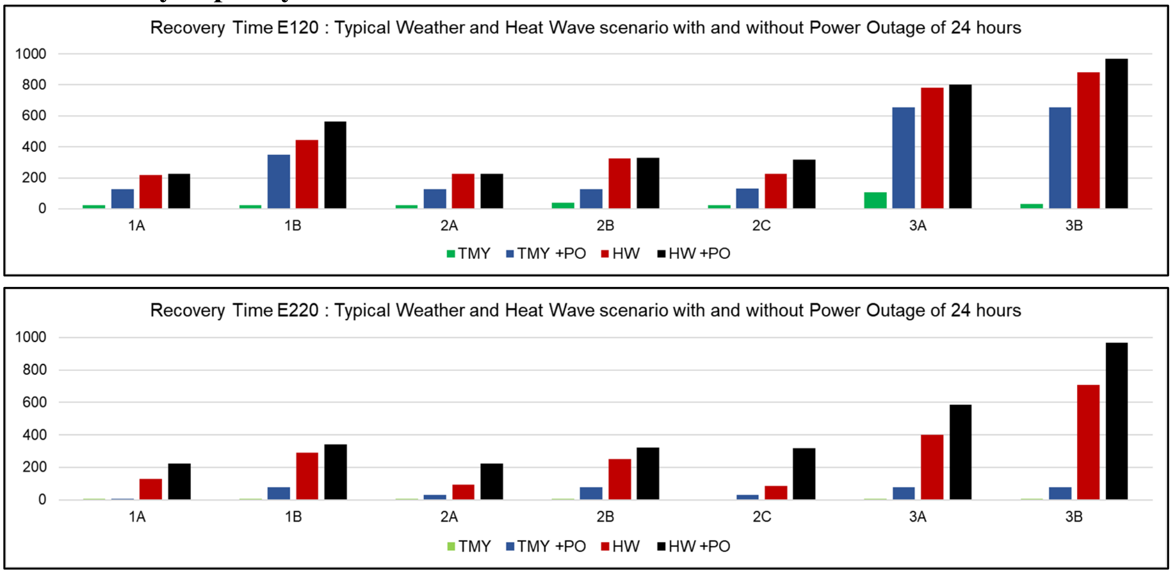


Figure 10. Comparison of the indoor operative temperature of the simulation result with the monitored data in E120

Recovery capacity assessment evaluates the time taken for the building and the system to get the zone temperature below a threshold of 24 °C after it has reached its peak temperature in that time period. Figure 10, shows the recovery capacity of the two test lecture rooms. The recovery capacity is influenced by the outdoor temperature, the building and the system properties. Since there is no active cooling in the two test lecture rooms, the outdoor environment has high impact. Passive cooling technology like IEC and natural night ventilation which works well in the TMY period, cannot guarantee thermal comfort in the heat wave period. Severe and longer heatwaves (both in historical and long-term scenario) impact the recovery capacity as seen in Figure 10. The duration of the heatwave has more impact on the recovery capacity than the intensity of the heatwave. Due to high outdoor temperature, the IEC is unable to meet the required load in the daytime and the high night-time outdoor temperature also unable to flush out the stored heat in the test lecture rooms.

5 Conclusions

The aim of this paper is to analyse thermal resilience in two test lecture rooms of an educational building at the Ghent technology campus, KU Leuven. The study demonstrates:

a) Overheating can occur in the summer months due to the high airtightness and high along with a high window-to-wall ratio.

b) In typical weather period, test lecture tooms with passive cooling strategies maintains temperature below 24 °C. However, a 24 hour power outage effects the thermal comfort. This effect is more prominent in the test lecture room E120 due to its heavy thermal mass. The results also shows, when the building is subjected to a shock like power outage or heat waves, the absorptive capacity of the building is good, that is the temperature starts to increase in a slow pace. However, once the temperature thresholds are violated, the restorative capacity of the building is low.

c) The building resists to increase in temperature post a power failure. But if the power failure occurs during a heatwave when the outdoor and indoor temperatures are already higher than the cooling set points, the passive strategies are take more than a few days to bring the temperature below 30°C.

d) Finally, it can be concluded that building with good thermal comfort as seen in the base case scenario is still subjected to overheating in during heatwaves and power outages, have low thermal resilience. Thus, the building demonstrated low thermal resilience. It can also be concluded that the building design parameters like the thermal mass and air-tightness has considerable impact in the thermal resilience to overheating. Lighter thermal mass is able to store less heat and thus has lower risk of overheating, whereas heavier thermal mass stores the heat and the recovery capacity of the building is low.

6 Acknowledgement

This study is performed under the framework of International Energy Agency's Energy in Buildings and Communities (IEA EBC) Annex 80-Resilient Cooling of Buildings and was conducted on the test lecture rooms in Technology Campus Ghent, KU Leuven.

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