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Assessing Thermal Resilience To Overheating In An Office Building

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ABSTRACT

Overheating has become a recurring problem in airtight and highly insulated buildings even in moderate climates. This study aims to analyze thermal comfort and thermal resilience in an office building during summer and mid-seasons by means of dynamic simulations. Thermal comfort assessment shows, this office building without improvements has a 'good' indoor climate for 79.6% of total occupied hours. However, the results also confirm that the office building will suffer from overheating during summer with full occupancy (primarily during afternoon when the outdoor temperature > 16°C). Simulations and on site measurements indicate, in winter and midseason (Temp < 16°C), there is no overheating. Two existing indicators of thermal resilience are assessed in this study, namely-(a) Thermal autonomy and (b) Passive Survivability. It has been demonstrated that the case study building has low threshold for both the resilience indicators. The office building has a low thermal autonomy to overheating in its current status (17.4%) due to low thermal mass,high heat gains and relying on the cooling and ventilation system to mitigate overheating risk rather than relying on the building and system parameters. This can be improved to 61.7% with additional natural ventilation of 5 ACH. For passive survivability, the temperature of Workplace 1 remains below 30℃ only for 8 hours when the power is switched off for heating and cooling, without sun shading or natural ventilation. This can be improved up to 12 hours with sun shading and natural ventilation. Thus, Passive survivability of the building is also low. This study demonstrates cooling and solar shading are indispensable to mitigate overheating in buildings. However with the addition of natural ventilation during day and night ventilation, good thermal comfort can be achieved for 86.1% of occupied hours.

INTRODUCTION

Buildings in Belgium are subjected to climate change and frequent heatwaves, increasing overheating risk and cooling energy need in buildings. Overheating in buildings is expected to increase as global warming continues (AECOM 2012). Overheating risks in buildings, leading to higher cooling demands, are mainly influenced by building design parameters (like glazing ratio, high insulation rate, increased airtightness, internal heat gains and energy performance) (Jenkins et al. 2013), (Psomas et al. 2016). Overheating of buildings has negative health impacts amongst occupants, like thermal discomfort, productivity reduction, illness and even death (Hamdy et al. 2017). 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 (European Commission 2018). A study on Dutch dwellings shows poorly ventilated dwellings are vulnerable to overheating and are the most sensitive to climate change, particularly if their windows are not well protected against direct solar radiation (Hamdy et al. 2017)(Sengupta, Steeman, and Breesch 2020). Studies show that even though the buildings have good summer thermal comfort, buiding thermal resilience in events like heatwaves or higher occupancy, is not adequate (Frankel and Edelson 2015). Building Resilience can be defined as "An ability of the building to withstand disruptions caused by extreme weather events (natural disasters such as earthquakes, tornados and tsunamis), man-made disasters (explosions and fire), power failure, change in use (increase or decrease of occupancy and internal heat gains) and atypical conditions (sun shading failure, overheating); and to

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maintain capacity to adapt, learn and transform" (Palme, Isalgué, and Coch 2013)(Mavrogianni et al. 2015). Thus, apart from energy performance, resilience is gaining importance to assess building performance (Plumblee and Klotz 2014) (Kesik et al. 2019) and can be considered as a primary function of the building (Pizzol 2015). Thermal Resilience can be assessed by indicators like Thermal Autonomy(Levitt et al. 2013) and Passive survivability (Brien 2016). 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.

The objective of this paper is to assess the thermal resilience of a newly built office building in Antwerp (Belgium). In this paper, thermal resilience of the case study building during summer and mid-seasons, has been assessed based on two indicators-(a) Thermal Autonomy and (b) Passive Survivability. This paper is based on the master's thesis of Jonas Deleu and Brecht Lucidarme(Deleu 2020).

CASE STUDY BUILDING

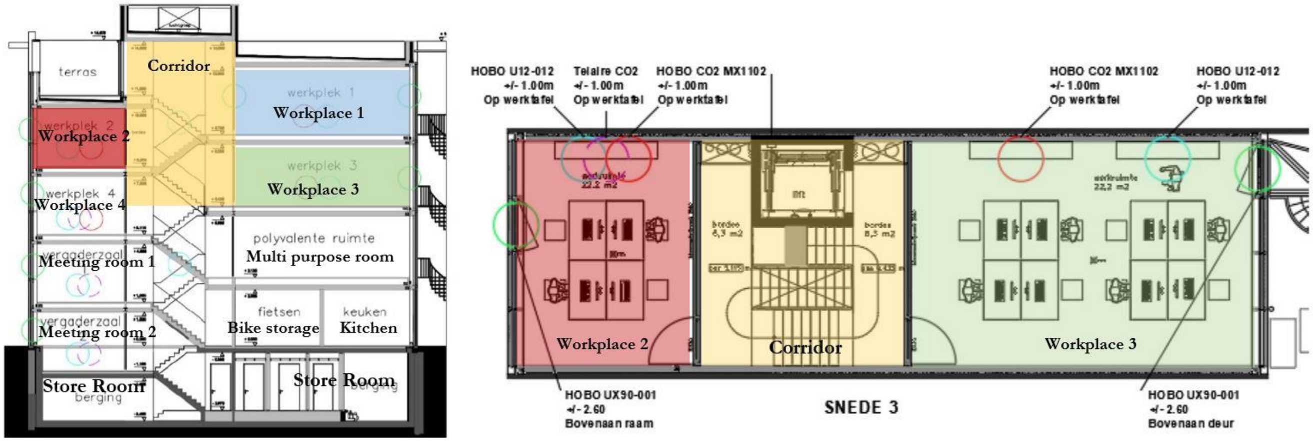

Figure 1. Section (left) and floor plan with sensors(right) of the case study building

The case study building is an office building in Berchem, near Antwerp, designed by Urbain architect, constructed in 2019. The office building is south-southwest facing. Figure 1 shows plans and sections indicating the thermal zones and sensor positions. Table 1 indicates areas of each thermal zone and the ventilation rate for each zone. The ventilation air flow rates are calculated according to (NBN D50-001 Annex V:2005). Workplace 2 & 4 are small workplaces suitable for 6 people. Workplaces 1 and 3 are larger workplaces suitable for a maximum of 12 people. Table 2 provides an overview of the different types of construction elements and the U-values respectively. The building is constructed out of cross laminated timber (CLT). This construction method falls under timber construction. The front and rear facades of the building are completely glazed. The airtightness was calculated from the measured data at site as 0.0465 1 / h per room under natural pressure.

Table 1. Zones (Areas and airflows) of the case study building

Zone	Area(m^2)	Air Flow(m^3/h)
Workplace 1 (WP1)	45	540
Workplace 2 (WP2)	22	324
Workplace 3 (WP3)	45	540
Workplace 4 (WP4)	22	324
Multipurpose Room (MPR)	45	1100
Meeting Room 1 (MR1)	22	430
Meeting Room 2 (MR2)	22	430
Corridor (CR) each floor	9	25
Kitchen (KIT)	16	132
Bicycle Storage (BS)	13.5	25

Table 2. Details and characteristics with U values of the different construction types

Construction Type	Description	U value(W/m^{2}K)
Attached Basement Walls	Reinforced Concrete with Resol plates insulation-340 mm thickness	0.26
Basement Wall-Front	Reinforced Concrete with XPS insulation-380 mm thickness	0.22
Basement Wall-Rear	Reinforced Concrete with Resol plates insulation-350 mm thickness	0.22
Detached Common wall	CLT structure with PIR (Polyisocyanurate) insulation-400 mm thickness	0.15
Attached common wall	CLT structure with rockwool insulation- 200 mm thickness	0.34
Basement Floor	250 mm Reinforced Concrete with XPS insulation-500 mm thickness	0.13
Intermediate Floors	Parquet flooring with Fiber Cement Board with total thickness of 450mm	0.13
Roof	Green Roof with CLT Structure and 120 mm insulation-430mm thickness	0.14
Exterior Window Property (Façade)	Double glazing- Thermobel Advanced	$U_{glazing}$- 1, U_{frame}- 1.27 g-value- 0.5, Light Transmission -76%
Interior Window Property	Single Glazing- Contraflam E130	$U_{glazing}$- 4.8, g-value- 0.74

Sun Shading: Since the entire front and rear façade consist of glazing, sun shading was necessary to guarantee thermal comfort and prevent overheating. During on site measurements, the solar shading was not yet adjusted with the weather station, thus the blinds were switched ON manually. The automation scheme was only operational from February 2020. Shading is provided with sun blinds. The solar shading has a battery and solar panel so that the solar shading can still be used in the event of a power failure. The solar shading is deployed when the radiation on the surface reaches above 250 W/m^2.

Systems: The building is heated with a geothermal heat pump with control for each room separately. To heat the building completely, there are 2 modular heat pumps of 37.6 kW each. The rooms are heated by fan convectors built into the floor. The geothermal heat pump is also utilized for cooling. This can be done in 2 ways: active and passive. Here passive cooling is implemented. In this case, the heat pump compressor is not used and the cool ground is used as a cold source. The cooling is activated when the indoor temperature exceeds the desired temperature of 24°C by 1°C during office hours. During weekend and weekdays(after office hours), the cooling is only switched on when the indoor temperature is 3°C higher than the set point temperature. This office building uses a balanced mechanical ventilation system. The Air Handling Unit (AHU) has a maximum capacity of 4100 m^3/h, Table 1 shows the air flows per room. To be more energy efficient a heat recovery device is linked to the ventilation system.

Simulation Model: One week (25/10/2019 to 31/10/2019) is chosen to compare measurement and simulation data to validate the simulation model. It was decided to simulate only the top three rooms (see Figure 1). These are most likely to be overheated in the summer because they are least shaded and they are located under the roof with high solar gains. For the internal heat gains electrical appliances, lighting and occupancy are considered. The maximum occupancy for workplaces are 10 people. A heat gain of 120 W per person has been implemented in the simulation software. Lighting loads of 360 W and 180 W are implemented, this corresponds with the number of luminaires and the capacities described in Table 3. For the electrical appliances, a laptop (42.7 W) and 2 monitors (2x32 W) per person is taken into account, which equates to 1067 W for 10 people. The schedule of the electrical appliances follows the occupancy schedule. The occupancy in the building is divided into a weekday and weekend profile. The lighting is supposed to be ON for the entire period of occupancy. Sufficient light fixtures ensure optimal lighting to guarantee visual comfort, on average it is 423 lux in the horizontal working plane. The lighting is not dimmable. 8 luminaires for Workplace 1 & 2 , 4 for Workplace 3 & 4 and 2 for meeting room 1 & 2 two have been assigned. A fraction of 30% for the radiative gain and 70% for the convective gain have been assigned.

Table 3. Internal gains of workplace 1, 2 and 3

Type	Zone	Maximum load
Occupancy	Workplace 1 and 3	1200 W(10 persons)
	Workplace 2	1200 W (10 persons)
Lighting	Workplace 1 and 3	360 W
	Workplace 2	180 W
Electrical Devices	Workplace 1 and 3	1067 W

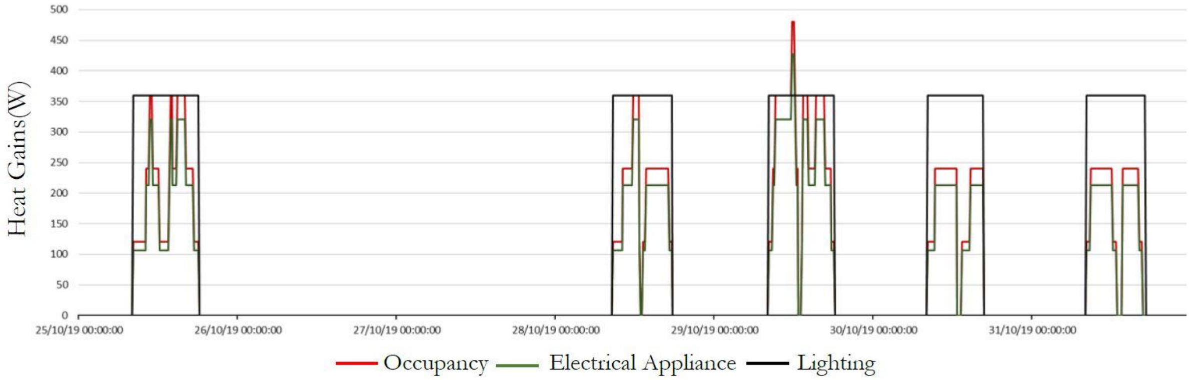

Figure 2. Internal heat gains in Workplace 1 between 25th to 31st October 2019

Table 4. Heating and cooling setpoints for weekdays and weekends

Type	Days	Setpoints
Heating	Weekdays excluding Tuesday	8-17h: 20°C, Rest: 18°C
	Tuesday	8-19h: 20°C, Rest: 18°C
	Weekend	18 ° C
Cooling	Weekdays	8-17h: 22°C, Rest: 24°C
	Weekend	24 °C

METHODOLOGY

Measurements and Building Energy Simulations (BES)

Measurements on site- Parameters like relative humidity, interior temperatures, CO2 were acquired through strategic placement of HOBO data loggers (as seen in Figure 1). Each occupied room was monitored from 30th September to 22nd November, 2019. Occupation was registered for a week during this period, i.e.from 25th to 31st October, 2019. The outdoor temperatures were provided by the RMI of Belgium (Weather Belgium - RMI n.d.).

Dynamic simulations- The case study building and the system are modeled in Open Studio (OpenStudio). The output of these simulations are the operative indoor temperatures of each thermal zone. To assess the thermal comfort during summer, simulations are conducted from 1st April to 31st October with occupation based on maximum capacity. The thermal resilience assessment is done during the warmest week in the weather data. For the passive survivability and thermal autonomy, a sudden power failure (HVAC and shading system shut down) is implemented and the power is restored back after 2 days. In the event of a power failure, the electrical appliances (PC, monitor, lighting etc.)accounting for internal gains remain working. The objective? is to determine the number of hours after the power failure temperature remains below 30°C and the number of hours it takes for the building to drop the temperature below 30°C again when the power is turned back ON.

Evaluation of Thermal Comfort

The indoor thermal condition of the office building is evaluated according to the adaptive temperature limits set by (Van Der Linden et al. 2006). Therefore, depending on the building type, indoor temperature limits are imposed as function of the weighted outside temperature. The thermal comfort can be evaluated by plotting the interior operative temperatures in relation to the running mean outdoor temperatures in a graph with adaptive comfort limits. These limits are based on degrees of thermal acceptance in accordance to the building type(Van Der Linden et al. 2006). As specified by the guideline, this office building can be defined as a building / climate type Beta. In Beta type building, the user has limited adaptive capacity, i.e., cannot open/ close the windows. A good thermal indoor climate is associated with 80% of occupancy period within accepted limits of threshold. Summer comfort is assessed on the basis of the adaptive temperature limit values (ATG) based on temperatures measured on site as well as by dynamic BES (Building Energy Simulations) done with OpenStudio.

Validation of the simulation model

Validation of simulation with measurement data: Before the thermal resilience can be evaluated, the simulation model needs to be validated. Comparison of the measured data on-site with simulated indoor temperatures for workplace 1 for the period between October 25 to and October 31, 2019, is done. Assigning the exact location and orientation of the building, input correctly the HVAC system parameters and opening/closing of the solar shading in the simulation model at par with the real case scenario. This simulation model can now be further used to analyze the thermal resilience of the building.

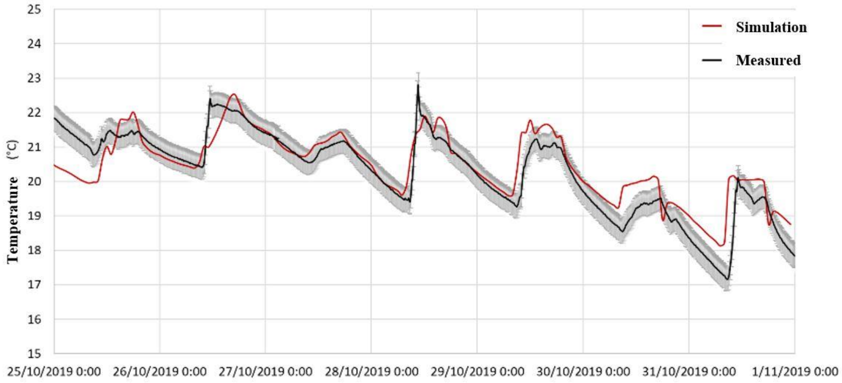

Figure 3. Verification of the simulation model, comparing the simulation result with the monitored data in Workplace 1

RESULTS

Base case scenario

The base case is the simulation with the heating and cooling ON. Figure 3 shows, of the occupied hours, 79.6% are within the 80% acceptance limits. Summer days have a high impact on the exceeding of the upper temperature limits. 17.9% of all indoor temperatures are above 80% of acceptance limit.

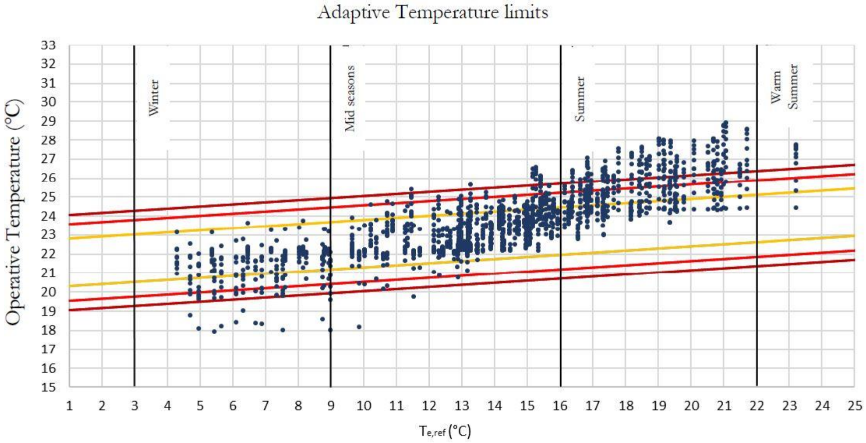

Figure 4. Base case scenario, 79.6% occupied hours are within the 80% acceptance limits

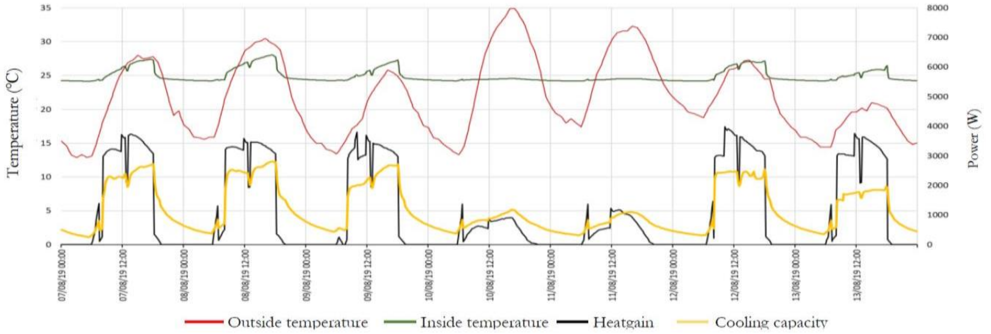

Figure 5. Base case scenario- Overview of the warm week (7-13th August)

The cooling capacity is assessed as the capacity at which the fan convectors cool the room when the indoor temperatures are over the cooling setpoints. The heat gains rise to 3500 W on working days, but on weekends they are much lower (1000 W) due to the absence of people. Indoor temperature profiles demonstrates that the night cooling is able to partially compensate for the heat gains in the week and to lower the indoor temperature by a few degrees. At night and during the weekend, the night cooling is able to guarantee a maximum indoor temperature of 24 ° C.

Thermal Autonomy Assessment

Five different scenarios are assessed to check the thermal autonomy. The thermal autonomy is assessed for the period from April 1 to October 31 in workplace 1(WP1). The windows were close during the simulation, i.e. the occupants cannot open the windows.

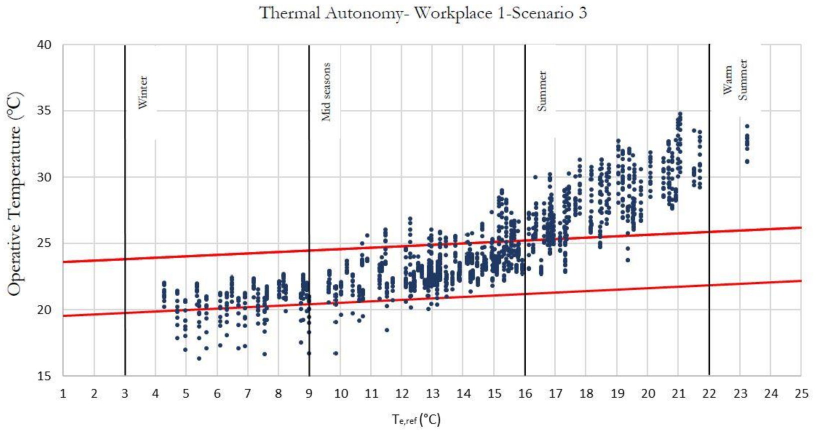

Figure 6. Assessment of Thermal Resilience(Thermal Autonomy): Scenario 1- Free running building with sun blinds

Table 5. Assessment of Thermal Autonomy- % of occupied hours within the comfort range

Scenario	Too cold(%)	Good(%)	Too Hot(%)
1- Free-running building with sun blinds	2.4	17.4	80.2
2- Free-running building with natural ventilation 1 ACH	4.3	39.5	56.2
3- Free-running with natural ventilation 5 ACH	4.7	61.7	33.6
4- Natural ventilation 1 ACH & Night ventilation 5 ACH	4.3	47.6	48.1
5- Free-running with night ventilation 5ACH	2.5	24	73.5

Scenario 1: In Scenario 1(Free-running building with sun blinds)for WP1, only 17.4% of the number of occupied hours is located within the thermal comfort class B. 80.2% of the occupied hours are above the comfort zone. In summer days the indoor operative temperatures are permanently above the comfort zone. This confirms the assumption that the building is vulnerable to overheating in the absence of any cooling.

Scenario 2- Free-running building with natural ventilation 1 ACH: evaluates the effect of the natural ventilation on the existing free-running state. 39.5% of the occupied hours are within the comfort class B, while 56.2% are considered too hot. This is an improvement over scenario 1. Although peak summer temperatures have fallen from +/- 40°C to +/- 37°C, the indoor temperatures are still above the comfort zone. Natural ventilation with a realistic flow rate of 1 ACH is therefore not a sufficient solution to prevent overheating in free-running condition.

Scenario 3- Free-running with natural ventilation 5 ACH: the internal temperatures are 61.7% within the acceptance area. The intermediate season has also improved compared to scenario 2. Although peak summer temperatures have fallen by 5°C due to the addition of the increased natural ventilation compared to scenario 1, this is again not a solution to prevent overheating on free-running summer days. The indoor temperatures in the summer days are already well outside the comfort zone at around 8am. Possible solution to this problem is to add additional night ventilation in the simulation model to add. IEA EBC Annex 62 reviews the state of the art of different ventilative cooling techniques(IEA/EBC 2015). Natural ventilation, also called passive ventilation, uses natural outside air movement and pressure differences to both passively cool and ventilate a building.
However, night ventilation or night cooling utilizes the thermal mass of the building to store heat to reduce the day time temperature of the next day. Night time ventilation is suitable for areas with high diurnal temperature range and where night temperature is not so cold to create discomfort.

Scenario 4- Natural ventilation 1 ACH & Night ventilation 5 ACH: assesses the result of natural ventilation combined with the night ventilation. The indoor temperatures are within 47.6% of the occupied hours temperature limits. This is a clear improvement from scenario 2, only 48.1% of the occupied time it is above comfort range. The night ventilation does have an observable effect on the indoor temperatures in the morning. These temperatures are 4 to 5 °C lower than in scenario 2. However a peak of 35℃ indoor temperature remains. This indicates that the building has a low thermal mass and can absorb and release heat quickly.

Scenario 5- Free-running with night ventilation 5ACH: evaluates how night ventilation alone impacts the thermal resilience. Simulation is done with night ventilation of 5 ACH. The indoor climate is only thermally comfortable for 24% of office hours.

Passive survivability Assessment

From the weather file for a typical Belgian climate, the hottest week is chosen. The week from 7 August to August 13 appears to have the highest outdoor temperatures with maxima situated between 26 °C and 35 °C. The power outage in the building will take place on August 8, 00:00. No HVAC system is operational from then on. The solar shading are no longer automatically controlled during the power outage, but is assumed to be either be completely down(ON) or all the way up(OFF). The power will be turned on again on August 10, 00:00. In this test, passive survivability is evaluated in several cases-

(1) There is natural ventilation, the solar shading is always up (OFF)
(2) There is no natural ventilation, the solar shading is always up (OFF)
(3) There is no natural ventilation, the solar shading are always down (ON)
(4) There is natural ventilation, the solar shading is always down (ON)

Figure 7 shows the result of the indoor temperature evolution for the different scenarios in the event of a power failure. Table 6 shows the number of hours that the indoor temperature remains below 30°C after the power failure and the number of hours it takes? before the indoor temperature drops below 30°C after switching on the power. Results shows that the sun protection has the greatest influence in this scenario. Without blinds the peak of 30 °C is already reached after 8 hours, while with sun protection it is only reached after 10 to 12 hours. The indoor temperatures with blinds are relatively lower on August 8. The passive survivability is low without natural ventilation and without sun protection. 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 8 hours without the intervention of sun shading or natural ventilation. After switching back the power, it takes about 2 nights before cooling the temperatures at night back cooling setpoint of 24 °C. During the power failure, the internal temperatures rise during the office hours always above 30 °C for the warm week. So the passive survivability is low for this office building.

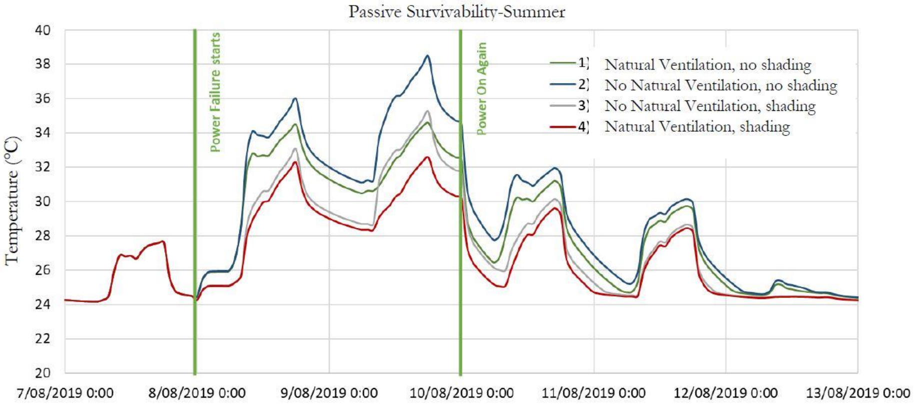

Figure 7. Assessment of Passive Survivability for four scenarios in the case study building

Table 6. Assessment of Passive Survivability- hours above 30℃ during and post power failure

Scenario	Hours below 30℃ post power failure	Hours above 30℃ when power is switched back on
1. There is natural ventilation, the sun protection is always up.	8	1
2. There is no natural ventilation, the sun protection is always up.	8	2
3. There is no natural ventilation, the blinds are always down.	10	1
4. There is natural ventilation, the sun protection is always down.	12	1

CONCLUSION

The aim of this paper is to analyze thermal resilience in a case study office building. It has been demonstated that overheating can occur in the summer months due to the airtight and light construction of the office building with a high window-to-wall ratio. The building's thermal resilience was investigated with two existing indicators- thermal autonomy and passive survivability. The thermal autonomy, a first evaluation method, was used to keep the building in free-running condition. The results show that the building has a low thermal autonomy, i.e., the indoor temperatures on summer days never even fall within the acceptance area without cooling intervention. From this it can be concluded that the cooling installation is indispensable for this office building. Passive survivability was used as a second evaluation method to assess thermal resilience. When a power failure (HVAC shutdown) occurs at midnight in a warm week, the building will reach a temperature of 30 °C after eight hours. When two days later the power is resolved, the building will not be within thermal comfort temperature range until the second night. Damping the temperature rise after power outages and accelerating the drop after recovery can be achieved by the sun blinds and natural ventilation. Finally, it can be concluded that building with good thermal comfort as seen in the base case scenario is still subjected to overheating in the summer months and have low thermal resilience. Furthermore, during the summer months, there is almost always the overheating risk in the afternoons. Thus the building demonstrated low thermal resilience. Implementation of cooling systems (active or passive) and sun blinds are essential in case of extreme shocks like heat waves.

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