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Analysis of resilience of ventilative cooling technologies in a case study building

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Abstract

Buildings globally are subjected to climate change and heatwaves, causing a risk of overheating and increasing energy use for cooling. Low-energy cooling solutions such as night cooling are promising to realize energy reduction and climate goals. Apart from energy performances, resilience is gaining importance in assessing the performance of the building and its systems. Resilience is defined as "an ability to withstand disruptions caused by extreme weather events, man-made disasters, power failure, change in use and atypical conditions; and to maintain capacity to adapt, learn and transform." However, there is a clear lack of Resilience indicators specific for low energy cooling technologies. In this paper, the resilience of the night cooling in a residential building in Belgium is assessed for two external events: heat wave and shading failure. This paper shows the first attempt of a resilience indicator for night cooling as the effect on the shock of solar shading failure, heat wave or combination of both. It takes 3.4 days to bring down the temperature below 25℃, in case of shading failure and heatwaves compared to 9 hours in the reference case. Further research is needed to determine resilience indicators as a performance criteria of low-energy cooling systems.

Keywords: Resilience; Ventilative Cooling; Climate Change

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Abbreviations

IPCC	International Panel on Climate Change
EU	European Union
IEA	International Energy Agency
BES	Building Energy Simulations
nZEB	Nearly Zero Energy Building
ACH	Air Change per Hour
g_{tot}	Solar transmittance

1. Introduction

IPCC’s Special Report on Global Warming of 1.5℃ concludes there is a growing risk of overheating in buildings and an increase in severity of heatwaves[1]. Europe has witnessed in the last two decades, 18 of the warmest years and an increase in the frequency and intensity of extreme weather events [2]. Mitigating the adverse effects of climate change is a high priority for the EU. Studies on the Future of Cooling by IEA shows that, by 2050, without action, the cooling demand will be more than triple and around 2/3rd of the world’s households will have an air conditioner [3]. Thus focus should be on the low energy cooling technologies to mitigate climate change and overheating in buildings while respecting the energy reduction goals. To combat climate change, overheating in buildings and the parallel energy reduction goals, there is a need for passive cooling technologies. Night cooling is a promising solution. The state of the art report of Ventilative cooling in the framework of Annex 62[1], a study[4] on the performance of night cooling using uncertainty and sensitivity analysis and on the predictive performance of natural night cooling concluded that the efficiency of night cooling depends mainly on (1) thermal mass of the building and (2) local climate conditions, i.e. night-time wind speed and temperature swing of the ambient air. The efficiency is largely dependent on the difference between the indoor and outdoor temperature. The lower the outdoor temperature during night and the higher the fresh air supply, the higher the efficiency. Studies on future climate scenarios suggests increase in night temperatures[5]. Therefore the effectiveness of Night Cooling will likely decrease.

1.1. Resilience of low energy cooling technologies

Studies on the performance of the low energy cooling technologies concluded that even with current satisfactory performance, these technologies fail to provide excellent thermal comfort in the future climate scenario and in case of events like high occupancy, heatwaves, power failure, solar shading failure, etc. [6] [7]. Apart from energy performance, non-energy matrices like comfort, health, economic efficiency, resource optimization and building functionality; resilience, is gaining importance when assessing the building performance[8]. Resilience needs to be considered parallel with energy and environmental performance[9] and be considered as a primary function of the building[10].

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 maintain capacity to adapt, learn and transform”[11][12][13]. A qualitative approach as seen in Fig. 1 is “adaptive cycle theory” that considers three phases of a system’s cycle: a reliable initial condition (a state of equilibrium); a vulnerability-survivability response to a disruptive event; and a recovery phase aimed at achieving new stable equilibrium conditions[14]. When a system undergoes a shock or vulnerability, it takes a certain time to withstand and recover to its original standard of performance. This attribute can be co-related to Resilience of the system.

Existing building resilience indicators can be divided broadly into two categories-(a)qualitative indicators and (b) quantitative indicators. Quantitative indicators include--(1) Absorptive capacity [15] (2) Adaptation (3) Adaptive capacity and (4) Capacity of response [16]. On the other hand, quantitative indicators have been identified to evaluate Thermal Resilience of buildings-(1)Thermal Autonomy [17], (2)Passive Survivability [18](3)Ventilation Autonomy [19]. However, these resilience indicators focus on the building and not on the cooling technologies.

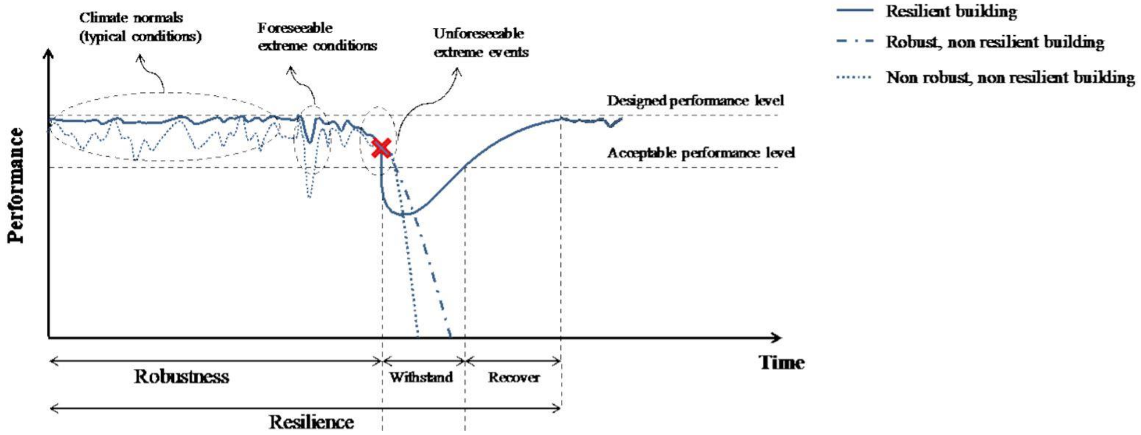

Fig. 1 Phase of Vulnerability, Resistance, Robustness and Recovery of a system[20]

2. Objective

The objective of this study is to identify and assess the resilience of the night cooling during the events like heatwaves and sun shading failure. This study shows the first attempt of an indicator to assess resilience of low energy cooling technologies to ensure robust thermal summer comfort in dwellings. The effect of heat wave and solar shading failure on the performance of the night cooling system is studied in a typical dwelling in Flanders (Belgium). The applied methodology is described in detail, followed by a discussion of the main results, resulting in conclusions and final recommendations.

3. Methodology

3.1. Building Energy Simulations (BES)

For the analysis of thermal summer comfort, annual hourly BES were performed using Modelica[21]. In the BES model, the floor to the ground was assumed to be adiabatic. The simulation is started four weeks prior to the studied period. The set point temperature used for the heating is set at 20℃ with a dead band of ±0.5℃.

3.2. Case study building

A nZEB single-family residential building (see Fig. 2), designed by the BAST Architects & Engineers, to be built in 2020-2021 in Belgium, is studied. The building is North-East oriented and designed for a family consisting of 4 people. The building consists of two floors (3 m high each) with a conditioned floor area of 186m^2. The building will be cooled by natural night ventilation using the stack effect by opening the windows in the living and sleeping rooms and on top of the stairway (see Fig. 2).The building has been divided into 7 thermal zones (see Fig. 2 and Table 1). The building has light thermal mass according to EN ISO 52016-1[22] and airtightness value of 1.5 ACH. Table 2. shows more building properties in detail. The window-to-wall ratio is 29.3% (Southwest), 23.7% (Northwest), 41% (Northeast) and 48.6% (Southeast). The windows on the Southwest and Northwest façade are equipped external solar shading (g_{tot} = 0.04), modelled to provide shading when the radiation on the window is above 250 W/m^2. The solar shading for this building is moveable motorized screens controlled manually by occupants with remote control.

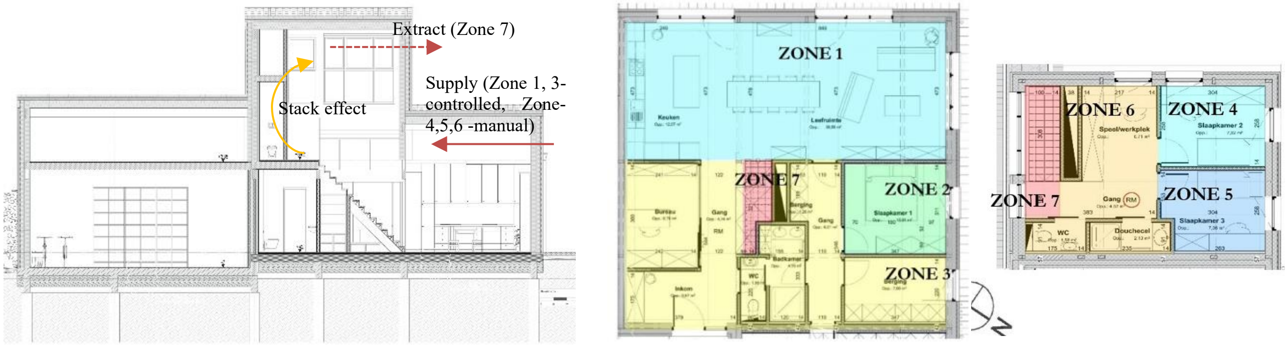

Fig. 2 Section of the of the residential building showing the supply and extract for stack effect(left) and ground floor & first floor indicating the zones(right) designed by the BAST architects & Engineers

Table 1 Zone Description

Zone	Type	Total Floor Area (m^2)	Design Ventilation Flow (m^3/h)
1	Living and Kitchen	63.5	150 (supply & extract)
2	Bedroom	6.2	36 (supply)
3	Office, Toilet, Corridor, Store	65.7	150 (supply & extract)
4	Bedroom	7.5	36 (supply)
5	Bedroom	7.5	36 (supply)
6	Study and Playroom	33.2	36 (supply & extract)
7	Staircase	2.50	No supply and extract

Table 2 Building Properties

Construction Type	Type	U value (W/m^2K)
External Wall	Insulated 445mm thick wall with air cavity	0.10
Common Wall	Double insulated 485mm wall with air cavity	0.09
Common Wall with Garage	Insulated, triple gypsum board, 425mm wall	0.10
Internal Wall	Double insulated,195mm internal wall	0.23
Ground Floor	Use of Geocell and concrete,500mm thick	0.22
Intermediate Floor	Insulated and wooden beam structured,350 mm	0.31
Roof	Insulated, use of cellulose and multiplex insulation,350mm	0.14
Glazing	Double glazing	U glazing- 1, U frame- 0.85 g-value- 0.52

The building is equipped with an air-water heat pump with heating capacity of 9 kW for space heating. A mechanical ventilation system with heat recovery has been implemented. The ventilation air flow rates are calculated according to the NBN D50-001[23] (see Table 1). The occupancy level in the building is divided into a weekday and weekend profile. Four people are assigned to be in work/school from 9h to 17h from Monday to Friday except Wednesday afternoon from 13h. Hours of occupancy are 132h/week. The occupant density is 44 m^2/pers. The internal gains for each zone has been calculated according to the ISO/FDIS 13791[24], (see Fig. 3) and the average internal sensible load during all days is 1.44 W/m^2.

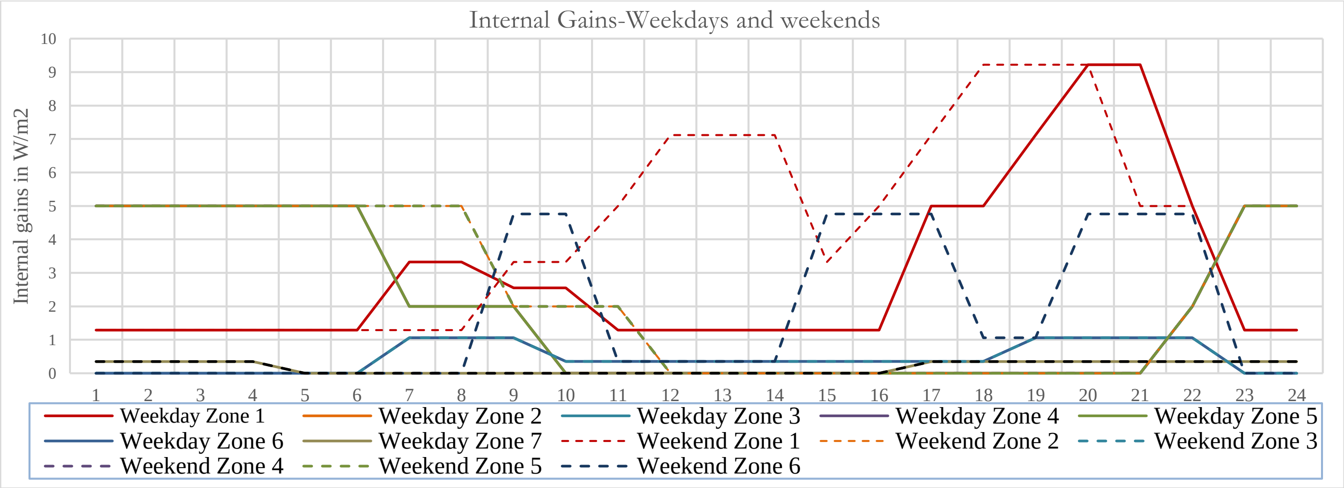

Fig. 3 Internal gains (Equipment +people gains) in weekday and weekend in different zones.

3.3. Night Cooling System and effective area of the operable windows

Natural night cooling is implemented as passive means to cool the building. Stack effect is utilized by opening windows to supply and extract air. The air flow relies on the opening and closing of the bottom hung windows (see Table 3). Each zone is provided with operable windows which are automatically controlled for night cooling. The effective area of these windows is calculated based on the method proposed in [25] taken into account the window area, height and opening angle. The total effective area of all windows is 1.7% of the floor area.

Table 3 Effective area of operable windows

Zone	Window Type	Total area of the window (m^2)	Total Area of openable part of the window (m^2)	Height of the openable part(m)	Base Height of openable part from ground level (m)	Opening angle φ(°)	Effective Area A_{eff} (m^2)	% of openable area compared to floor area of the zone
1	4	7.48	0.45	0.45	2.32	30	0.54	0.85
	5	7.48	0.45	0.45	2.32	30		
2	7	2.50	0.50	0.45	1.82	5	0.09	1.45
3	1	5.26	0.45	0.45	2.32	30	0.52	0.79
	6	2.50	0.50	0.45	1.82	5	0.09	0.13
4	8	1.29	1.29	1.17	3.9	10	0.17	2.26
5	9	1.29	1.29	1.17	3.9	10	0.17	2.26
6	9	1.29	1.29	1.17	3.9	10	0.17	0.51
7	2	6.23	2.86	1.10	4.67	45	0.79	31.6
	3	3.05	1.10	1.10	4.67	45	0.79	31.6

3.4. Weather data and Heat Wave

Weather data is retrieved from the weather station at the KU Leuven Ghent Technology Campus (Belgium). An average hourly weather file is generated, with hourly temperature, global horizontal radiation, wind speed and direction, relative humidity and precipitation based on the period 2015-2016. The monitored data is similar to the typical weather file (See Fig. 4) and also due to the availability of weather data of 2015-2016, it has been used for this simulation. In Belgium, a heatwave is officially declared when the maximum temperatures are above 25 degrees for at least five consecutive days. Furthermore, at least three of the days must exceed 30 degrees[26]. For the heat wave period, data of 2019 is used from the same weather station. The extreme heat wave condition(20-25th July) with the highest recorded temperature of 40.6°C on July 25th 2019, has been chosen for this study. Operative temperatures of the different zones are evaluated for a total of 12 days (20-31 July), for a week(26th – 31 July) post the heat wave period (20-25th July). A comparison of typical weather year has been done with the 2015-2016 weather conditions and the warmer weather conditions with heat waves are shown in Fig. 4.

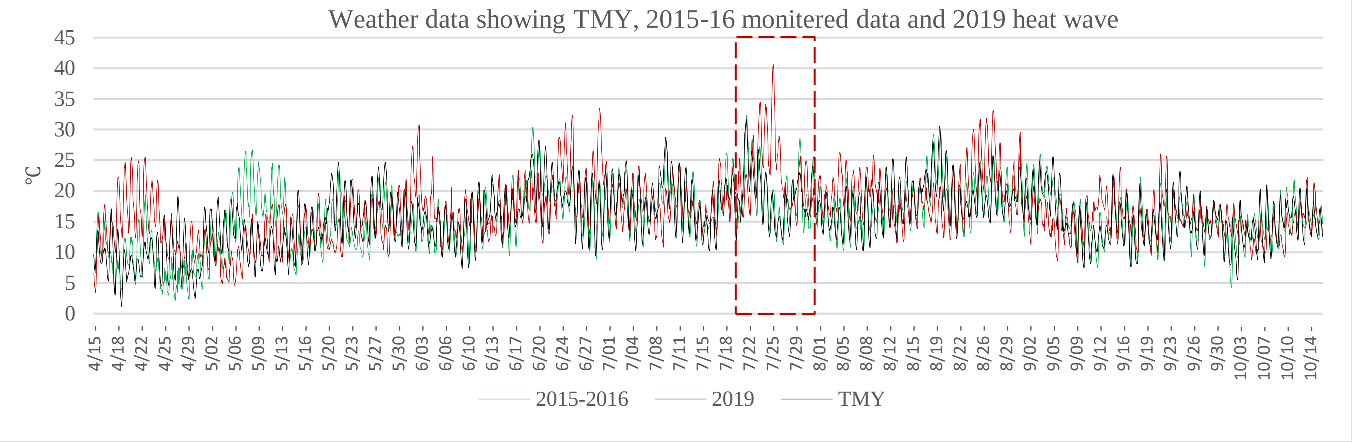

Fig. 4 Monitored weather data of the 2015-2016 compared to TMY and the warmer weather of 2019 showing the heat wave period assessed in this paper.

3.5. Control Strategy

The control strategy for night ventilation that actuates the opening of the windows is based on internal temperature and relative humidity and external weather conditions (temperature, rain) measured on the site of the building. This strategy is inspired by the recommendations of [6]. The windows remain open/closed for at least 15 min. Windows are opened between 10:00 p.m. and 6:00 a.m. from April 15th to October 15th when the following criteria are fulfilled -(1) Air temperature in the room exceeds the 22°C, (2) The external temperature is lower than the internal temperature, (3) There is no or lesser than 0.7mm/min rainfall and (4) Wind velocity on site is smaller than 10m/s.

3.6. Evaluation of thermal comfort

Method A as described in Annex F of the EN 15251[27] is selected for the evaluation of summer comfort. For this study, the number or % of occupied hours when the operative temperature is above 25°C, 26°C and 28°C is evaluated. 5% or 438h is considered acceptable and 3% or 262h is considered good.

3.7.Resilience scenarios

Table 4 shows the parameter variations for the study. One variation at a time is analyzed. The first case is the design case with 2015-2016 weather scenario and the controls for the windows in Zone 1, 3 and 7 ON. Windows in bedrooms are opened manually at night from 10 pm to 6 am. The shading in the windows operate for the whole period of simulation. The sun shadings are modelled to be not working during 3 days in the hottest period for the typical weather scenario-July 20, 21 and 22 (cases 2 and 4).

Table 4 Resilience scenarios

Case	Weather	Automatic Opening Control	Manual Opening Window Bedroom	Shading
1	2015-2016 monitored data	ON	ON	ON
2	2015-2016 monitored data	ON	ON	OFF(3 days)
3	Heat Wave Period 2019	ON	ON	ON
4	Heat Wave Period 2019	ON	ON	OFF(3 days)

4. Results and Discussions

4.1. Effect of night cooling and determining critical zone

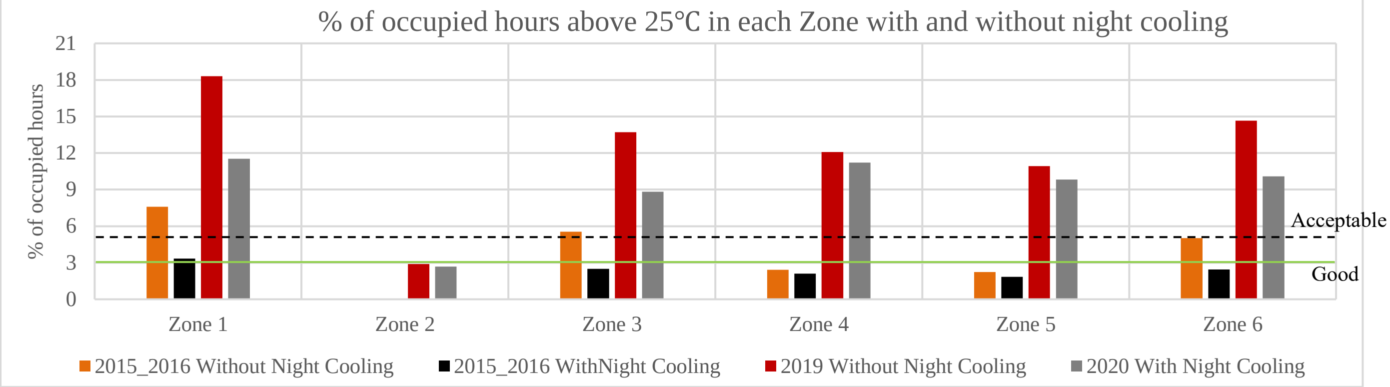

Fig. 5 Percentage of occupied hours exceeding 25°C in each Zone, with and without the Night Cooling

Initial simulation with and without the night cooling proves:

(a) that the overheating hour is within the criteria due to the night cooling solution (See Fig. 5) and
(b) Zone 1 is the most critical zone in the case study building.

Fig. 5 shows the percentage of hours in each zone above 25°C. With night cooling, overheating hours are 3.34 % opposed to 7.6% without night cooling in 2015-2016. The percentage of occupied hours when the temperature is above 25°C, in warmer weather condition (2019) decreases from 18.3% to 11.5% due to night cooling. Zone 7 is the staircase and is not taken into consideration evaluation of thermal comfort. High percentage of hours above 25°C in Zone 1, are due to the high window-to-floor ratio, orientation of the Zone 1 (Southwest and Northwest façade) and high internal heat gains, causing high operative temperatures, up to 28.1°C, during hot summer weeks.

4.2. Resilience scenarios

The effects of 2 external events influencing the performance of the night cooling and the thermal conditions of the zones are assessed:(1) Heat wave (23rd to 25th July 2019) and (2) Shading Failure (20th to 22nd July). To check the effect of these events on the thermal condition of the zones, the following scenarios are compared:

(a) **Effect of heat wave**: The effect of heat wave on the thermal conditions of the Zones are assessed by comparing Case 3 to 1. In the reference case (Case1), the hottest day was 21st July when the temperature reaches 32.3°C. The night cooling takes 9 hours to bring the temperature of Zone 1 below 25°C. Highest operative temperature of 28.1°C in Zone 1 during Case 1 is reached on 24th July at 4 pm and it takes 8 hours to bring the temperature below 25°C. However, after the heat wave of 25th July, assessed in Case 3 when the outside temperature reaches 40.6°C, the system takes 82 hours (3.4 days) to bring the temperature below 25°C in Zone 1 from the highest operative temperature of 32.2°C. In

Zone 1, the percentage of hours above 25°C increase to 11.53% (578h) in heat wave period (23rd to 25th July 2019) compared to 3.34% (91h) for Case 1.

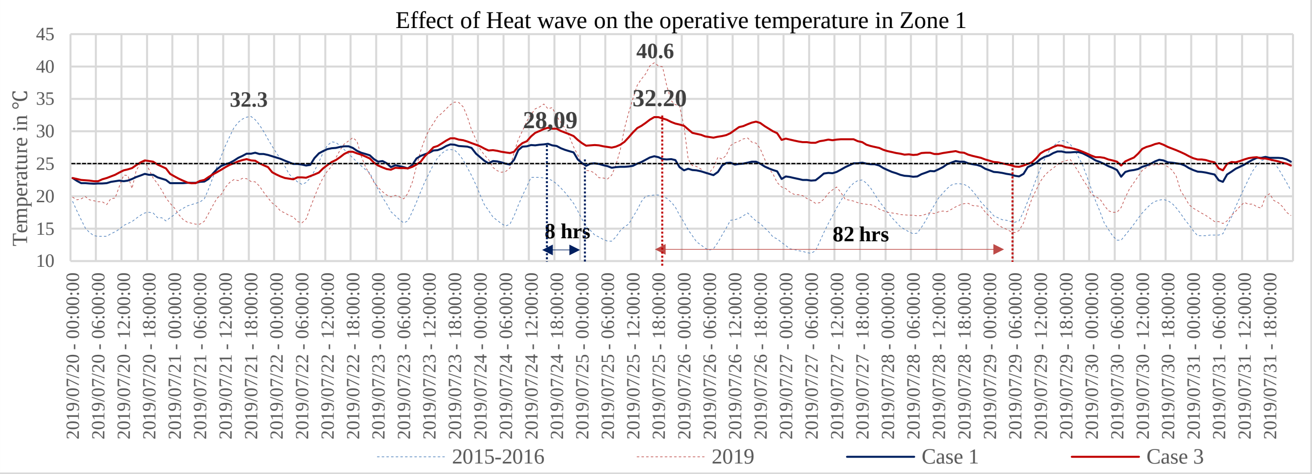

Fig. 6 Effect of heat wave on the operative temperature in Zone 1

(b) **Effect of Shading Failure**: As shown in Fig. 7, significant variations in operative temperature occurs if the solar shading fails during the summer period of 2015-2016 weather conditions (July 20, 21 and 22) or during a heat wave scenario. For 2015-2016 weather scenario the highest temperature in Zone 1 is 29.4°C on 22nd July and it takes 62 hours to bring the temperature below 25°C. Similarly, for the heat wave weather file, highest operative temperature in Zone 1 is 33°C compared to 32.3°C without shading failure and takes 84 hours to bring the temperature below 25°C. In Zone 1, the percentage of hours above 25°C increase 13.29% (1164 h) in heat wave period (23rd to 25th July 2019) Case 4, compared to 4.25% (372h) for Case 2.

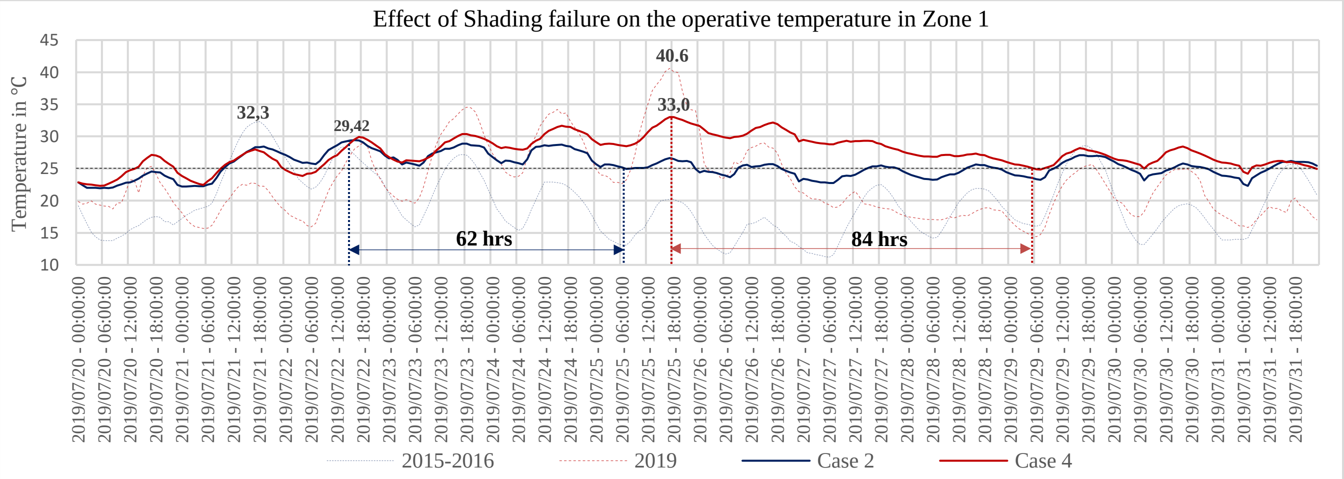

Fig. 7 Effect of shading failure on the operative temperature in Zone 1

Comparing the same scenarios in 2015-2016 and 2019 heat wave scenario, the performance of the night cooling and - resilience of the system be assessed.

4.3.Number of hours the Control is ON-As seen in Fig. 8, in Zone 1, the number of hours the control is ON and the windows open to cool the zone ranges from 718h in reference case to 747h in extreme scenario of combined heat wave and shading failure. More so, the total number of hours, the Control remains ON differs for each case-100 hour for Case 1(2015-2016 weather scenario and shading ON), 102 hour for Case 2 (2015-2016 weather scenario and shading failure), compared to 106 hour for Case 3(2019 weather scenario and shading ON) and 107 hour in Case 4(2019 weather scenario and shading failure) in the period between 20th to 31st July. The control remains same but the number of hours at night for which the windows remain open to bring the temperature to comfort conditions increases considerably.

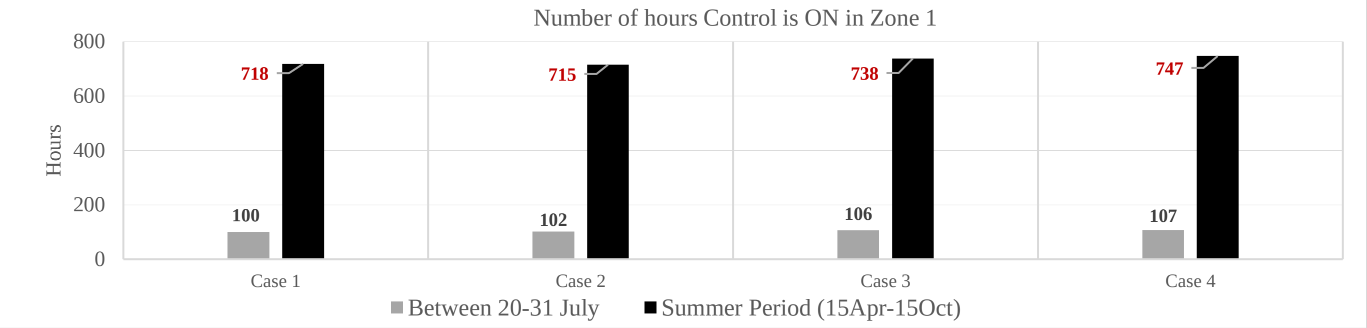

Fig. 8 Number of hours the night cooling control was ON during the studied time period (10th July to 10th August) and the whole simulation period.

5. Conclusions

This study demonstrates that for ensuring good indoor comfort in summer by the low energy cooling technologies like night cooling, the system should be resilient. Night ventilation ensuring comfort conditions in typical weather may fail to perform satisfactorily in events like heat waves and shading failure. The results of this study clearly indicate the necessity of resilience as performance indicator for the night cooling system. The night cooling system when subjected to a shock like the heatwave or solar shading failure demonstrates the ability to withstand the shock and robustness and spring back to its state of designed performance to bring back the temperature in the Zones below 25°C. The system adapts to the shock to recover and function. It can be identified that the system undergoing a vulnerable phase during a solar shading failure or a heat wave, do respond and transform itself to a more robust or resilient system. The system however already shows resilience- the night cooling helps to reduce the temperature below 25 °C in each Zone after a certain time period after it undergoes a shock.

The change in the number of hours the control is ON and the corresponding hours it takes the system to bring the temperature of a Zone within specified comfort limit (25°C) in this case, demonstrates the robustness of the system. This aligns with the 'adaptive cycle theory' where the system under vulnerability, displays a survivability response and a recovery phase is present to regain a new equilibrium. If the 2015-16 weather scenario is taken as reference case where the temperature is below 25°C within 8 hours after reaching the highest operative temperature, the system is resilient to shading failure, where it takes 2.6 days and 3.4 days during the heat wave period of 2019, to bring the operative temperature below 25°C.

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