Evaluating thermal resilience to overheating in a Belgian apartment in shock scenarios

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ABSTRACT

Building designs to be in line with energy efficient and carbon reduction goals, often focus on energy efficient techniques like high insulation, airtightness. However, these buildings are often subjected to overheating risks due to unforeseeable events like frequent heatwaves and power outages even in moderate climate zones like Belgium. Overheating risks in residential buildings have negative impact on the health of the building occupants (especially on the vulnerable occupants like elderly, infants and sick persons), causing sleep deprivation, heat stress and even mortality. In future climate scenarios, measures to reduce overheating risk in buildings while limiting the energy use of space cooling are gaining importance. This calls for a new design approach where thermal resilience (ability of the building and system to withstand shocks, adapt and maintain its normal function) is taken into account. The focus of this research is to evaluate existing resilience indicators (thermal autonomy, passive survivability, absorptive capacity, recovery capacities, etc.) for a typical Belgian apartment, by dynamic Building Energy Simulations (BES). A parametric study was conducted by implementing passive (night cooling) and active cooling technologies (air conditioning) and by changing building parameters (glazing ratio and shading) to check which building parameters and passive cooling strategies have the biggest impact on the overheating risk. Thermal resilience will be evaluated by subjecting the case study building to different shocks like heat waves (varying intensity, duration and severity) and power outages (varying duration and time of occurrence). The heatwave files, used for the BES are developed adopting the methodology of the 'Weather Data Task Force of IEA EBC Annex 80 "Resilient Cooling of Buildings". Finally, the evaluation of the thermal resilience for different shocks (heatwaves, power outages etc.), will indicate the most influencing design parameters (system's + building's) contributing to the resilience to overheating. Results show that the recovery time of the apartment building is shortened from more than 2 weeks to 28 hours during an intense heatwave. Implementing solar shading can improve the thermal comfort during an intense heatwave by approximately 30% of the occupied hours. When changing the window-to-wall ratio in combination with night cooling, it was found important to find a balance between window opening and solar heat gains.

KEYWORDS

Climate change, Heat waves, Power outages, Overheating risk, Resilience to overheating

1 INTRODUCTION

Human activity has caused the global annual average temperature to rise with 1.1°C. In the Glasgow climate pact, there was decided to try to limit this increase to 1.5°C. This will ask for a big effort (UNFCCC, 2021). In Belgium the annual average temperature has already risen with 2.1°C (KMI, 2020). In the future heatwaves will become more frequent. The heatwaves will also become more intense, longer and more severe (Berk et al., 2021). There will be an increase in cooling demand because of the increase in the outdoor mean air temperature and the higher number of heatwaves. Energy use for cooling accounted in 2018 for approximately 20%

of the total energy use worldwide. According to the IEA, this could triple by 2050, if no measures are taken (International Energy Agency, 2018). During future heatwaves, the cooling load will be even higher, which will result in a higher electricity demand. When the peak demand exceeds the capacity of the electricity network, power outages will occur (Wang et al., 2021). To fight climate change the focus is currently put on an energy efficient and airtight building design. This causes a bigger risk to overheating during heatwaves (Zhang et al., 2021). Overheating risks in residential buildings have negative impact on the health of the building occupants (especially on the vulnerable occupants like elderly, infants and sick persons), causing sleep deprivation, heat stress and even mortality (Laouadi et al., 2021). In future climate scenarios, measures to reduce overheating risk in buildings while limiting the energy use of space cooling are gaining importance. This calls for a new design approach where thermal resilience is taken in to account (Zhang et al., 2021). Thermal resilience is the capacity of a building to not only withstand, but also recover from a shock (Moazami et al., 2019).
This study aims to evaluate the impact of existing building designs and passive strategies on the overheating risks in buildings. The thermal resilience to overheating of the building and passive and active cooling strategies (night cooling and air conditioning) will be tested in a parametric study varying building parameters (solar shading and window-to-wall ratio) during shocks such as heatwaves and power outages.

2 METHODOLOGY

2.1 Case Study Building

The Open Studio Model is base of an exiting apartment building in Aalst (Belgium) (see Figure 1). The apartment is South-East oriented. The U-value of the external walls is 0,17 W/m²K. The window-to-wall ratio is 40,86% (East) and 32,34% (South). The U-value of the windows is 1,0 W/m²K. External solar shading with a solar reflectance of 0.37 is implemented for all windows, to provide shading when the direct radiation on the window is above 250 W/m².

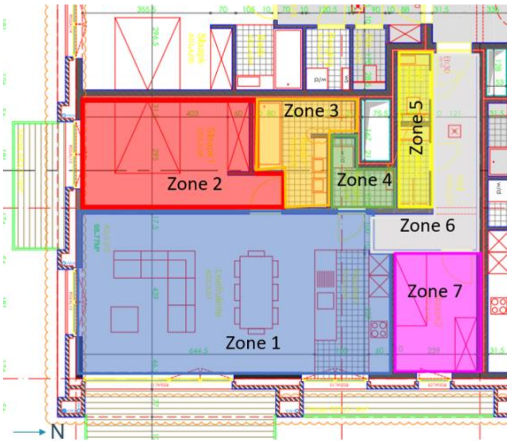

Figure 1: Floorplan indicating thermal zones

Table 1: Thermal Zone Description

Thermal Zone	Type	Total floor area (m²)	Ventilation flow (m³/h)
Zone 1	Living and Kitchen	44,04	125 (supply and extract)
Zone 2	Bedroom	18,13	75 (supply)
Zone 3	Bathroom	7,51	50 (extract)
Zone 4	Storage	3,21	50 (extract)
Zone 5	Bathroom	5,41	75 (extract)
Zone 6	Corridor	11,09	/
Zone 7	Bedroom	10,1	75 (supply)

The thermal mass is classified as heavy. There is a ventilation type D with heat recovery. The ventilation rates were calculated according to the (Flemish) EPB-directive (NBN, 2005). There is currently no cooling technology in the apartment building. The apartment is designed for 3 people. The occupancy level in the building is divided into a weekday and weekend profile (Figure 2). Two people are at work from 8h30 to 18h from Monday to Friday. One person goes to school from 8h30 to 16h from Monday to Friday.

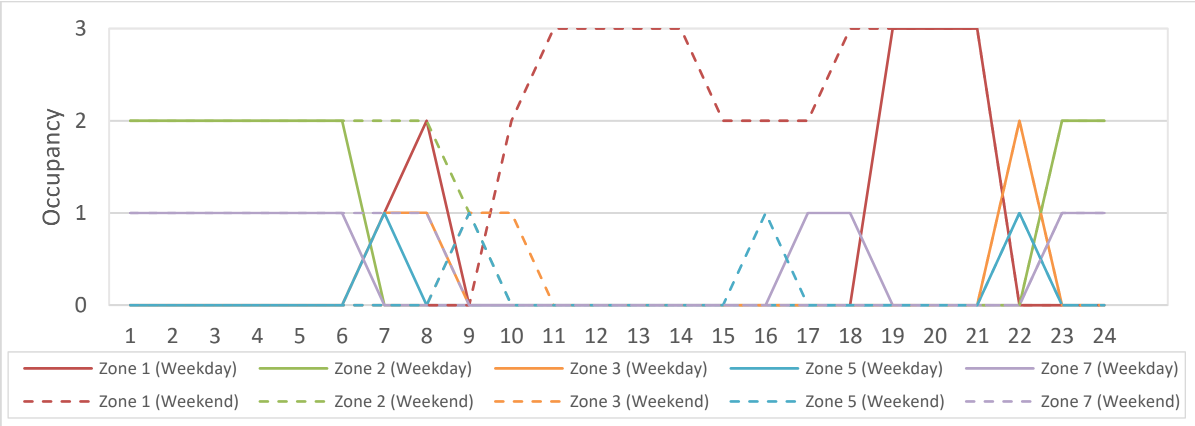

Figure 2: Occupancy Schedule

2.1.1 Cooling strategy and Control system

The night cooling is implemented in Open Studio using the element 'OS:ZoneVentilation:WindandStackOpenArea.' The opening windows are located in zones 1, 2 and 7, in the east facing and south facing facades. The windows open in tilt stand. The window opening is calculated according to (Van Paassen A H C, Liem S H, 1998) using the window area, height and opening angle.

The night cooling is activated if all of following conditions are fulfilled (Vanvalckenborgh & Decrock, 2017):

- Between April 1st and October 31st;
- Between 10 pm and 6 am;
- Indoor temperature >20°C;
- Outdoor temperature >12°C;
- Temperature difference between indoor and outdoor >2°C;
- Wind speed < 10m/s;

The air conditioning is an air-to-air heat pump. It is implemented in open studio by adding the element OS:ZoneHVAC:PackagedTerminalAirConditioner to thermal zones 1, 2 and 7. The air conditioning is based on an existing unit from Midea type MSMBAU-09HRFN1. It has a cooling capacity of 2,6 kW. The setpoint temperature is 24°C. The unit is continuously available during the heatwave. Data that was not specified in the Midea brochure were set according to the recommendations on the BigLadderSoftware website (Big Ladder Software, n.d.).

2.2 Building Energy Simulation and parametric study

To analyse the thermal resilience, hourly Building Energy Simulations were performed using Open Studio. A parametric study was conducted.

An overview of the methodology is given in Figure 3. In a first step, the standard model is subjected to the typical weather data (Scenario A). The results are used as reference data, this is the base case scenario. The standard model is also submitted to two different shock scenarios: (scenario B) a heatwave and (scenario C) the combination of a 24-hour power outage and heatwave. In the 2nd step, night cooling is implemented. During the 3rd step, different building parameters are changed. This study was limited to change two building parameters, namely the solar shading (implemented or not) and the WWR (30% and 50%).

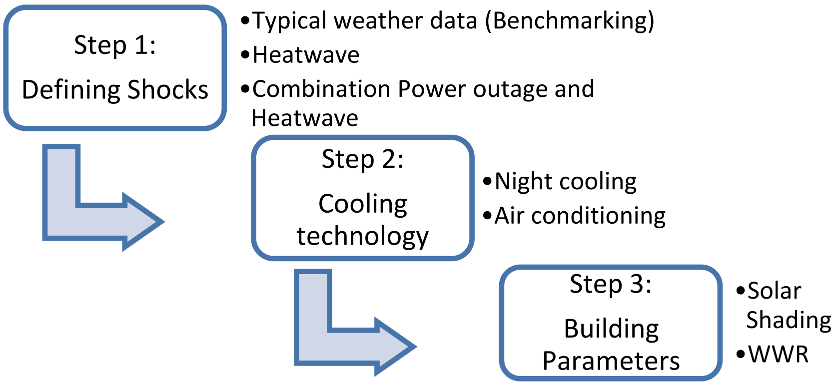

Figure 3: Flowchart Methodology

2.2.1 Resilience Scenarios

Table 2 gives an overview of the parameter variations for this study. Scenarios 1A to 6A occur during typical weather data. The simulation is run during the cooling season (from April 1st until September 30th). Scenarios 1B to 6B during the most intense heatwave in the midterm future and scenarios 1C to 5C during a combination of the heatwave with a power outage. The power outage starts at 9 am on the hottest day of the heatwave and continues for 24 hours. During the power outage, a solar shading failure is assumed. During the heatwave scenarios (B and C) simulation are run during the heatwave period, two weeks before and two weeks after the heatwave. Testing the air conditioning during the combination of heatwave and power outage and the impact of building parameters on this cooling technology is not in the scope of this study.

Table 2: Resilience Scenarios

Shock Scenario	Cooling Technology	Building Parameter	Scenario
Typical weather data	/	/	1A
	Night Cooling	/	2A
		No Solar shading	3A
		WWR 30%	4A
		WWR 50%	5A
	Air conditioning	/	6A
Heatwave (Midterm Most Intense)	/	/	1B
	Night Cooling	/	2B
		No Solar shading	3B
		WWR 30%	4B
		WWR 50%	5B
	Air conditioning	/	6B
Heatwave (Midterm Most Intense) + Power Outage (24h)	/	/	1C
	Night Cooling	/	2C
		No Solar shading	3C
		WWR 30%	4C
		WWR 50%	5C

2.2.2 Weather data and heatwave

The typical weather data as well as the weather data for the heatwave was developed according to the methodology of the "Annex 80 Weather Data Task Force" (Berk et al., 2021). The typical weather data consist of a combination of the weather data between the years 2000 and 2020. In Belgium a heatwave is officially declared when the maximum temperature is above 25°C for at least five consecutive days and is above 30°C during at least three of these days (KMI, 2020). The most intense heatwave in the midterm future has been chosen for this study. According to simulations (Berk et al., 2021), this heatwave occurs from June 29th 2043 to July 4th 2043.

2.3 Evaluation of thermal comfort and thermal resilience

The parameters that were used in this study to evaluate the thermal resilience are:

- Thermal comfort: the % of occupied hours when the operative temperature is above 25°C, 26°C and 28°C. 5% is considered as acceptable and 3% as good according to Method A as described in Annex F of the EN 15251 (Olesen, 2012)
- Unmet Degree Hour (UDH): sum of $\Delta\theta_i$ per hour over the analysed period. $\Delta\theta_i$ is the amount of degrees that 25°C was exceeded (Sun et al., 2021).
  Remark: the UDH of scenario B and C can be compared, but scenario A has a different duration, so comparing the UDH will not be possible.
- Recovery time: the amount of hours that the apartment needs to recover, counted from the moment were the maximum operative temperature is reached until it drops beneath 25°C (Zhang et al., 2021).

3 RESULTS

3.1 Base case scenario (Scenario A) and Determining Most Critical Zone

In the first simulation, the standard model is simulated during the typical weather. The thermal comfort of zones 1, 2 and 7 are presented in Figure 4. Thermal zone 1 is considered as the most critical zone in the apartment. Zone 1 will be further investigated during the remainder of the study. From the results in Figure 4 it can be concluded that the thermal comfort of the apartment during the typical weather data only acceptable is when using the 28°C threshold, and not acceptable when using the thresholds of 25°C and 26°C. A cooling technology will be needed to fight overheating.

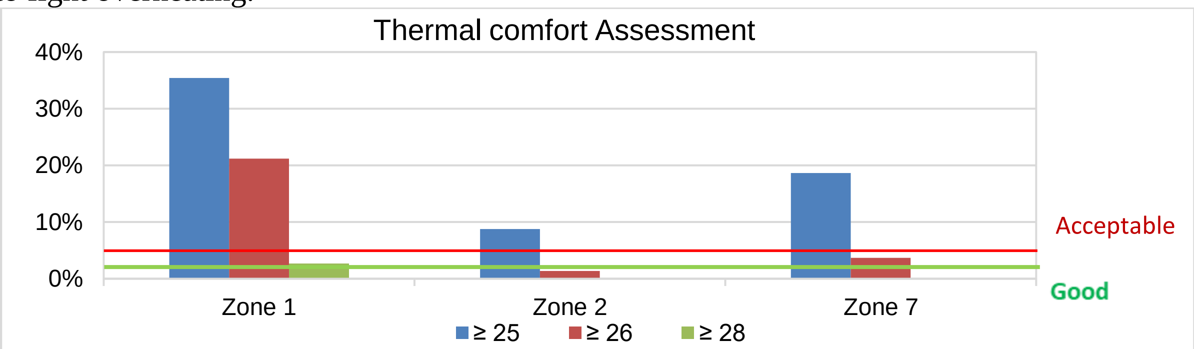

Figure 4: Thermal Comfort Base Case Scenario

3.2 Shock scenarios

In Figure 5 the performance of the standard model during shock scenarios is displayed. During the heatwave scenario (scenario B) and with a heatwave and power outage (scenario C), the thermal comfort is not acceptable in the standard apartment. The indoor temperature exceeds the threshold of 28°C during 100% of the occupied hours in both scenario B and C. The effect of the power outage and solar shading failure are clear in the UDH, where the UDH increases slightly in scenario C compared to scenario B. The solar heat gains have a considerable influence.

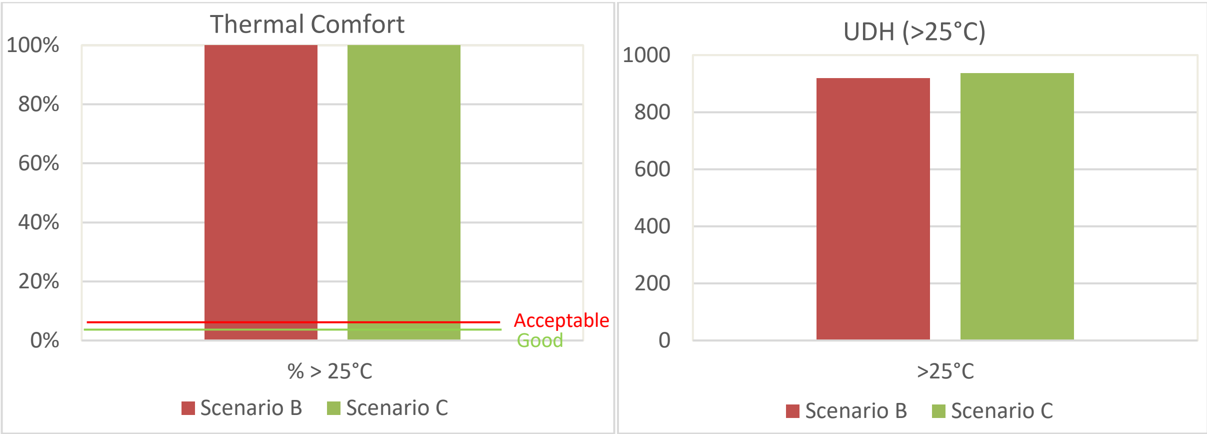

Figure 5: Results Base case During Shocks

3.3 Implementing cooling strategy (night cooling)

Implementing night cooling has a big effect on the thermal comfort and resilience of the apartment. The results are displayed in Table 3 and Figure 6. By implementing night cooling, the thermal comfort has become good in all shock scenarios if the threshold of 28°C is used. When using the threshold of 25°C, the thermal comfort is acceptable during the typical weather (scenario 2A) but not acceptable during the heatwave scenarios (2B and 2C). During the heatwave scenarios, the thermal comfort did improve, the indoor temperature exceeds 25°C during 64% of the occupied hours less than without night cooling. The UDH has also been improved by approximately 800 in both heatwave scenarios. The recovery time has improved from more than 2 weeks to 28 hours during scenario 2B and 14 hours during scenario 2C.
During the heatwave, the outside air does not always drop beneath 25°C during the night, this results in a recovery time that is longer than 24 hours.

Table 3: Results Night Cooling

Scenario	**Hottest Day**	$\boldsymbol{\theta_{e,max}}$**(°C)**	$\boldsymbol{\theta_{i,max}}$ **(°C)**	**%>25°C**	**%>26°C**	**%>28°C**	**Recovery Time**	**UDH**
1A	23/07	30,18	29,28	35,45%	21,22%	2,72%	/	758,70
2A	23/06	32,9	26,42	4,53%	0,45%	0,00%	/	32,75
1B	01/07	40,23	31,25	100%	96,11%	51,59%	>2 weeks	919,65
2B	01/07	40,23	27,85	36,40%	18,37%	0,00%	28 hours	107,14
1C	02/07	30,5	31,23	100%	96,11%	52,30%	>2 weeks	936,60
2C	02/07	30,5	27,40	36,40%	19,43%	0,00%	14 hours	104,75

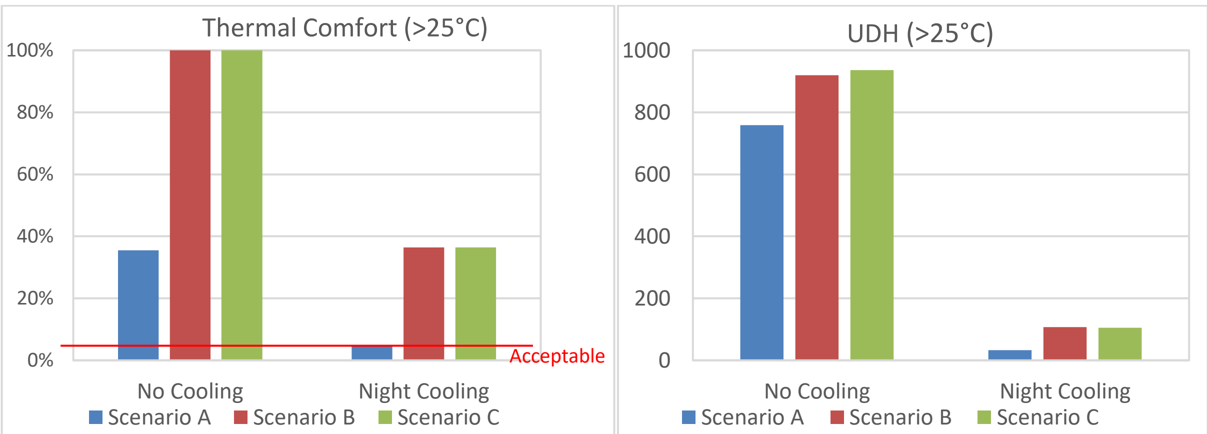

Figure 6: Results Night Cooling

3.4 Building Parameters

3.4.1 Effect of Solar Shading

The impact of the presence of solar shading in combination with night cooling is simulated, the results are displayed in Table 4 and Figure 7. The solar shading has an influence on the resilience of the night cooling. Without solar shading the thermal comfort is not acceptable (using the threshold of 25°C) during the typical weather data (3A). The UDH without solar shading (3A) increases to almost 9 times the UDH during the typical weather scenario with solar shading (2A). During the heatwave scenarios (3B and 3C) the removal of the solar shading results in an increase the number of occupied hours where the indoor temperature exceeds 25°C with approximately 20%. The UDH during these scenarios' doubles. The recovery time during scenario 3B is one hour longer than the same shock with solar shading (2B). This is the case because the highest temperature occurs one hour earlier during the scenario without solar shading (3B). During the combination of heatwave with power outage, the peak temperature occurs 3 hours later when there is no solar shading, this is the case because during the power outage there is also a solar shading failure. This results in a decrease of the recovery time with 3 hours.

Table 4: Results Night Cooling and Solar Shading

Scenario	Hottest Day	$\theta_{e,max}$(°C)	$\theta_{i,max}$ (°C)	%>25°C	%>26°C	%>28°C	Recovery Time	UDH
2A	23/06	32,9	26,42	4,53%	0,45%	0,00%	/	32,75
3A	23/06	32,9	28,01	18,05%	6,02%	0,06%	/	250,30
2B	01/07	40,23	27,85	36,40%	18,37%	0,00%	28 hours	107,14
3B	01/07	40,23	29,17	57,24%	32,51%	5,30%	29 hours	232,83
2C	02/07	30,5	27,40	36,40%	19,43%	0,00%	14 hours	104,75
3C	02/07	30,5	28,91	57,24%	32,51%	4,24%	11 hours	226,30

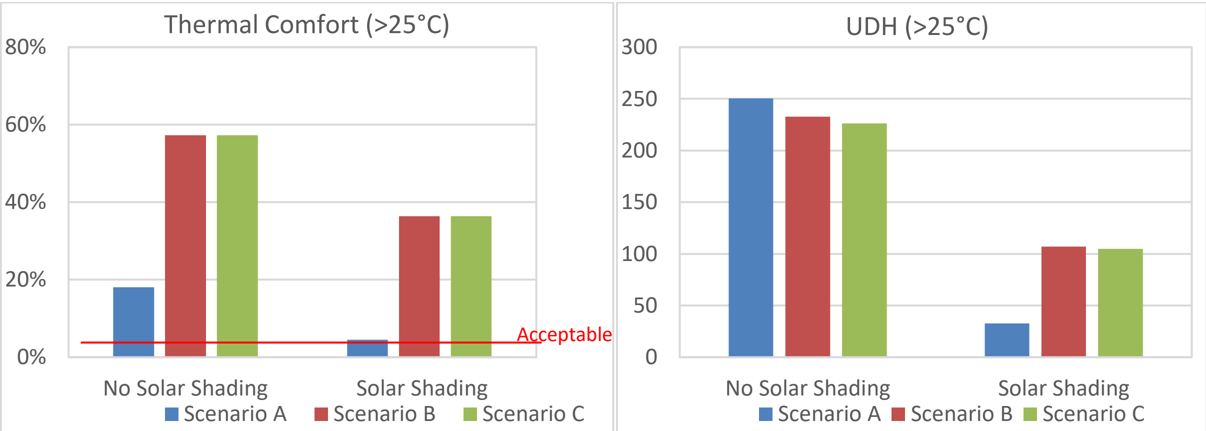

Figure 7: Results Night Cooling and Solar Shading

3.4.2 Effect of WWR

Changing the WWR was tested in combination with night cooling, the results are shown in Table 5 and Figure 8. Both increasing and decreasing the WWR have a negative effect on the thermal comfort and UDH. The decrease of the WWR to 30% during the heatwave scenarios (4B and 4C) increases the number of occupied hours that the indoor temperature exceeds 25°C with 6% to 7%. During the heatwave scenarios (5B and 5C) the increase of the WWR to 50% increases the amount of occupied that the indoor temperature exceeds 25°C with approximately 30%. The UDH changes accordingly. There is not a big effect on the recovery time.

The reason the thermal comfort is worse with bigger windows is because the solar heat gains are higher. The smaller windows result in less solar heat gain, but the window opening is also decreased resulting in less ventilation. It will take longer to get the cool outside air inside. A good balance between window opening and solar heat gains is needed.

Table 5: Results Night Cooling and Change of WWR

Scenario	Hottest Day	$\theta_{e,max}$(°C)	$\theta_{i,max}$ (°C)	%>25°C	%>26°C	%>28°C	Recovery Time	UDH
2A	23/06	32,9	26,42	4,53%	0,45%	0,00%	/	32,75
4A	23/06	32,9	26,5	5,17%	0,97%	0,00%	/	46,52
5A	23/06	32,9	27,69	14,17%	5,17%	0,00%	/	181,40
2B	01/07	40,23	27,85	36,40%	18,37%	0,00%	28 hours	107,14
4B	01/07	40,23	28,01	42,76%	21,20%	0,35%	28 hours	124,59
5B	01/07	40,23	29,42	66,08%	39,22%	6,01%	29 hours	274,94
2C	02/07	30,5	27,40	36,40%	19,43%	0,00%	14 hours	104,75
4C	02/07	30,5	27,64	43,11%	21,91%	0,00%	14 hours	125,92
5C	02/07	30,5	29,61	66,08%	39,58%	7,42%	14 hours	279,67

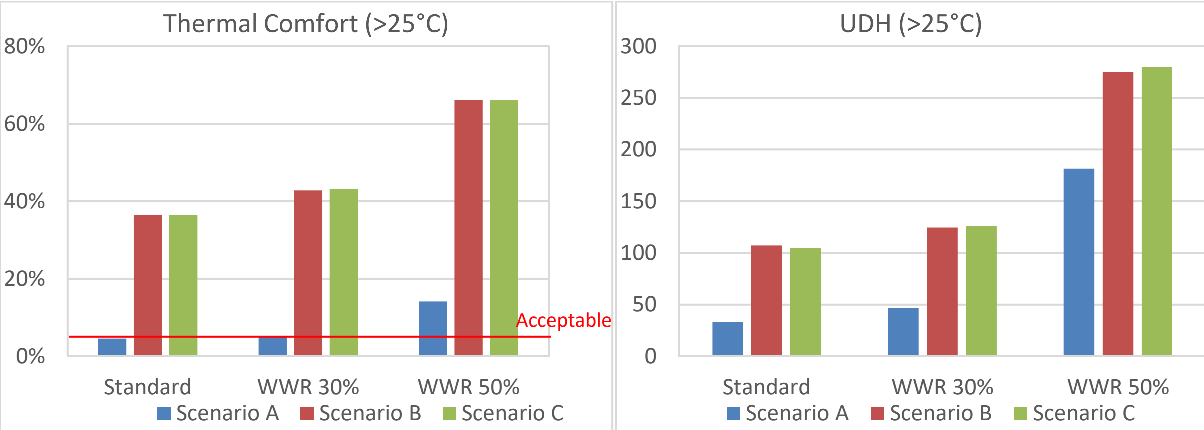

Figure 8: Results Night Cooling and Change of WWR

3.5 Implementing cooling strategy (air conditioning)

The typical weather data as well as the heatwave are simulated only during the heatwave period, and 72 hours before and after the heatwave period. The results are displayed in Table 6 and Figure 9. The thermal comfort (25°C) improves by approximately 50% when implementing air conditioning during the typical weather data, and by approximately 65% during the heatwave scenario. While it seems like the thermal comfort is not yet acceptable and the UDH is still quite high when using air conditioning, this is not the case. The hours where the temperature exceeds 25°C, are before and after the heatwave period. During this time, the air conditioning is not working. As seen in Figure 10, when the air conditioning starts working, the indoor temperature drops in less than an hour to the setpoint temperature (24°C) and stays there until the unit is shut off.

Table 6: Results Air conditioning

Scenario	Hottest Day	$\theta_{e,max}$(°C)	$\theta_{i,max}$ (°C)	%>25°C	%>26°C	%>28°C	Recovery Time	UDH
1A	23/07	30,18	29,28	64,89%	27,66%	0,00%	/	55,38
2A	23/06	32,9	26,42	4,53%	0,45%	0,00%	/	32,75
6A	/	/	/	13,13%	0,00%	0,00%	/	5,47
1B	01/07	40,23	31,25	100%	100%	60,34%	< 1 hour	420,39
2B	01/07	40,23	27,85	36,40%	18,37%	0,00%	28 hours	107,14
6B	/	/	/	35,32%	20,20%	5,05%	< 1 hour	50,63

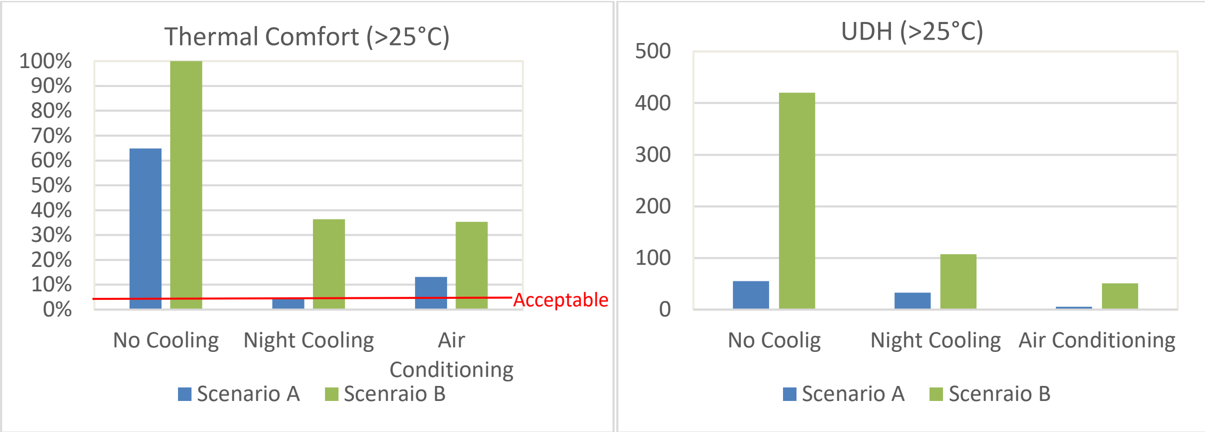

Figure 9: Results air conditioning

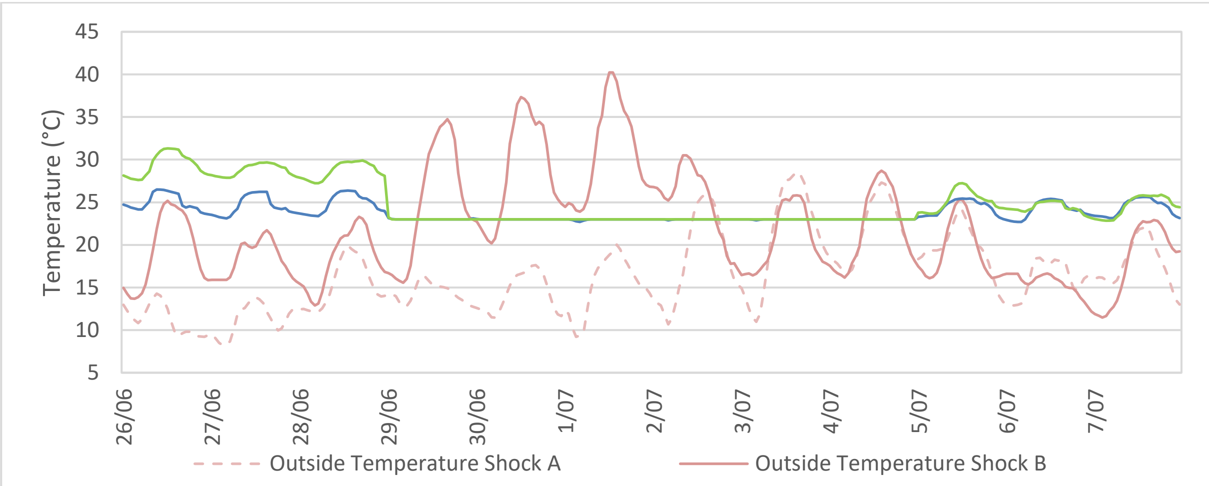

Figure 10: Graph Temperature with Air conditioning

4 CONCLUSIONS

Night cooling makes the apartment resilient, but the help of another passive cooling technology or an active cooling technology will be needed to withstand future heatwaves. The recovery time is reduced from more than 2 weeks in both heatwave scenarios to 28 (no power outage) and 14 (power outage). During standard weather data there is an improvement of the thermal comfort (25°C) with 30% making it acceptable. During the heatwave scenarios there is an improvement of the thermal comfort (25°C) with 64%.

Solar shading has a positive effect on the resilience of the night cooling. When the solar shading is removed, the recovery time during the heatwave scenario increases with 1 hour. The thermal comfort (25°C) during the standard weather scenario, worsens with 14% and exceeds the threshold for an acceptable thermal comfort when the solar shading is removed. Removing the solar shading during the heatwave scenario results in double the UDH, and the thermal comfort (25°C) worsens with 30%.

In this case study changing the WWR has a negative impact on the resilience of night cooling. Increasing the WWR will result in more solar heat gains, which results in a higher UDH and worse thermal comfort. A decrease in WWR will result in lower solar heat gains and a smaller window opening. A smaller window opening results in a lower ventilation rate, the apartment will need more time to recover.

Air conditioning can be a solution to help withstand future heatwaves, the recovery time is <1 hour. But it is recommended to only use this active cooling technology as an additional help to withstand future heatwaves. It consumes a lot of electricity, which can result in a power outage and puts a strain on the climate.

5 ACKNOWLEDGEMENTS

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