Which design parameters impact the resilience to overheating in a typical apartment building?

Abantika Sengupta*[1], Jef Kerckaert[1], Marijke Steeman[2], and Hilde Breesch[1]

Gebroeders de Smetstraat 1
9000, Gent, Belgium
**Corresponding author :*
abantika.sengupta@kuleuven.be
Presenting author: Abantika Sengupta

2 Ghent University
Campus Boekentoren - Plateau
Jozef Plateaustraat 22
9000 Gent, Belgium

ABSTRACT

Airtight, highly insulated, and passively cooled buildings in the EU are designed under typical outdoor and indoor thermal conditions. With increasing risk and uncertainty with regards to climate change and associated heatwaves(HW), the design thermal performance of these buildings is not guaranteed. It is crucial to focus on improving thermal resilience to overheating and futureproof these buildings. "Thermal resilience to overheating" is the characteristic that describes the extent to which buildings and their cooling strategies can maintain habitable conditions during or post shocks. Thus, a new design approach to improve the thermal resilience to overheating of existing and newly built buildings is a growing need in the building sector. Within the framework of IEA EBC Annex 80-Resilient Cooling of Buildings, the aim of this study is to determine the most influential building and system design parameters that impact the thermal resilience to overheating. To achieve this aim, building energy simulation (BES), is conducted on a reference typical apartment building in Belgium. A 2 bedroom apartment for 3 occupants is simulated in Open Studio and EnergyPlus during summer (April-September) of typical meteorological year (TMY). The apartment is evaluated with its default design (very heavy thermal mass, window to wall ratio (WWR) 10% and with no shading and no passive cooling strategy (in this case natural night ventilation -NNV). Apart from the default design, design parameters were altered such as thermal mass (very heavy-medium-light),WWR (10-30%), implementation of solar shading and NNV. The impact of the worst, improved and the optimized designs are also evaluated during a 6 day intense heatwave period. Overheating are most likely to occur in current buildings with higher WWR (>30%), no shading and with lighter thermal mass. WWR has highest impact on the thermal resilience followed by thermal mass. Apartment with very heavy thermal mass,WWR 10%, with NNV and solar shading shows the best result (80% reduction in the percentage of occupied hours above 25°C threshold). However, in buildings with higher WWR (>30%) and lighter thermal mass, thermal resilience can be improved with implementation of solar shading and passive cooling strategies such as NNV. Even during heatwave, an apartment without NNV has better (45%) thermal resilience to overheating than an apartment with NNV if the WWR is
< 30%) and has a medium thermal mass rather than a light thermal mass.

KEYWORDS

Thermal Resilience, Overheating-risk, Apartments, Heatwaves, Design parameters

1 INTRODUCTION

A recent study in Europe, shows the cooling degree days (CDD) value was almost four times higher in 2022 than in 1979, indicating that the need for cooling (air conditioning) significantly increased over the last decades [1]. Additionally, Intergovernmental Panel on Climate Change (IPCC)s 2022 report warns about the severity of the climate change impacts (frequent and severe heatwaves) in future climate scenarios and also stresses on adaptation and mitigation plans[2]. Thus, overheating risk in buildings is expected to increase as global warming continues [3]. Apartment buildings accounts for a large share of building stocks and have implemented energy efficient technologies and practices (e.g., high-insulation, airtight envelopes, improved glazing). 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 in future climate scenarios and during HWs[3][4]. Thus, to avoid any health risks such as sleep deprivation, heat stress and even mortality due to overheating in these buildings, the thermal resilience to overheating of apartments should be assessed and improved. A buildings' thermal resilience can be defined as "An ability of the building to withstand disruptions; and to maintain capacity to adapt, learn and transform" [5][6]. Thus, apart from energy performance, resilience is gaining importance to assess building performance [7] [8] and can be considered as a primary function of the building [9]. However, in order to improve the thermal resilience to overheating, the impact of different building and system parameters on the thermal resilience should be evaluated.

Building design parameters such as, building setting and micro-climate, building orientation and space zoning, window orientation and window to wall ratio (WWR), envelope properties (U-values, thermal mass, air-tightness), glazing properties, implementation of solar shading and passive cooling strategies impact the thermal resilience to overheating. Window orientation and WWR has significant impact on thermal resilience to overheating [10]. Norwegian residential building with WWRs greater than 50% experienced higher indoor temperatures and greater overheating risk during HWs compared to buildings with lower WWRs [11]. A study conducted to evaluate the most optimal WWR in different European climates concluded that although there is an optimal WWR in each climate and orientation, most of the ideal values can be found in a relatively narrow range ($0.30 < WWR < 0.45$). Apart from WWR, thermal mass of a building impacts the thermal resilience to overheating [12]. Incorporating materials with high thermal mass, such as concrete or brick, into the building envelope can help to absorb and store heat during the day, and release it at night when temperatures are lower. A recent study on an educational nZEB in Belgium showed that heavy thermal mass performs well in short-term shocks like short HWs when the building takes longer time to absorb the heat but once the heat enters the building, without proper ventilation, the heat is retained in the building for longer period and negatively impacts the buildings' thermal resilience to overheating C. A simulation study [13] evaluating the performance of solar shading in offices in several climates shows cooling energy use reductions by 5 to 77%. A study to evaluate the recovery aspect of thermal resilience of a residential building equipped with solar shading showed that when shading is active in a typical meteorological year (TMY) scenario, the temperature in the living room reaches below 25°C after peak within 9 hours. However, same building takes significantly higher recover time (takes 62 hours without the shading in a TMY period and 84 hours during HW period). Sengupta et al. [14] evaluated the thermal resilience of a Belgian dwelling during the HW of 2020 with and without natural night ventilation (NNV). The results showed that with implementation of NNV, the building recovers 90% faster from the HW and decreases maximum temperatures indoors by 4.3°C compared to the building without NNV.

The objective of this paper is to evaluate the impact of building design parameters and implementation of solar shading and passive cooling strategy (NNV) on the thermal resilience to overheating in a typical Belgian apartment. For this a base case scenario of the apartment (with default construction, no shading or no NNV) during TMY scenario is evaluated altering the design parameters. The worst, improved and optimized design cases are then assessed during a 6 day long HW.

2 CASE STUDY BUILDING

In order to perform parametric study, typical apartment building floor plans, while maintaining some degrees of freedom, has been developed by Renson [15] and KU Leuven. The floor plans are based on new buildings (2016-2020) data from Valaams Energie-en Klimaatagentschap (VEKA)[16] and are evaluated against EPBD guidelines [17]. The developed individual apartment floor plans have multiple bedrooms (ranging from 1 to 3). The surface of the living room, kitchen, utility room and bathroom increase in function of the number of bedrooms. Multifamily dwellings (in Belgium) typically have an open plan kitchen and living area.

Based on the VEKA [16] data (Figure 1), the most common type of apartment (2 bedroom apartment) has been selected for this study. The gross and net floor area of the apartment is 101.5 m^2 and 85.2 m^2 respectively with each floor height of 2.55 m. The apartment has a very heavy thermal mass according to the EN ISO 13790 [18] and n50 value of 1.89. The default apartment is north-south oriented and has been divided into 7 thermal zones (TZs) (see Figure 2 and Table 1). Table 2. shows building envelope properties. The apartment has double glazed windows (u-value: 1.00 W/m^2K, g-value: 0.56) with window-to-wall ratio (WWR) of 18% on the South, 25% on East and 15% on west facade. The window-to-floor ratio is 14%. The windows on South and West are equipped with external solar shading (g_{tot} = 0.04), which activates when the radiation on the window is above 250 W/m^2. The apartment is designed for 3 occupants with internal gains (people and equipment) calculated according to EN 16798-1[19]. The building is equipped with balanced mechanical ventilation system with heat recovery, with a total supply airflow of 200 m^3/h. The ventilation air flow rates are calculated according to the NBN D50-001[20] (see Table 1).

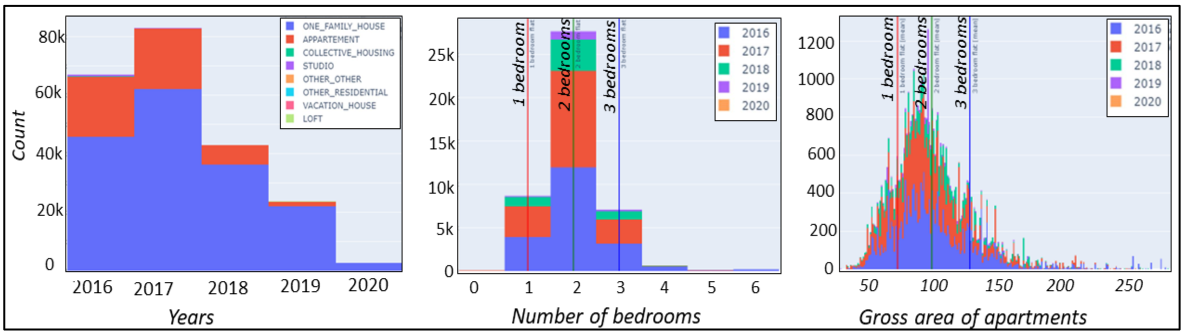

Figure 1. VEKA[16] data from 2016 to 2020 (new buildings) showing the typology of buildings, number of bedrooms and gross area of each apartment

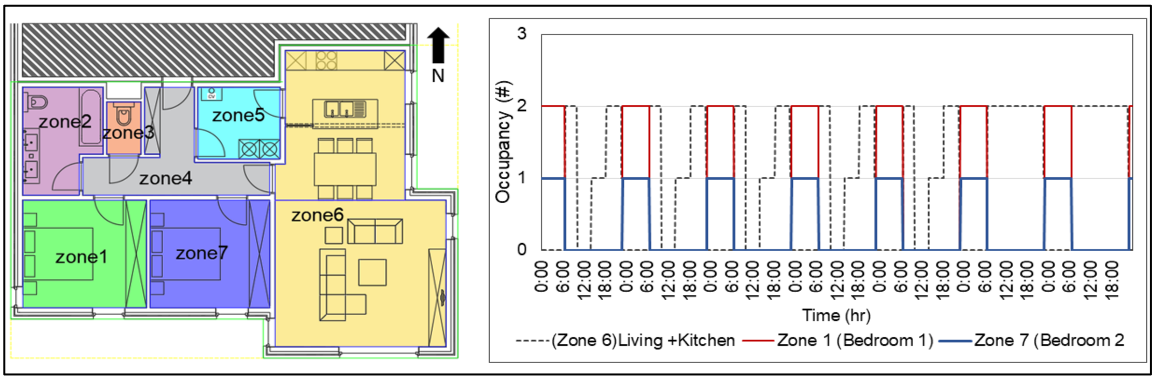

Figure 2. Floor plan with thermal zones (left) and occupancy pattern in different thermal zones (1 week)

Table 1. Thermal zones

Thermal zone	Area (m^2)	Ventilation flow rates (m^3/h)
TZ 1 (Bedroom 1)	11.9	Supply =50, Extract =0
TZ 2 (Washroom)	2.5	Supply =0, Extract =50
TZ 3 (WC)	5.5	Supply =0, Extract =25
TZ 4 (Corridor)	9.0	Supply =0, Extract =0
TZ 5 (Utility room)	5.3	Supply =0, Extract =50
TZ 6 (Living+ kitchen)	38.9	Supply =100, Extract =75
TZ 7 (Bedroom 2)	11.6	Supply =50, Extract =0

Table 2. Construction packages and u-values

Construction package	Description	u-value (W/m^2K)
External Wall	Brick with air layer and 8 cm PUR	0.24
Common wall	Concrete reinforced with 3 cm rockwool	0.60
Internal wall	Gypsum board and brick	2.10
Separating floors	Concrete with screed and 6 cm rockwool	0.50

3 METHODOLOGY

To access the impact of design parameters on the thermal resilience to overheating in a typical Belgian apartment, different building parameters such as thermal mass, WWR implementation of solar shading and passive cooling strategy were altered.

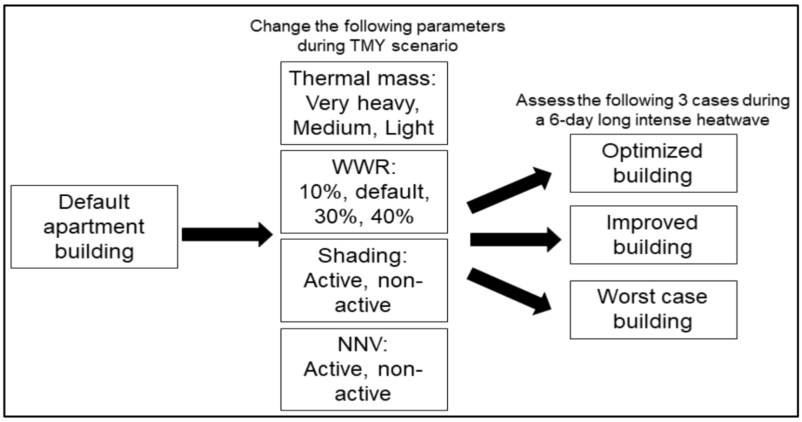

Figure 3. Altering the design parameters and testing the optimized, improved and worst-case scenario during the HW period

3.1 Design parameters

Thermal mass

Apart from the default (very-heavy) construction set, a medium and light thermal mass construction set was evaluated. For the default construction set (very heavy) to medium thermal mass, floor construction was altered and for light thermal mass, the external wall was altered. Table 3 gives an overview of the altered construction sets.

Table 3. Design alternatives for thermal mass

		Construction sets	d [m]	ρ $[Kg/m^3]$	C (J/KgK)	λ [W/(m.K)]	R $[(m^2.K)/W]$	U $[W/(m^2.K)]$
Default (very heavy)	Floor (i-e)	Tiles	0,03	1700	1000	1,10	0,03	0,34
		Screed	0,06	2000	1000	0,40	0,15	
		Polyurethane (PUR)	0,06	30	1400	0,02	2,73	
		Heavy reinforced concrete	0,14	2240	900	1,75	0,08	
	External wall (i-e)	Gypsum	0,01	1120	840	0,52	0,02	0,24
		Light brick	0,14	850	880	0,80	0,18	
		Polyurethane (PUR)	0,08	30	1400	0,02	3,64	
		Non ventilated air layer 25 =< d < 50					0,18	
		Light brick	0,14	850	880	0,80	0,18	
Medium thermal mass	Floor (i-e)	Wooden boarded floor	0,02	600	1880	0,15	0,13	0,34
		Pressure-resistant wood fibre cement board	0,04	1000	1470	0,23	0,17	
		OSB 18 mm	0,02	600	1700	0,13	0,14	
		Glass wool + wooden slats	0,15	139	1138	0,06	2,38	
		Promatect plate 2x	0,03	900	1000	0,18	0,14	
Light thermal mass	External wall (i-e)	Light brick	0,14	880	850	0,80	0,18	0,24
		Non ventilated air layer 25 =< d < 50					0,18	
		Mineral wool (MW) - plates or blankets	0,04	10	1030	0,04	1,05	
		Hempcrete	0,19	340	1700	0,07	2,76	
		Gypsum	0,01	1120	840	0,52	0,02	

Window to wall ratio (WWR)

A range of WWR between 10%-40% was tested. Table 4 gives an overview of the window areas varied to set WWR between 10%-40%.

Table 4. Design alteration to set WWR between 10%-40%

	Area (m^2) when WWR=10%	**Area (m^2) when WWR=30%**	**Area (m^2) when WWR=40%**
Zone 6 (Living+ Kitchen)	9,1	20,3	27,1
Zone 1 (Bedroom 1)	1,1	6,9	9,2
Zone 7 (Bedroom 2)	1,1	2,1	2,8

Shading

The building was assessed with and without solar shading to evaluate the impact of solar shading on the thermal resilience to overheating.

Natural Night ventilation

Natural night ventilation (NNV) is implemented as passive means to cool the building. TZ1, TZ 6 and TZ 7 are provided with operable windows which are automatically controlled. The effective area of these windows is calculated based on the method proposed in [21] taken into account the window area, height and opening angle. The total effective area of all windows is 2.7% of the gross floor area. Once open, the window will remain open for at least 15 min. The windows are open between 10 pm to 6 am from in summer period (April-September) if the following conditions are met:

- Room temperature exceeds both the heating set point (=22°C) and the external temperature +2°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

3.2 Weather Data

Two types of weather data sets for Ghent, Belgium were used- (a) Typical meteorological year (TMY) 2010s to benchmark and (b) mid-term 2050s HW to assess the resilience of the building during shock. These weather data files were formulated adapting the method of Weather data task force of IEA Annex 80 and Ouzeau et al. [22]. The 6 day HW occurs between June 29th and July 4th with mean temperature of 28.6°C and peak outdoor temperature of 41.6°C[12].

3.3. Thermal resilience evaluation

To assess the impact of design parameters, the following indicators were used:

Adaptive thermal comfort

For buildings without cooling systems (default case): adaptive model with adaptive temperature limits (ATL), Category II is applied. The allowed indoor operative temperature is calculated as a function of the running mean outdoor temperature based on the ISO 17772-1 Annex H.2 [23].

Standard effective temperature

During the HWs, the occupants face health risks or even life-threatening consequences. Therefore, the threshold for the indoor environment should be selected by considering the impact on occupants' health. In this study, Standard effective temperature (SET) is adapted (ASHRAE 55-2017 [23] recommended to evaluate human response to heat stress). To calculate the SET, a clo of 0.5, airspeed of 0.1m/s and metabolic rate of 1 in bedrooms and 1.4 in living-dining-kitchen was assumed[24].

Unmet degree hours

Unmet degree. hours (K.h) was used as the resilience key performance indicator [25]. For this study, a fixed temperature limit (FTL) of 24°C for bedrooms and, 25°C, 26°C and 28°C for the living-dining-kitchen was chosen as the overheating threshold for European buildings (CIBSE TM52 standard [26]). The acceptable threshold according to the same standard is equal to 6 K.h./day. A SET threshold of 28 °C for the building under a HW was used calculate the unmet hours.

Percentage of occupied hours above threshold

To compare the impact of different design parameters, Method A as described in Annex F of the EN 16798 [27] was selected. Following this method, the percentage of occupied hours when the zone operative temperature is above FTL and ATL was evaluated. A percentage of occupied hours below 5% is considered as acceptable and below 3% is considered good.

3.4. Building Energy Simulations (BES) and scenarios

For the evaluation of impact of different design parameters, annual hourly BES were performed using Open Studio[28] and EnergyPlus [29]. In the BES model, the separating floors and common walls were assumed to be adiabatic. Results were evaluated for summer period (April-September).The simulation is started two weeks prior and was run for four weeks after the studied period. Table 5 shows the simulation scenarios during the TMY period. Furthermore, 3 cases –(a) worst, (b) improved and (c) optimized designs from both no cooling and cooling strategy implemented will be analysed during a 6 day HW period.

Table 5. Simulation scenarios during TMY period

Scenario No	Thermal mass	WWR	Shading	cooling strategy	Scenario No	Thermal mass	WWR	Shading	cooling strategy
A1	Heavy	10%	NO	None	A19	Heavy	10%	NO	NNV
A2	Medium	10%	NO		A20	Medium	10%	NO	
A3	Light	10%	NO		A21	Light	10%	NO	
A4	Heavy	30%	NO		A22	Heavy	30%	NO	
A5	Medium	30%	NO		A23	Medium	30%	NO	
A6	Light	30%	NO		A24	Light	30%	NO	
A7	Heavy	40%	NO		A25	Heavy	40%	NO	
A8	Medium	40%	NO		A26	Medium	40%	NO	
A9	Light	40%	NO		A27	Light	40%	NO	
A10	Heavy	10%	Yes		A28	Heavy	10%	Yes	
A11	Medium	10%	Yes		A29	Medium	10%	Yes	
A12	Light	10%	Yes		A30	Light	10%	Yes	
A13	Heavy	30%	Yes		A31	Heavy	30%	Yes	
A14	Medium	30%	Yes		A32	Medium	30%	Yes	
A15	Light	30%	Yes		A33	Light	30%	Yes	
A16	Heavy	40%	Yes		A34	Heavy	40%	Yes	
A17	Medium	40%	Yes		A35	Medium	40%	Yes	
A18	Light	40%	Yes		A36	Light	40%	Yes	

4 RESULTS AND DISCUSSION

4.1 Base case scenario (No solar shading, no cooling strategy)

In base case scenario (with default design), TZ6 is the most critical zone due to high solar and internal gains (occupancy and equipment). With fixed temperature limit (FTL) of 24°C and 25°C, unmet degree hours are above daily limit of 6 (K.h). With FTL of 26°C and 28 °C, unmet degree hours in TZ 6 is within daily limit of 6 (K.h). In both the bedrooms (TZ 1 and TZ7), with FTL and ATL, daily unmet degree hours were below daily threshold.

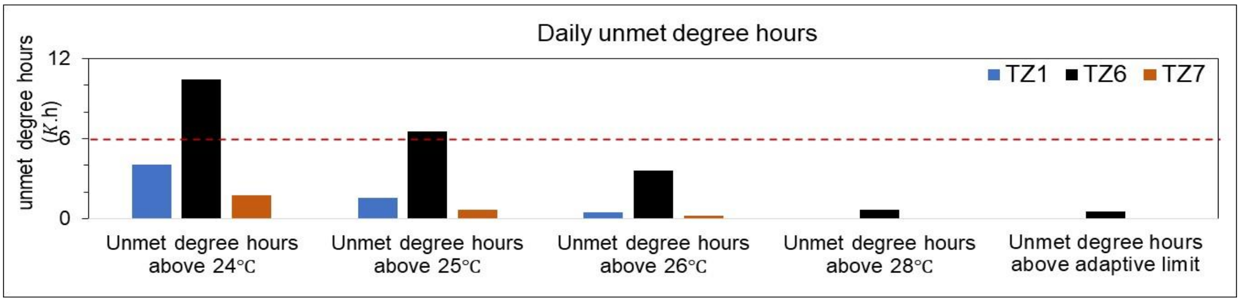

Figure 4. Unmet degree hours with fixed (24°C, 25 °C, 26°C and 28°C) and ATL in the base case model (default design)

Between June and August, more than 5% occupied hours were higher than FTL and ATL in TZ6. In TZ1 and TZ7, there were no occupied hours above FTL of 28°C and ATL during the entire summer period (April to September). With 26°C threshold, for TZ1, June and July was overheating period and for TZ7 only July was overheating period. Between June and August, more than 5% occupied hours were above FTL of 24°C and 25°C for TZ1 and TZ7. For further assessments, only the most critical zone (TZ 6) will be discussed.

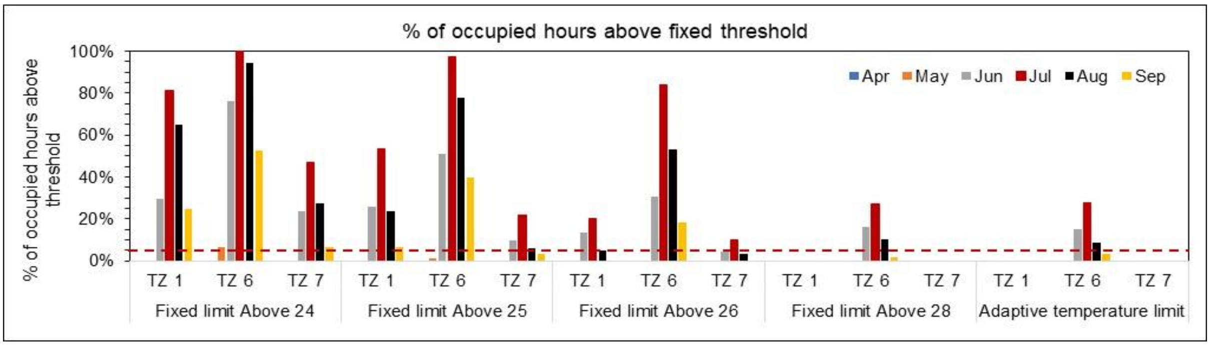

Figure 5. Percentage of occupied hours above fixed (24°C, 25 °C, 26°C and 28°C) and ATL in the base case model (default design)

4.2 Impact of design parameters and solar shading

Figure 6 shows the % of occupied hours above ATL for the whole summer period (April-September) for the altered design parameters (see Table 5).

Keeping 10% WWR, thermal mass is altered from very heavy to medium to light, (case 01-03). When thermal mass is altered from very heavy to medium, and from very heavy to light, there is a 3.1% and 8.2% increase in % of occupied hours above ATL. For all 3 thermal zones, % of occupied hours above adaptive threshold increases with increase in WWR. For TZ6 with default (very heavy) thermal mass, if WWR is increased from 10% to 30%, there is 66.5% increase in the % of occupied hours above ATL. Additional 10% increase i.e., 40% WWR, increases % of occupied hours above ATL by 83.1% compared to 10% WWR. However, it is interesting to notice that with 40% WWR, the % of occupied hours decreases as the thermal mass is altered from very heavy to medium (-0.8%) and further when thermal mass is light (-2.5%). The increased solar gains due to increase in WWR is flushed out faster by a lighter thermal mass compared to heavier thermal mass.

With implementation of solar shading, there is significant (9-70%) decrease in the percentage of occupied hours above ATL. With solar shading, in the default design case, % of occupied hours above ATL decreases from 9.2% to 0.07%, i.e., it is within 5% acceptable limit. The default apartment (no shading, 10% WWR, very heavy thermal mass) has 2.5% lower percentage of occupied hours above ATL than a building with solar shading with light thermal mass and 30% WWR. It can be concluded that to improve the thermal resilience to overheating, along with implementing solar shading to reduce solar gains, it is crucial to find optimal balance between thermal mass and WWR of the building.

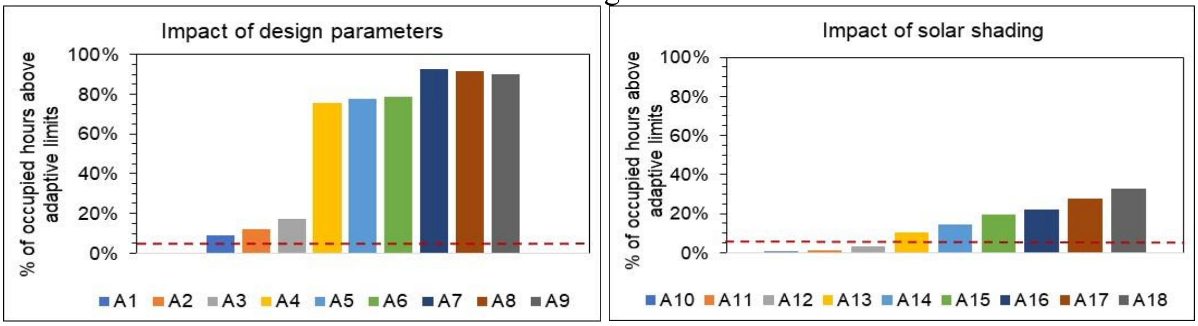

Figure 6. Impact of different design parameters and solar shading on the thermal resilience to overheating

4.3 Implementation of NNV and NNV+ solar shading

Even with NNV implemented, the % of occupied hours (with FTL 25℃ and 26 ℃) is above 5% accepted limit. With 28℃ FTL, only with 10% WWR, the % of occupied hours above threshold is below 5% acceptable limit. With implementation of NNV, the % of occupied hours above FTL (25℃) decreased significantly (average 45%) except when WWR is increased to 30% and 40% without the solar shading (increased in occupied hours above threshold by 50% compared to base case). With solar shading, even if the WWR is increased to 30% and 40%, there is an average decrease of 35% in occupied hours above threshold limit. With NNV+ solar shading implemented, with 26℃ FTL, the 5% limit is violated if WWR is above 30% and the thermal mass is medium. Thus, with increased 30% WWR, NNV with solar shading can reduce overheating risk. Case A28 (very heavy thermal mass + 10% WWR + NNV+ solar shading) shows the best result with 80% reduction in the percentage of occupied hours above FTL 25℃.

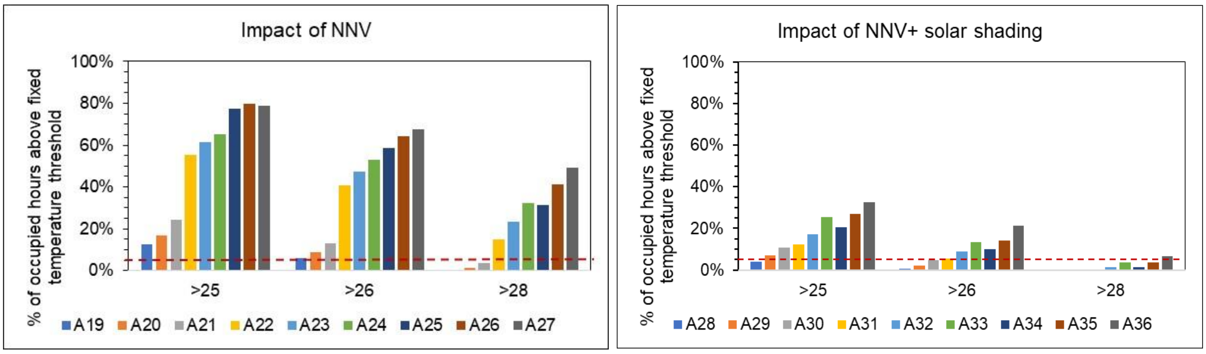

Figure 7. Impact of different NNV and NNV+ solar shading on the thermal resilience to overheating

4.4 Impact of heat wave

Table 6 shows the worst, improved and the optimized cases selected to evaluate the impact of HWs on the design parameters.

Table 6. Worst, improved and optimized design cases

	Scenario No	Case	Thermal Mass	WWR	Shading	Cooling
Worst	E1	A9	Light	40	No	No cooling
Improved	E2	A14	Medium	30	Yes	
Optimized	E3	A10	Heavy	10	Yes	
Worst	E4	A27	Light	40	No	NNV
Improved	E5	A32	Medium	30	Yes	
Optimized	E6	A28	Heavy	10	Yes	

To evaluate the impact of design parameters during HWs, % of occupied hours above 28℃ SET is assessed. With the worst design case (Light thermal mass+WWR40%+No shading+ No NNV), 97% of occupied hours are above 28℃ SET limit. The thermal resilience of the building is poor and the occupants are under heat stress. The optimized design case (Heavy thermal mass+WR10%+ solar shading+NNV), the % of occupied hours above 28°C SET is within 5% threshold even during HW. The result also demonstrates that implementing a passive cooling strategy such as NNV will not improve the thermal resilience unless it is coupled with the building design parameter. For example, case E3 has 45% less occupied hours without NNV than case E4 with NNV. This is due to higher solar gains (no shading and higher WWR) and also due to lighter thermal mass when absorbs the heat faster during a HW.

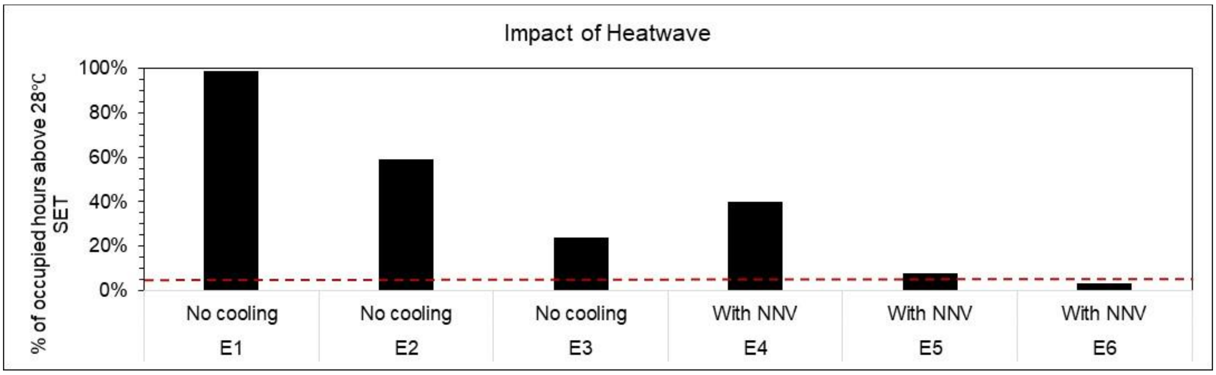

Figure 8. Impact of design parameters, solar shading and NNV on the thermal resilience to overheating during a 6 -day HW

5 CONCLUSIONS AND FUTURE OUTLOOK

The aim of this paper is to evaluate the impact of design parameters on the thermal resilience to overheating. The study demonstrates:

a) Overheating is most likely to occur in current buildings with high WWR, no solar shading and with lighter thermal mass. WWR has highest impact on the thermal resilience followed by thermal mass. However, in buildings with higher WWR and lighter thermal mass, thermal resilience can be improved with implementation of solar shading and passive cooling strategies such as NNV.

b) NNV and solar shading can improve the thermal resilience and heat stress during a short and intense HW. However, the thermal mass should be between medium and heavy and WWR should be between 10-30%. Buildings without NNV, but with heavy thermal mass and low WWR during HW performs better than buildings with light thermal mass and high WWR. NNV is not effective during a HW period as the diurnal variations of temperature are limited during HW period. To improve the buildings' thermal resilience to overheating, implementation of solar shading and WWR has the highest impact.

c) Apart from the design parameters that were evaluated in this study, there is a need to evaluate other building design parameters such as orientation of the building, level of insulation, air-tightness, type of glazing, type of solar shading etc. There is also a need to evaluate other passive and active cooling strategies coupled with different building parameters.Future work will include a sensitivity analysis to evaluate the most influential building and system design parameters that impact the thermal resilience to overheating.

6 ACKNOWLEDGEMENT

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