A novel indicator to assess thermal resilience of buildings to overheating

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ABSTRACT

The increasing frequency and intensity of heatwaves highlight the necessity for resilient building design to reduce heat-stress-related discomfort and mortality among occupants. "Thermal resilience" refers to a building's capacity to endure thermal disruptions, maintain habitable conditions, and return to its intended state. This study aims to develop a thermal resilience indicator to make resilience an actionable concept for architects and HVAC engineers to assess and improve thermal resilience of buildings to overheating. To do this, different building types such as mid-sized offices, schools and apartments were evaluated during 3 different type of heatwaves (severe, intense and long) conducting building energy simulations. Building and system design parameters such as building orientation, envelope and glazing properties, occupancy pattern, airtightness, operation of solar shading and natural night ventilation, cooling capacity and cooling set-points were varied within standard design ranges. This study utilised global sensitivity analysis to identify the most influential design parameters affecting shock impact on heat stress of occupants i.e. degree hours above Standard Effective Temperature (SET-Dh) of 28°C. Sensitivity analysis revealed that for all three increasing shocks, and two cooling systems (convective and radiant), parameters such as window-to-wall ratio (WWR), cooling capacity, and the operation of passive strategies like natural night ventilation (NNV) and solar shading had twice the influence compared to building orientation, envelope and glazing properties, occupancy pattern, airtightness, and cooling set-point. Based on the results of the sensitivity analysis, regression models/thermal resilience indicators were developed to predict SET-Dh for each type of buildings- office, apartments and classrooms during 3 increasing shocks. The indicator is based on the most influential design parameters and the impact of overheating on the occupants health during increasing degree of shock (in this case, different types of heatwaves). The performance of the developed indicators are tested on two case study building type-(a) office and (b) residential buildings during 2 heatwaves. This research aims to guide architects, engineers, and policymakers in assessing and enhancing buildings' ability to withstand and recover from overheating risk.

KEYWORDS

Heatwaves, Thermal resilience to overheating, Resilient design, Standard Effective Temperature, Thermal resilience indicator

1. INTRODUCTION

Overheating in buildings during heatwaves elevates core-body temperatures, disrupting essential bodily functions and causing heat-related illnesses like sleep deprivation, heat stroke, and even death [2]. Historical data shows increased mortality during heatwaves in Europe [3]. By 2050, such heatwaves are expected to become more frequent, potentially increasing heat-related mortality by 257% [4]. This underscores the urgent need to enhance buildings' thermal resilience. The IEA EBC Annex 80 defines thermal resilience as a building's ability to withstand disruptive thermal events, maintain habitable conditions, and recover to its designed state [5]. Studies have both qualitatively and quantitatively evaluated building thermal resilience [6] [7]. Research has also focused on developing resilience assessment frameworks, such as, Zhang et al. [8] outlined criteria such as absorptive, adaptive, and restorative capacities, while Ji et al. [9] created a Thermal Resilience Index linking performance with occupants' predicted heat strain. Despite these advancements, existing methods often fail to compare resilience across varying shocks and overlook the influence of building parameters.

To address this, Sengupta et al. [10] introduced the degree of shock (*doS*) metric to compare varying thermal shocks and test buildings and systems' thermal resilience performance and identify the most influential design parameters affecting thermal resilience. This study focuses on developing a thermal resilience indicator to assess and improve thermal resilience to overheating in buildings.

2. METHODOLOGY

The methodology for this study involves a structured, eight-step process (see **Figure 1**) to develop and test the novel thermal resilience indicator. Initially, shocks such as heatwaves are defined in step 1 to establish the context for resilience assessment. Key Performance Indicators (KPIs) are then determined in step 2, focusing on critical aspects and thresholds of thermal resilience. Subsequently, reference buildings, including apartments, offices, and schools, are selected, and detailed Modelica models are developed for these structures in step 3. Uncertainty and sensitivity methods are defined in step 4, encompassing parameter selection, sampling techniques, and sample size determination. Simulations are conducted in step 5 to assess the thermal resilience performance of the models under various design variations. An uncertainty analysis is performed in step 6 to understand the impact of design choices on resilience, followed by a sensitivity analysis in step 7 to identify the most influential design parameters. Finally, regression models are developed in step 8 to predict thermal resilience performance, resulting in the creation of a thermal resilience to overheating indicator for different building types and heatwave scenarios. Furthermore, the developed thermal resilience indicator is evaluated based on the simulation studies conducted by the project partners of the project 'ReCOver++: Improving resilience of buildings to overheating' [11] in their case study buildings- mainly offices and residential buildings. The research process involves first defining the shocks relevant to thermal resilience assessment, followed by establishing key performance indicators (KPI) for heat stress, including assessment aspects and thresholds. Next, case study building models (such as apartments, offices, and schools) are selected and developed, with Modelica. The research then defines the methods for uncertainty and sensitivity analysis, determining the appropriate techniques, parameters, and sampling methods. Simulations are run to assess thermal resilience performance across different design variations. Following this, an uncertainty analysis is conducted to evaluate how design choices impact thermal resilience, and a sensitivity analysis identifies the most influential parameters. Finally, regression models are developed to predict thermal resilience based on these parameters, and these models are tested on other case study buildings to refine and validate the thermal resilience indicator.

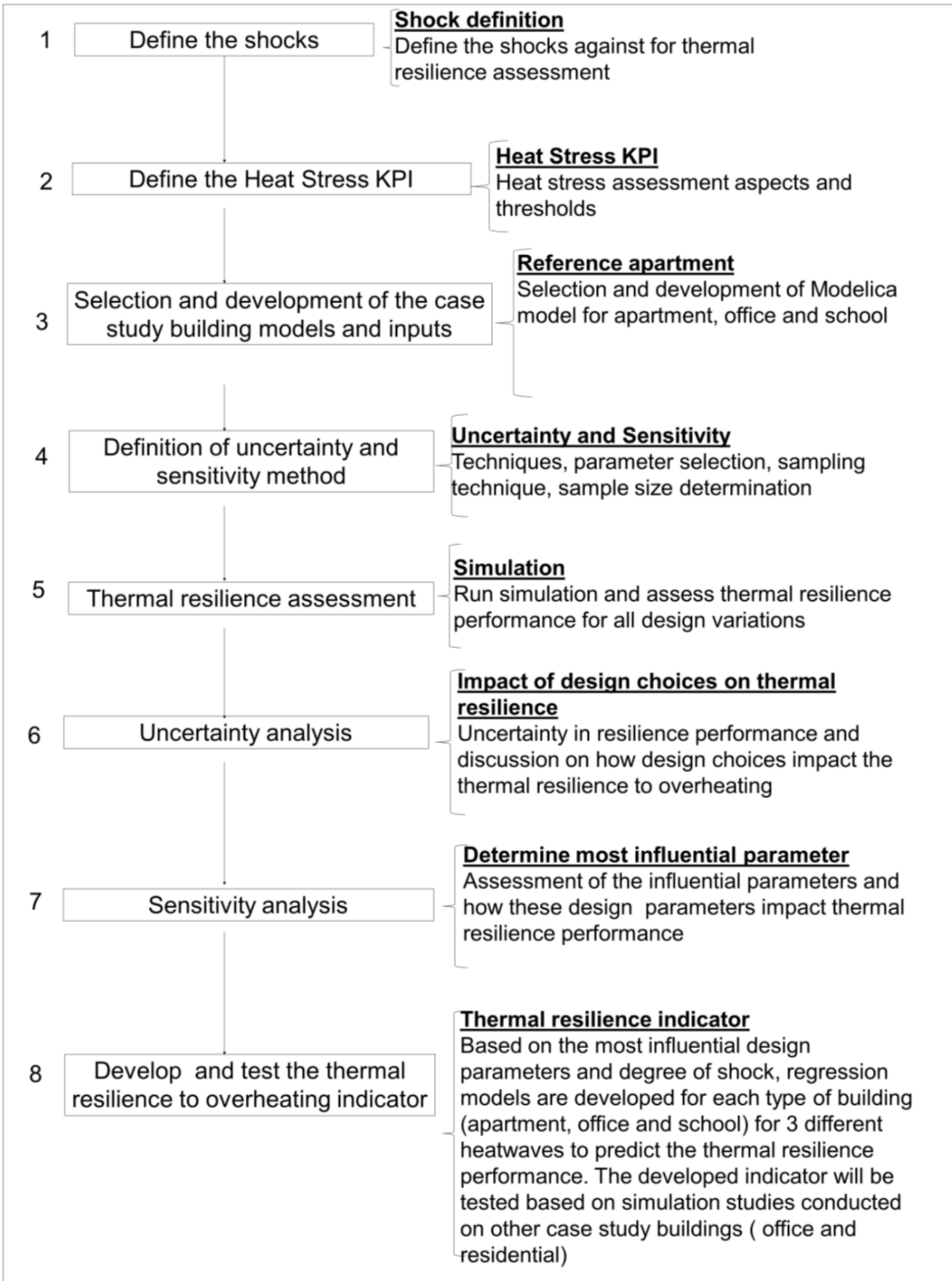


Figure 1. Methodology to develop the thermal resilience indicator

2.1. Shock definition

A shock is defined as a sudden disturbance that causes the building to deviate partially or completely from its designed conditions for a certain period. This disruption tests the resilience performance of buildings. Shocks are characterized by both severity and duration which triggers different thermal response from the building. To evaluate and compare the impact of different shocks and determine most influential design parameter affecting building's thermal resilience it is essential to define, classify, and quantify these disturbances. In a prior study, Sengupta et al. [10] classified and quantified normalized degree of shock (*doS*) to compare different shock types. The study demonstrated that heatwaves notably affect buildings more than system shocks, emerging as the most severe shocks due to their effects on temperature and passive cooling strategies. Highlighting the growing frequency and severity of heatwaves in current and future climate scenario, this study focused on different heatwaves. Normalized *doS* for heatwaves is expressed as:

$$doS = \underbrace{\frac{T_{shock} - T_{ref}}{T_{ref}}}_{Severity} \times \underbrace{\frac{t_{shock}}{t_{ref}}}_{Duration} \qquad (1)$$

For this study, three heatwaves with increasing *doS* (low, medium and high) were selected from six different extreme heatwaves predicted for Ghent for a period between 2001-2100 (see **Table.1** and **Fig.2**). The extreme weather datasets were developed using the methodology developed by the IEA EBC Annex 80 [12].

Table 1. *doS* of the 6 extreme (severe, intense and longest) heatwaves for Ghent (Belgium) between 2001-2100

Heatwave period and ID	T_{shock} (average temperature during heatwave)	T_{ref} (average outdoor temperature during corresponding TMY period)	t_{shock} (Duration of heatwave in days)	t_{ref} (duration of the longest heatwave in days	*doS*
Contemporary 1A	26.8	15	10	45	0.167
Contemporary 1B	25	18.6	27	45	0.205
Mid-term **2A (doS $_{low}$)***	24.9	17.1	6	45	**0.060**
Mid-term **2B (doS $_{medium}$)***	26.3	17.5	16	45	**0.179**
Long-term 3A	25.3	17.9	34	45	0.311
Long-term **3B (doS $_{high}$)***	25.7	18.8	45	45	**0.368**

**Selected doS for this study*

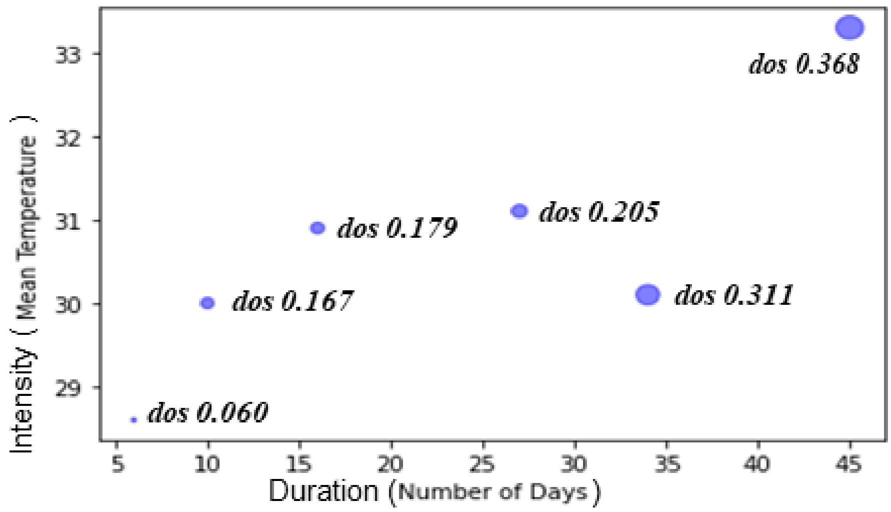


Figure 2. *doS* (diameter of each circle) with duration in days (x -axis) and the mean temperature during HWs (y-axis left)

2.2. Heat stress Index

To evaluate shock impact, it is crucial to select a rational heat-stress index that considers multiple indoor environmental parameters (temperature, RH, air velocity, etc.) and occupants' physiological responses (sweat rate, core temperature, heart rate, etc.). The Standard Effective Temperature (SET), based on the two-node physiological model by Gagge et al. [13] and recommended by ASHRAE Standard 55 [14], is a widely accepted metric. Hourly SET was calculated based on [15]. Previous studies have linked SET to human-predicted thermal sensation according to the ASHRAE 7-point scale [16], establishing three SET thresholds: SET-$_{comfortable}$ (24.1°C), SET-$_{alert}$ (28.1°C), and SET-$_{emergency}$ (32.1°C)[9]. These thresholds define habitable, heat alert, and emergency levels, impacting occupants' health based on exposure time. Set-Dh [17] was adopted to assess shock impact. SET-Dh was defined as :

$$SET - Dh = \sum_{t=1}^{N} (SET(t) - 28) * \Delta t \qquad (2)$$

Where, SET-Dh represents the total degree-hours above 28°C, $SET(t)$is the Standard Effective Temperature at time t, 28 the SET-$_{alert}$ threshold and Δt is the duration of each time interval (typically one hour). Dynamic metabolism (met) and clothing resistance (clo) for day and night were utilized in the calculations. Overheating is declared when SET-Dh exceeds 230 ± 42 °C*h for young healthy adults and 117 ± 30 °C*h for older adults [18]. Higher shock impact indicates lower thermal resilience to overheating. The buildings and system have higher thermal resilience if SET 28℃ threshold is not violated.

2.3. Case study buildings

2.3.1. Reference apartment-case study for the development of thermal resilience indicator

Unique floor plans for a reference apartment in Belgium were developed, while maintaining some degree of freedom (floor area, number of bedrooms, open/closed kitchen, number of surfaces exposed to external conditions, level of apartment-ground, middle or upper floor), in order to perform parametric study. The floor plans are based on information of Flemish Energy and Climate Agency (VEKA) [19] data from 2016 to 2020 (new buildings).

Figure 3 illustrates the plan of the selected reference apartment showing the four thermal zones (TZs). The default apartment has a brick wall with external insulation resulting in a U-value of 0.24 W/m^{2}K and has heavy thermal mass according to the EN ISO 13790 [20]. The separating floors and common walls connecting the apartment to common space were modelled as adiabatic. Since the apartment is situated between upper and lower floors, the floors and ceilings arre considered airtight. The sensible and latent heat generation from occupants are 75 W and 45 W respectively during sedentary activities [21]. For lighting, 300 lux of illuminance in each bedroom, 400 lux in kitchen and living room, 70 lux in corridor and 500 lux in washroom and toilet [22]. The lights turned on when occupants are present and are considered off during night time (10.00 p.m. to 7.00 a.m.). More details of the reference apartment can be found in **Table 2**.

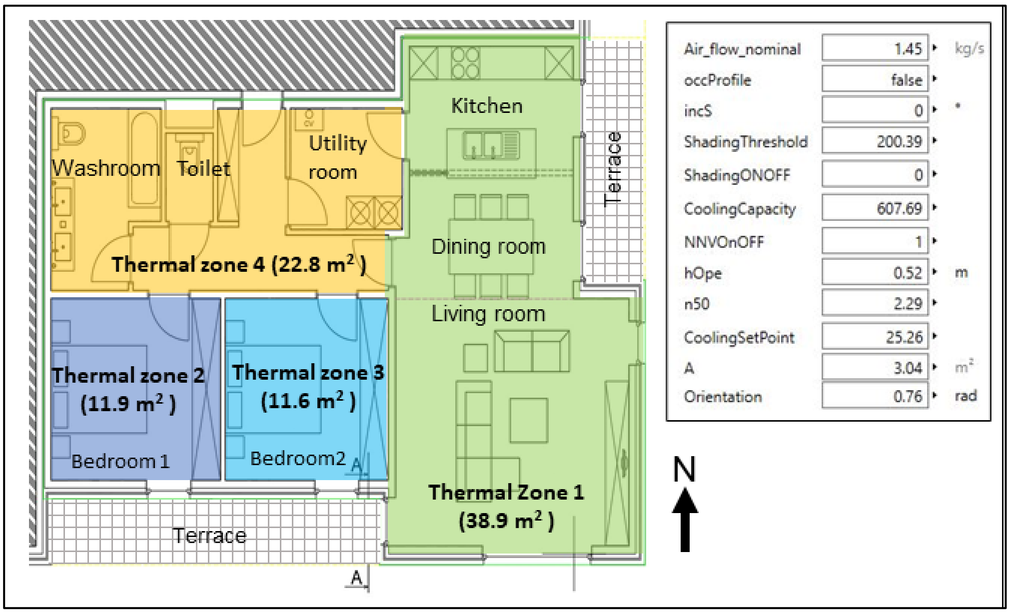


Figure 3. Plan of the reference apartment

Table 2. Characteristics of the reference apartment and ranges of the parameters tested

Parameters	Default value for the reference apartment	Ranges to be varied for the uncertainty and sensitivity analysis
Number of occupants Internal gains (people, and equipment) calculated according to EN 16798-1 [23].	3	-
Net floor are (m^2)	85.2	-
Floor Height (m)	2.55	-
Orientation of living room and bedroom	0° (South)	0°-360°
Airtightness n50 (h^{-1})	1.47	0.6-3
Thermal mass (according to EN ISO 13790 [20])	Heavy	Heavy-Medium-Light
External envelope U-value (W/m^2K) Brick wall with external insulation	0.24	0.1-0.3
U-value of the window (double glazed windows)	U-value = 1.00 W/m^2K g-value = 0.56	0.6-1.0
Window-to-wall ratio (WWR)	25%	25-75%
Solar shading operation	ON	ON-OFF

Solar shading threshold (W/m^2)	250	100-300
Cooling setpoint	25℃	24℃-26℃
Cooling capacity(W/m^2)	21	0-40
Natural Night Ventilation (NNV) Operation	ON	ON-OFF
Effective opening area of windows for NNV expressed as % of floor area	4%	1-8%

2.3.2. Case study buildings for testing thermal resilience indicator

To test the developed thermal resilience indicator 3 case study buildings are selected. **Table 3** shows the details of each of the demonstration case study details. The details of Office 01 (case study -Archipelago) and residential (Renson concept home) can be found in [1].

Table 3. Details of the case study office and residential building to test the developed Thermal Resilience Indicator

Building Type	Residential	Office 01	Office 02
Thermal zones	4	3	2
u-value of external wall (W/m^2K)	0.15	0.16	0.14
u-value of glazing (W/m^2K)	1	1.06	1
Occupant density (m2/per person)	28.5	10	10
Occupied hours	Always present at least 1 occupant	From 8h to 17h	From 8h to 17h
Ventilation rates (m3/h per person)	30 for bedrooms (it varies depending on the zone type)	42	40
Thermal mass	Medium	Medium	Medium
Building orientation	South-east	North-east	South-east
WWR (%)	49.1	41.3	33
Air tightness (n50)	3	0.5	1
Solar shading threshold (external blinds)	300	100	250
Effective window opening area for natural night ventilation (represented as % of floor area)	-	4.1	5.3
Cooling set-point (℃)	26	25	26
Cooling capacity (W/m^2)	30	29.3	38

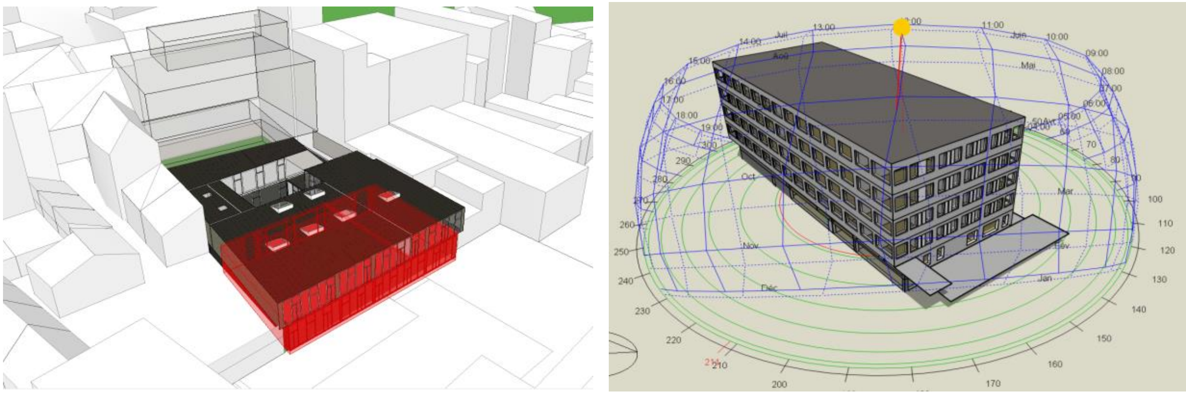
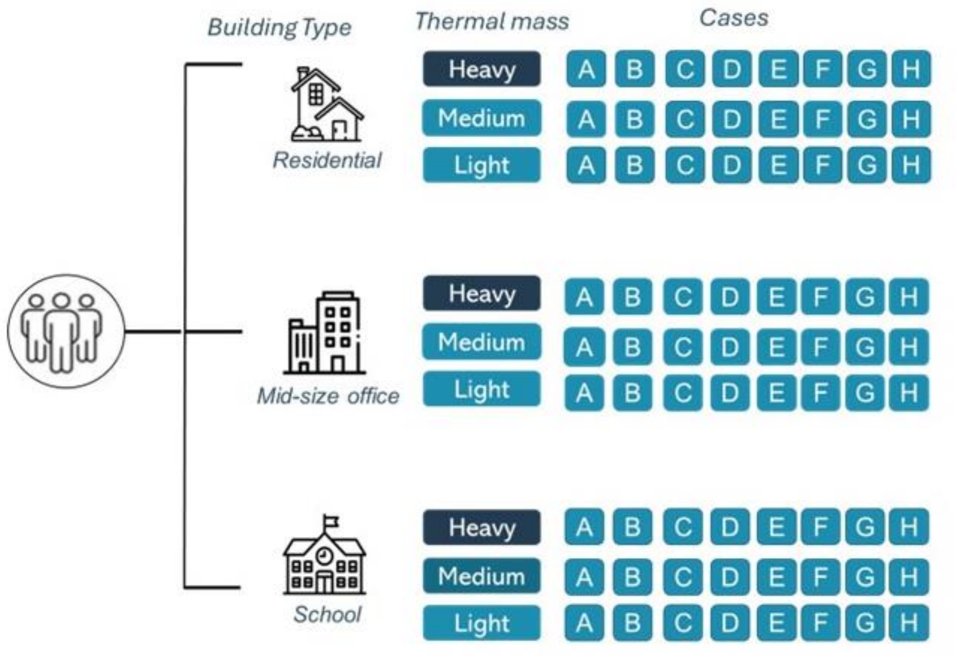


Figure 4. Demonstration case study office buildings (office 01-left, office 02-right)

2.4. Development of the thermal resilience indicator

Uncertainty and sensitivity analysis was conducted on 3 building types- (a) office (b) apartment and (c)classrooms during 3 increasing *doS*. Building and system design parameters were varied within the ranges as mentioned in table 2.



cooling technology	Shading	NNV	Cooling	Cases
No cooling strategies	0	0	0	Case A
Cooling	0	0	1	Case B
Natural Night Ventilation (NNV)	0	1	0	Case C
NNV + Cooling	0	1	1	Case D
Shading	1	0	0	Case E
Cooling +shading	1	0	1	Case F
Shading +NNV	1	1	0	Case G
Cooling + NNV+Shading	1	1	1	Case H

Figure 5. Decision tree for the development of thermal resilience indicators for different building types, thermal mass and operation of resilient cooling strategies

Uncertainty analysis demonstrated the uncertainty in thermal resilience performance of buildings due to varying design choices. Sensitivity analysis evaluated the most influential design parameters that impact thermal resilience performance. Based on the sensitivity analysis, linear regression models are developed for each type of buildings and each type of *doS*. The validity of the developed regression models are assessed on the simulation study of the case study buildings (in this paper, the focus is on the office 01). **Figure 5** shows the decision tree of the thermal resilience indicator developed for different building types, thermal mass and operation of systems.

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