Building Resilience to Heatwaves: Parametric Simulation Approach Aiding Passive Design Strategies for Thermal Comfort in Future Climate

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Abstract: Future weather predictions indicate more frequent and intense heatwaves, demanding that buildings ensure adequate comfort during those events. Current research focuses on climate adaptation and estimating thermal comfort with rising temperatures. This study investigates heatwave-resilient architecture, particularly where air conditioning is unavailable and cooling relies on passive strategies. Numerous simulations were conducted on a simplified building model using future-updated weather data and a parametric approach. This method enabled a detailed exploration of the effects of specific parameters (One-at-a-time Sensitivity Analysis) on thermal comfort during early design stages. The results suggest that buildings without mechanical air conditioning will struggle to maintain thermal comfort. The most influential parameters were window shading style, solar heat gain coefficient, and window-to-wall ratio. The main contribution of this study is developing a highly applicable model for a medium-sized residential building and a sensitivity analysis of thermal comfort during heatwaves, considering key geometric and physical parameters.

Keywords: heatwave resilience, thermal comfort, design in early stages, sensitivity analysis

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1 Introduction

Extreme weather events are expected to increase in frequency and intensity in the future [1]. Among those events are heatwaves, which are natural hazards that may potentially harm human health [2]. Buildings should serve as shelters, isolating their users from such harmful external conditions, and achieving this goal requires both adaptation and resilience.

Climate adaptation involves strategies to reduce risks and vulnerability, ensuring buildings maintain comfortable conditions despite the rising temperatures [3]. Resilience, similarly, refers to the building's ability of systems to withstand, adapt to, and recover from temporary disruptions like extreme weather events [4]. The key attributes of resilience include robustness, redundancy, resourcefulness, and rapidity, ensuring that systems can adapt, learn, and transform in the face of challenges [5]. This

implies that resilient buildings could potentially be unsustainable, as their resilience features might contradict the sustainability aspect of resource sufficiency.

The response of a building to a heatwave depends both on the character of the heatwave and the properties of the building. For instance, building materials can mitigate shorter heatwaves, whereas longer and more intense heatwaves would likely require air conditioning systems. This study evaluates building heatwave resilience and user thermal comfort during extreme heat events, focusing on sustainability and sufficiency by relying on passive design strategies instead of air conditioning. A parametric approach was used to generate numerous design variants and perform one-at-a-time (OAT) sensitivity analyses, assessing thermal comfort using a broadly applicable shoebox-like building model. The research questions addressed are: What insights can parametric simulations provide on building heatwave resilience? What parameters are the most critical for buildings without air conditioning?

1.1 Thermal comfort

Elevated temperatures impact the thermoregulation processes of the human body, making prolonged exposure especially dangerous [2]. Thermal comfort models can be used to assess whether a building can protect its users against such events. Thermal comfort assessment is a topic that has been largely studied and utilized in the building industry and research. Developed in the 1970s by Ole Fanger, the PMV (Predicted Mean Vote) model assesses thermal comfort on a scale from +3 (hot) to -3 (cold), and then calculates the PPD (Predicted Percent of Dissatisfied) [6]. While widely adopted, some researchers argue its accuracy is limited, particularly for naturally ventilated spaces, leading to the development of adaptive comfort models, whose also include the influence of user behavioural adaptation and other factors [7]. The DIN EN 15251 norm defines a comfortable interior temperature in relation to outdoor temperature, as 22 °C for outdoor temperatures below 16 °C, 26 °C for outdoor temperatures above 32 °C and linearly interpolated values for outdoor temperatures between 16 °C and 32 °C [8]. However, predicting thermal comfort in the event of a heatwave could require a different approach. Related research on this topic includes a predictive model for overheating, considering that the human body can somehow tolerate hot temperatures if they are followed by the lower ones [9], and metrics to estimate the building heatwave resilience to extreme temperatures [10]. However, no established methodology exists to evaluate building design decisions in the early design stage.

1.2 Parametric modelling and building performance simulation

Building simulation allows for accurate reality emulation using complex equations and virtual experiments to evaluate building performance. Thermal comfort simulation in the context of climate change and heatwave resilience has already attracted researchers' attention, leading to the use of estimated future weather data for simulations. Approaches to estimating the influence of climate change on the built environment include evaluating thermal comfort in multi-family houses in Spain [11], assessing overheating risks in multi-family houses in Sweden [12], and examining impacts on buildings with various functions across U.S. climate zones [13]. The analysis of resilient strategies to mitigate these effects includes studies on the influence of the selection of insulation material in single-family homes in Brazil [14] and Central Europe [15], classroom retrofitting methods in Malaysia [16], and the effects of green facades on reducing operative temperatures inside buildings [17]. Despite the significant

contributions of previous works, there is still a need for a general approach that considers basic geometry and highly applicable scenarios, which could be especially beneficial in the early stages of building design when limited information is available, but the potential for design changes is greatest.

2 Methodology

The methodology employed in this study involves generating a large number of variants of the building model and conducting a performance simulation for each of them. The models were created using the parametric modeling Grasshopper plug-in for Rhino 3D modeling software. Thermal comfort simulations were conducted with components from the Ladybug Tools' Honeybee and Honeybee-Energy sets, which through OpenStudio SDK, utilize EnergyPlus simulation engine, allowing for complex thermodynamic modeling. The iterative process and result aggregation utilized Colibri components from the TTToolbox. Custom Python scripts facilitated data visualization and analysis.

2.1 Parametric building model

The basic model for the experiment consisted of a residential building, whose footprint was 10x45 m with 3 floors, each 4 meters high. Each variant of the model, representing an early-stage building, was defined by a combination of selected geometric and physical parameters, including, among others, window properties of the U-Factor (non-solar thermal transmittance) and the solar heat gain coefficient (SHGC) - ratio of the transmitted solar radiation to the total radiation hitting the element. As detailed in Table 1, 1,440 distinct model variants were formed, to facilitate a OAT sensitivity analysis. The influence of green building elements (roofs, façade greening) was deliberately omitted. Despite its decisive influence on climate adaptation [18], this topic requires a different kind of experiment.

Table 1: Set of the selected and tested simulation parameters

#	Parameter name	No. val.	Values
P1	Construction Set	4	sand-lime brick, clay brick, wood massive, wood light
P2	Building Orientation	5	0°, 30°, 60°, 120°, 150°
P3	Window Shading Style	4	nothing, louvers, overhang, external roll
P4	Window U-Factor $[W/m^2K]$	2	0.6, 1.2
P5	Window SHGC	3	0.4, 0.6, 0.8
P6	Window-To-Wall-Ratio	3	0.2, 0.3, 0.4
	Total no. Variants	1,440	

2.2 Weather data and analysis period

Ladybug Tools uses the EnergyPlus EPW weather format, which typically contains Representative Meteorological Years for various locations. However, this study focuses on heatwaves and extreme temperature events, which require the analysis of extreme rather than typical temperatures. To achieve this, the EPW files were updated using Meteonorm, which incorporates satellite data and future climate models from the IPCC CMIP5 framework. The pessimistic RCP8.5 scenario for the year 2100 was selected, representing a predicted future with high greenhouse gas concentrations. This scenario was chosen to simulate an extremely hot year. In order to focus on a heatwave event, the period between

June and August was chosen as the analysis period. Including the preceding month of June in the simulation allowed for accounting for the energy stored in the building's thermal mass, enhancing the accuracy of the simulation results. Figure 1 presents hourly charts for the outdoor dry bulb temperature in the selected location (Bamberg, Bavaria) for the years 2020 and 2100.

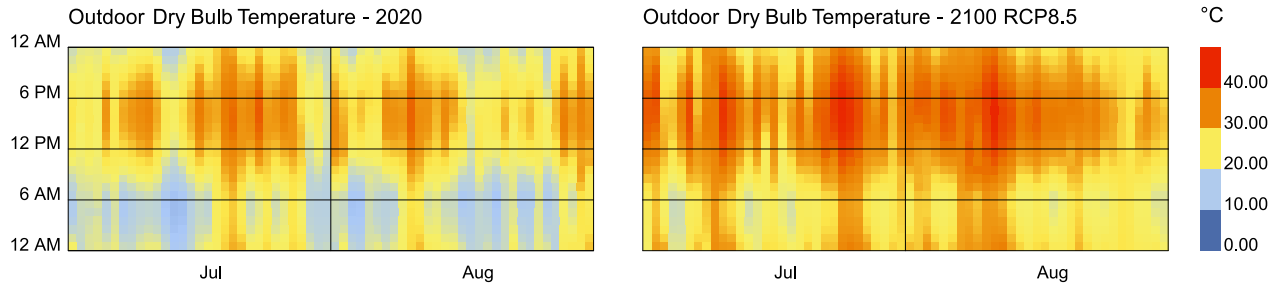

Figure 1: Temperature outside in 2020 and 2100 according to the RCP8.5 scenario

2.3 Thermal comfort indicators

Although there are many thermal comfort metrics, as described in Section 1.1, it was decided to compare the simulation's most general and universal information. These indicators allow for the calculation of other values, especially when considering additional details such as user characteristics. The sensor grid for the analysis was placed on the top floor, typically the most prone to overheating. The selected indicators are summarized in Table 2:

Table 2: Selected thermal comfort indicators

#	Indicator Name	Unit	Description
IC1	Number of Hot Hours	Hours	Total hours classified as "hot," determined by the HB-Energy component "Adaptive Comfort Map." This includes hours when at least 20% of building sensors exceed the defined comfortable temperature, based on the norm described in 2.1.
IC2	Average Temp. Difference Outdoor-Indoor	℃	Measures the building's ability to mitigate high outdoor temperatures.
IC3	Maximum Average Operative Temperature	℃	Operative Temperature, a measure of perceived temperature, considers factors such as air temperature, velocity, and mean radiant temperature, with guidelines set by DIN EN 15251 for various outdoor temperatures.

3 Results

The results from 1440 simulations on thermal comfort in naturally ventilated buildings during extreme heatwaves showed diverse results. However, none of the designs fully achieved heatwave resilience. Notably, the IC2 and IC3 indicators demonstrated an almost linear relationship (Figure 2), while IC1 and IC3 plots demonstrate first stable and then value growth, clustered by the highest IC1 values (Figure 3). Some designs facilitated effective nighttime cooling and heat storage within the thermal mass, maintaining indoor temperatures between 28 and 36 ℃ without exceeding 40 ℃. However, a significant proportion of models experienced indoor conditions hotter than comfortable for 90% of the time, with extreme cases exceeding 50 ℃, making it uninhabitable. Only eight (out of 1440) parameter

configurations provided comfortable temperatures for at least 10% of the time. The extreme values and the average indicator values are detailed in Table 3.

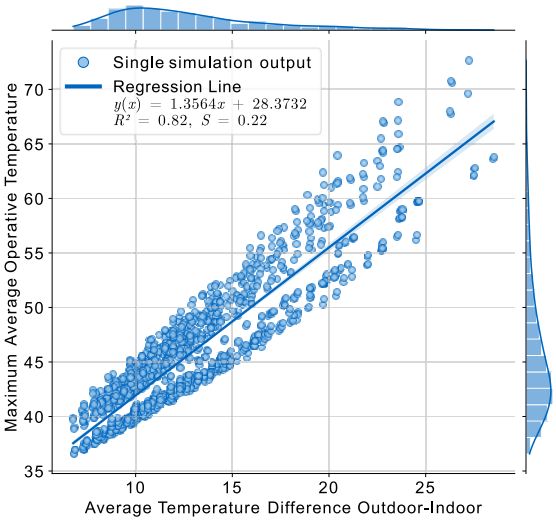

Figure 2: Comparison of Average Temperature Difference Outdoor-Indoor and Maximum Average Operative Temperature

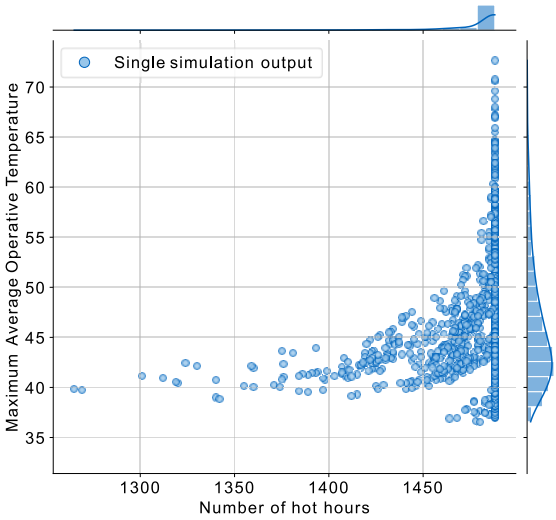

Figure 3: Comparison of Number of hot hours and Maximum Average Operative Temperature

3.1 Parameter sensitivity

The indicator values were averaged for all unique parameter values. The results for the IC3 indicator, presented in Figure 4, demonstrate that variants without shading devices performed the worst, with an average temperature of 50.29 °C. Louver shades (42.44 °C) and external roll screens (42.55 °C) were more effective than overhangs (47.97 °C). The window solar heat gain coefficient (SHGC) and the window-to-wall ratio significantly impacted the results, while the Construction Set had a lesser but still notable impact, with P1=[1] and [2] performing the best and [4] worst. The building rotation and the U factor of the window were the least significant. The sensitivity analysis (Figure 5) showed consistent relative importance of parameters across indicators, with Construction Set more influential for the Number of Hot Hours due to thermal mass and insulation effects. Ultimately, none of the variants is resilient in the given scenario, and mechanical conditioning will be essential to ensure adequate protection against heatwaves.

Table 3: Mean and extreme values for the thermal comfort indicators and corresponding parameters (P1-P6, see Table 1)

Indicator	Mean	Lowest	Parameters	Highest	Parameters
IC1: Number of hot hours [no. hours, max: 1488]	1477	1265	4, 60, 1, 1.2, 0.4, 0.2	1488	Many
IC2: Average Temperature Difference Outdoor-Indoor [°C]	12.86	6.77	4, 120, 1, 1.2, 0.4, 0.2	28.52	2, 0, 0, 0.6, 0.8, 0.4
IC3: Maximum Average Operative Temperature [°C]	45.81	36.57	1, 120, 1, 1.2, 0.4, 0.2	72.66	4, 0, 0, 0.6, 0.8, 0.4

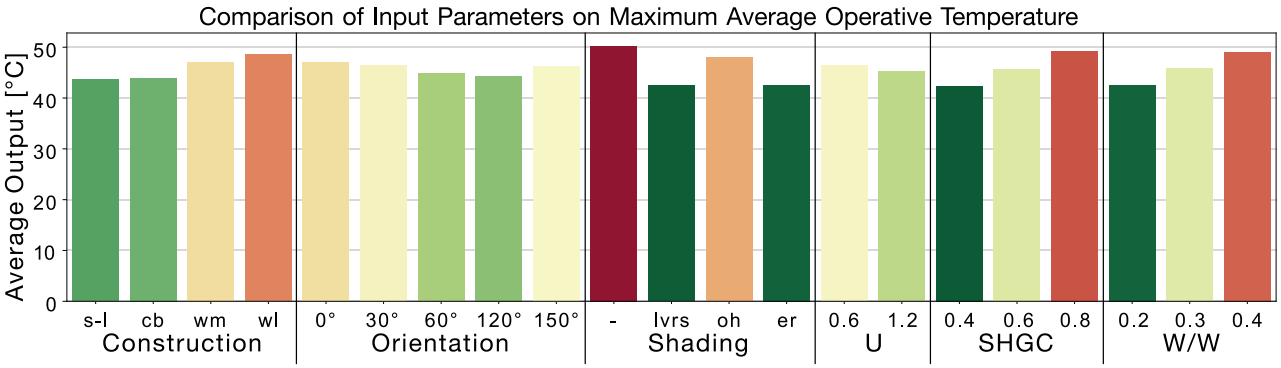

Figure 4: Average parameter values

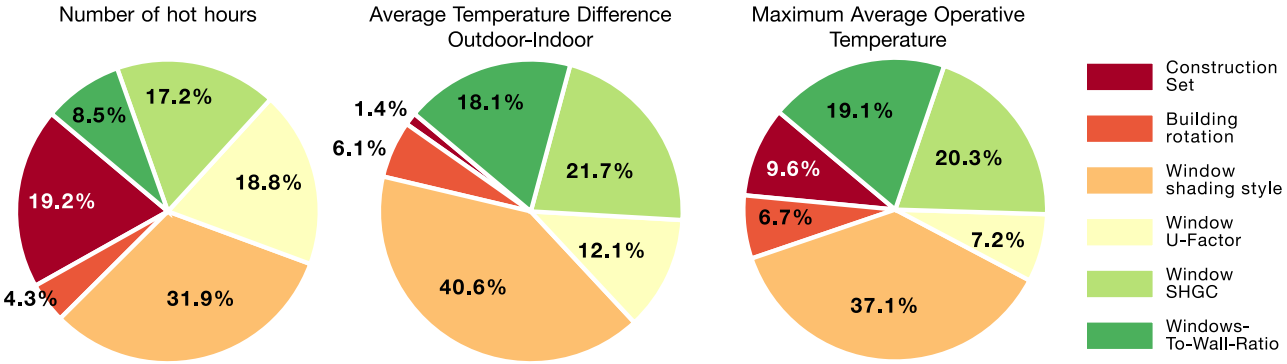

Figure 5: Parameter sensitivity of the three indicators

3.2 Comparison with a milder summer

After concluding that no building variants could provide comfort under the worst-case scenario (RCP 8.5) for 2100, the focus shifted to a more optimistic 'sustainability' scenario (RCP 2.6). This scenario features lower outdoor temperatures and fewer extremely hot days, allowing building elements more time to cool down. The same parameter combinations were simulated with the weather file exchanged. Analysis showed that in the RCP 2.6 scenario, some building variants could prevent overheating, with maximum interior temperatures on average over 5℃ lower than in the RCP 8.5 scenario. The number of uncomfortable hot hours decreased on average by 150, and while 572 variants still couldn't provide any comfortable hours, 496 offered more than 10% comfortable hours, and 80 provided comfortable conditions for half the time. The best-performing variant maintained indoor temperatures between 24 and 32℃, providing comfortable conditions for 62.5 % of July and August.

4 Discussion and conclusion

The described experiment provides valuable insights into the topics of thermal comfort and heatwave resilience. A OAT sensitivity analysis evaluated various parameters' influence on internal temperatures under extreme outdoor conditions, highlighting the critical importance of selecting appropriate shading devices, high-quality glass, and lower fenestration ratios to mitigate the effects of severe heatwaves. In contrast, building orientation and material selection played a minor role in the simulated setup, giving architects more flexibility when maintaining optimal values for the critical parameters described.

However, the methodology had some limitations, primarily due to the reduced scope of the model. The number of parameters and their selected values were significantly reduced to manage long computation times and the chosen evaluation method. Although this setting clarified which parameters are decisive and which are less influential, a more developed model could yield different results. Future studies should explore this further, possibly by employing a methodology that allows faster computation of numerous variants.

Despite these limitations, this research addresses critical issues of building resilience and thermal comfort in the context of climate change. As climate change continues to impact indoor thermal comfort, these findings underscore the necessity of integrating heatwave resilience into architectural design. Buildings constructed today will face future weather conditions; therefore, designs should not only adhere to current norms and requirements but also anticipate predicted future challenges. Making informed design choices now can minimize the need for future modifications or, in extreme cases, the demolition of structures that do not adapt to new conditions.

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