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Implications of window opening assumptions in English overheating regulation on assessing residential heat resilience under uncertain climate

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Abstract

Climate change causes more frequent and severe heatwaves in temperate regions, posing a grave risk of heat exposure to dwellings. To address this, the United Kingdom government recently implemented regulations to mitigate overheating in English and Welsh homes. Approved Document O (ADO), as its accompanying technical guidance, recommends a modelling approach to demonstrating regulatory compliance for summertime thermal comfort, which is based on the Technical Memorandum 59 (TM59) methodology with modifications to the standardised window control behaviours. Previous studies have highlighted adaptive ventilation as a crucial measure to enhance heat resilience of future homes; however, the impact of such modifications on overheating prediction has not been quantitatively discussed, particularly in consideration of climate uncertainty. This paper aims to investigate the implications of the tailored window control rulesets in ADO on heat resilience evaluation for future homes under uncertain climatic conditions. Results suggest a statistically significant difference ($p < 0.001$) in overheating assessment results between TM59 and ADO, with the greatest effect observed on the expected overheating risk in nocturnal bedrooms. Quantitative evidence also reveals the critical role of nighttime ventilation in enhancing thermal comfort in future summers regarding both effectiveness and robustness.

Key Innovations

- First quantitative assessment of the differences in the standardised window opening behaviours between TM59 and ADO and their impact on heat resilience evaluation.
- New statistical evidence about the significance of adaptive ventilation in ensuring both the effectiveness and the robustness of summertime thermal comfort under climate uncertainty.

Practical Implications

Enabling natural ventilation during sleeping hours is a critical aspect of occupant behaviour changes to adapt to the uncertain future heat exposure.

Introduction

Alongside the rising global temperature, climate change has profoundly altered regional weather patterns (IPCC, 2021). Within the built environment, a critical consequence is the heightened frequency and severity of heatwaves in historically temperate regions, such as the United Kingdom (UK) (Taylor et al., 2023). In conjunction with the substantial amount of time people spend indoors, a grave risk of heat exposure is posed to occupants of buildings (CCC, 2021). This has been further exacerbated by the prevalence of flexible working arrangements in recent years (Awada et al., 2021). Given that air conditioning units are installed in only approximately 2 % of the UK housing stock (BEIS, 2021), indoor overheating in residential buildings has emerged as a pressing health concern, drawing considerable attention across research, practice and policymaking.

The perception of overheating is subjective (Beckmann et al., 2021; Ratwatte et al., 2022), whereas addressing this heat stress issue at scale necessitates a standardised definition and assessment methodology. Technical Memorandum 59 (TM59) was thus developed to provide a standardised set of modelling guidance and internal gain profiles for quantifying indoor overheating through building energy modelling (BEM) (CIBSE, 2017). It has since been adopted for domestic overheating compliance in local contexts, such as within the Greater London area (GLA, 2018). A further milestone was marked by the introduction of Part O into building regulations for English and Welsh homes that came into force in 2022, signifying regulatory requirements of overheating mitigation at the national level. The implementation of Part O is accompanied by a technical guidance document, namely Approved Document O (ADO) (HMG, 2021b). Despite the provision of a simplified approach to demonstrating Part O compliance through prescriptive requirements for solar control and heat removal in ADO, the other performance-based approach via BEM is favoured (Hinge, 2023; Lomas and Li, 2023). The BEM method of ADO largely adheres to the TM59 methodology, with key differences pertaining to the standardised occupant behaviours of window operation.

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A growing body of evidence (e.g. Gupta et al., 2021; Bouhi et al., 2022; Lomas et al., 2024) has identified natural ventilation through windows as a pivotal passive measure to curb indoor overheating. These studies have also revealed the sensitivity of simulated overheating risk to its operational assumptions. When assessing the heat resilience of future homes, it was found that such an adaptive heat-expelling strategy offers significant potential for enhancing the robustness of summertime thermal comfort against uncertain climate conditions (Cui et al., 2022). These previous findings collectively underscore the need for investigation into the impact of varying window opening assumptions between TM59 and ADO on overheating assessment results. Given that Part O serves as an interim step towards the Future Buildings Standard in the UK (DLUHC, 2021), a comparative assessment can also provide quantitative evidence to inform its final implementation. Whilst several recent studies (e.g. Hinge, 2023; Toledo et al., 2025) have highlighted the alterations in ADO compared to TM59, their effects on overheating estimates has not yet been substantiated, particularly when considering climate uncertainty.

Recognising this knowledge gap, this paper aims to investigate the implications of the tailored window opening assumptions in ADO on the assessment of heat resilience of future homes considering climate uncertainty. Specific objectives of this study are to:

- examine the validity of the responsibility of different window opening assumptions for variations in overheating assessment and heat resilience quantification;
- explore the connection between the predicted indoor thermal profiles and the variations in the expectation and the variability of overheating risk under climate uncertainty;
- discuss implications of the impact of such differences in occupant behaviours for mitigating indoor overheating and enhancing heat resilience of future homes in England.

Methods

This study was conducted using EnergyPlus (Crawley et al., 2001) for BEM and Python (van Rossum and Drake, 2009) for overheating assessment and statistical analysis. Two representative dwelling archetypes in England, namely the mid-terraced house and the high-rise top-floor, were analysed based on the models developed by Cui et al. (2022), which comprise the base BEM specifications in line with the English building regulations on energy conservation (HMG, 2021a) and the adapted overheating quantification methods from TM59. Following the same study, the heat resilience of future homes under climate change was assessed via robustness analysis, whereby the building performance effectiveness indicates the average performance against climate uncertainty, and the robustness the variability. Specifically, the 2050s A1B climate scenario of the PROMETHEUS datasets (Eames et al., 2011) for London (Islington) was analysed, where the climate probability is described using five percentiles (i.e. 10th, 33rd, 50th, 66th, 90th). Figure 1 overviews the comparison scheme implemented for each modelled dwelling, and the detailed comparison scenarios and methods are discussed as follows.

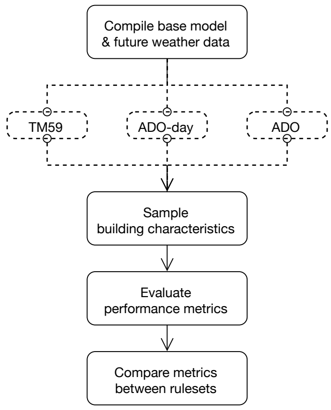

Figure 1: Comparison scheme. The comparison in this study was conducted between three window control rulesets, referred to as TM59, ADO-day and ADO, with coincidentally sampled building characteristics in each comparison group.

Window opening assumptions

The overheating assessment as per TM59, and inherently ADO, is exercised separately for diurnal and nocturnal occupied periods. This aligns with the distinct 'adaptability' of occupants between when they are awake and asleep, and the two sets of window control rules are a manifestation of such adaptability divergence. Both sets are refined in ADO, and their differences in trigger conditions and coincident window statuses are summarised in Table 1. To isolate their individual impact on overheating estimations, a third ruleset was curated by implementing solely the diurnal change of ADO to TM59, hereinafter referred to as ADO-day, representing an intermediate transition.

Parametric settings

This study examines the interaction between various natural ventilation schemes and indoor overheating risks, however, ventilation is not the sole determinant of indoor thermal profiles; significant heterogeneity in building characteristics exists within the housing stock. To validate the generalisability of the comparison outcomes, a range of input parameters for the base models were varied through Monte Carlo sampling. Specifically, two variable types, namely the envelope thermal insulation thickness and solar absorptance, were included in the analysis due to their close relationship with overheating (Taylor et al., 2023; Lomas et al., 2024).

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Table 1: Window opening assumptions. Conditions and statuses of window opening under the assumptions of TM59, ADO-day and ADO.

Occupied period	Condition	Status	Applicability		
			TM59	ADO-day	ADO
Diurnal	Above 22 °C	Fully open	×		
	Between 22 °C and 26 °C	Proportionally open		×	×
	Above 26 °C	Fully open			
Nocturnal	Above 23 °C at 11 pm	Fully open all night			×

The range of these variables is presented in Table 2, and a total of 1000 combinations were randomly drawn; the ground floor insulation thickness is only applicable to the mid-terraced house. For each set of sampled building characteristics, three simulation cases were populated with different window control rulesets corresponding to TM59, ADO-day and ADO respectively. The identical methods of quantifying overheating hours and heat resilience were then applied to all simulation cases for the summer period (i.e. May to September inclusive) as defined in TM59.

Table 2: Sample space of building characteristics. Value ranges for the envelope insulation thickness and solar absorptance.

Variable		Range
Insulation thickness	External wall	0.0 – 0.3 m
	Roof	
	Ground floor	
Solar absorptance	External wall	0.2 – 0.8
	Roof	

Statistical metrics

To compare three or more groups (i.e. window opening rulesets) that exhibit inherent variability (i.e. heterogeneous building characteristics) statistically, a hypothesis test via one-way analysis of variance (ANOVA) is commonly consulted, with the null hypothesis being no difference between groups (Casella and Berger, 2002). Specifically, repeated-measures ANOVA (rANOVA) was adopted, given each combination of insulation thickness and solar absorptance is coincidentally evaluated under all three rulesets as aforementioned (Mishra et al., 2019). When an overall statistically significant difference is discovered between tested groups via ANOVA, a post-hoc test is usually conducted to identify the exact group(s) contributing to the difference. In this study, a paired t-test with the Bonferroni correction was exercised after rANOVA (Mishra et al., 2019). The statistical analysis was undertaken using the `pingouin` package (Vallat, 2018).

Results

Operative temperature

The approach to estimating overheating risk established in TM59 is underpinned by a quantitative metric termed hours of exceedance, which is derived based on the operative temperature of each assessed room (CIBSE, 2017). Therefore, to obtain a first impression on the impact of the updated standardised occupant behaviours in ADO, the changes in the simulated operative temperature between the three assumptions were inspected. Figure 2 exemplifies the inspection by the mid-terraced bedroom 1 and the high-rise top-floor living room in mid and late summer under median climate projections, which illustrates differences in both the degree and the pattern of shifts in the operative temperature.

Comparing the two rooms, a clear observation is made that the overall lowest indoor temperature is produced by ADO in the bedroom 1, whilst by TM59 in the living room. The underlying cause of this difference is the absence of ventilation through windows in the living room with no occupancy at night. When the window opening ratio is constrained with respect to a linear correlation with air temperature during the daytime (i.e. from TM59 to ADO-day), the amount of excessive heat expelled from indoors through adaptive ventilation is naturally reduced, hence the temperature increase. Such an increase due to stricter control rules is mostly within 1 °C, and applies to both room types provided diurnal occupancy. In contrast, the provision of nighttime ventilation based on the indoor temperature before sleep in ADO significantly reshaped the thermal profile of bedrooms throughout the day. A drastic drop in the operative temperature, as much as 8 °C, can be identified during sleeping hours, particularly in midsummer. The effect of this overnight heat purging is shown to persist into the daytime, resulting in decreased temperature even in non-bedrooms.

Disregarding magnitude, the thermal profile of the living room is hardly discernible at different times during the summer period, whereas that of the bedroom 1 presents an outstanding distinction. In late summer, except for some nights (e.g. 22 - 23 Sep) with a similar overheating curbing pattern to midsum-

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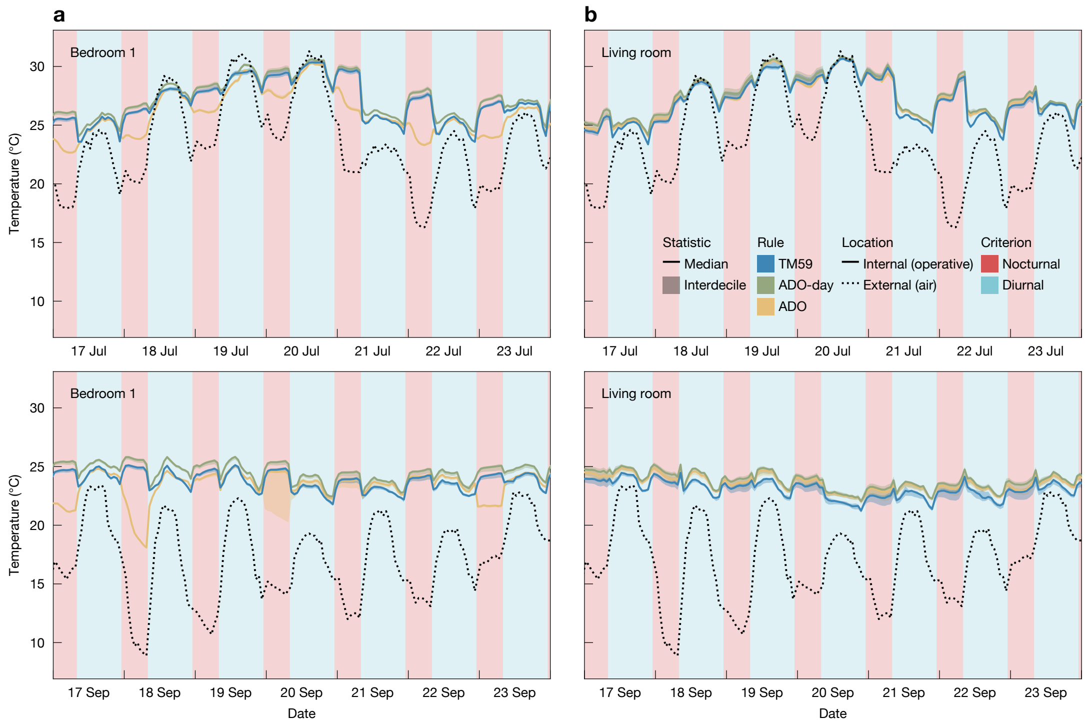

*Figure 2: Comparison of operative temperatures. The median and the 90 % percentile intervals of the operative temperature of the bedroom 1 in the mid-terraced house (**a**) and of the living room in the high-rise top-floor flat (**b**) in mid (top) and late (bottom) summer under the 50th percentile of the 2050s A1B climate scenario.*

mer and some (e.g. 18 - 19 Sep) with the bedroom windows shut overnight because the set point is not reached at 11 pm in all sampled simulations, there exists a third scenario (e.g. 20 - 21 Sep) where the temperature trends considerably vary between different combinations of the thermal insulation thickness and the albedo. This suggests a high sensitivity of the operative temperature to specific building characteristics near the transition period between winter and summer seasons in England, which coincidentally aligns with the significant role of the summer-winter transition in comprehensively tackling the overheating issue revealed by Cui et al. (2023). On the other hand, although the effectiveness of night ventilation in decreasing the indoor temperature is evident, it is also noteworthy that such decreases can sometimes be excessive around the transition period; the bedroom temperature even reached the commonly assumed heating set point 18 °C before dawn on the night of 17 - 18 Sep. Implications of such overly removed heat on the sleeping comfort warrant further investigation.

Overheating rate

Figure 3 depicts the different results of overheating assessment through the example of the mid-terraced kitchen during the daytime and the high-rise top-floor bedroom 2 at night under all evaluated climate percentiles. Specifically, a given data point below the identity line indicates a lower overheating rate compared to that derived using TM59.

In concurrence with the observation regarding the operative temperature, the overheating assessment results obtained under ADO-day and ADO assumptions exhibit a distinct unidirectional deviation from TM59. That is, the limiting of the diurnal window opening ratio will slightly increase the indoor overheating risk in bedrooms, which can be drastically lowered when ventilation is enabled during the sleep hours. In contrast, the heat purging effect of nighttime ventilation in bedrooms does get transferred to other living spaces in the following day, but the effectiveness is limited and highly contingent on specific building characteristics.

Exceptions to the temperature-overheating consistency concern data points under the 10th and the 33rd percentile of climate variability, where low to zero overheating hours are identified in the kitchen. This conveys that the impact of different window opening rules cannot always be manifested in overheating assessment, as a result of the cutoff effect of the temperature threshold. This temperature-overheating inconsistency can also be observed from the scatter of the data points within climate percentiles, which indicates the sensitivity of the overheating assessment results to building design variations. Such sensitivity is highlighted in the middle range of overheating rates (i.e. high climate percentiles for the kitchen and low to middle ones for the bedroom 2), whereas minimal when the number of overheating hours is extremely

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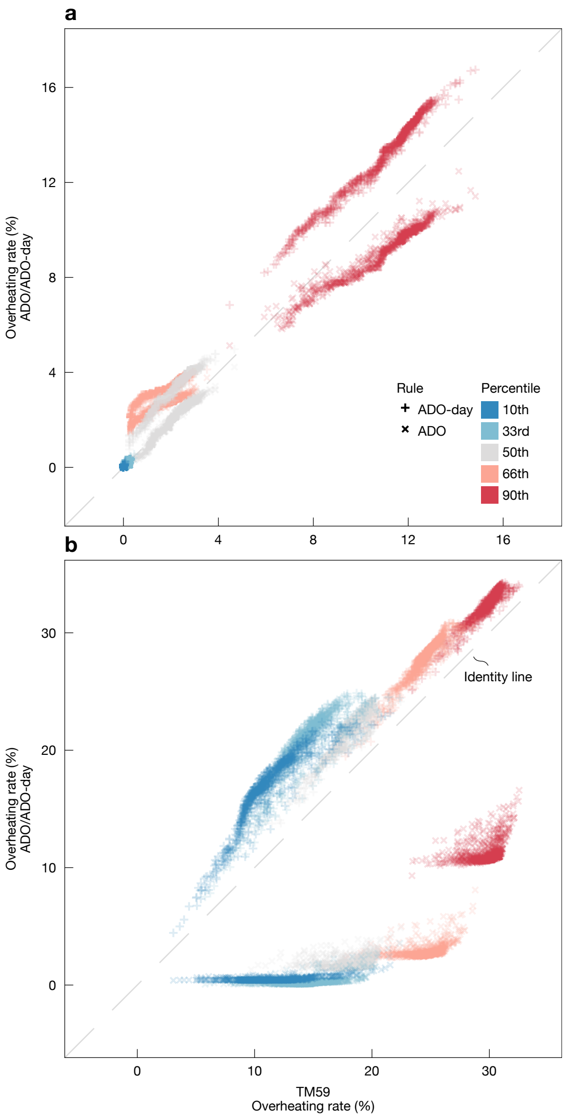

*Figure 3: Comparison of overheating rates. Coincident overheating rates of the diurnal kitchen in the mid-terraced house (**a**) and of the nocturnal bedroom 2 in the high-rise top-floor flat (**b**) based on TM59 (x-axis) against ADO/ADO-day (y-axis) with the same sampled building characteristics under the 2050s A1B climate scenario.*

low or high (i.e. low to middle climate percentiles for the kitchen and high ones for the bedroom 2).

Overheating variability

So far, the impact of the limiting window opening assumptions in ADO have been investigated separately for each climate percentile. However, when devising strategies to mitigate overheating risk and secure heat resilience of future homes in building design practice, these alternative climate trajectories need to be considered collectively. The heat resilience against climate uncertainty is examined via the robustness quantification method developed by Cui et al. (2022), as curated in Figure 4, with the mean and the upper interval of the bootstrapped overheating rates across climate variability respectively indicating the effectiveness and the robustness of summertime thermal comfort for a given room and occupied period. As confirmed by rANOVA with post-hoc t-tests, the limits that ADO imposes on occupant behaviours of window control prove to alter the predicted heat resilience of future homes regarding both expectation and variability with statistical significance, where all the pairwise p-values are less than 0.001.

The greatest impact of the ADO ruleset on the estimated mean overheating rates can be expectedly found in nocturnal bedrooms, where the opportunities of overnight ventilation can substantially lower the overheating expectation, even in the face of the deteriorating effect of the restricted diurnal window control. Similar patterns can be seen for the diurnal bedrooms with smaller magnitude, but not necessarily in other living spaces. For instance, the overheating expectation for the high-rise top-floor kitchen computed under the TM59 assumptions is lowest amongst three control scenarios. This means that the heat purging effect of nighttime ventilation, despite shared across the whole dwelling through internal door airflow or internal wall conduction as observed in previous sections, has considerably limited impact on daytime overheating prevention outside bedrooms.

A different primary area of impact is revealed for the variability of overheating estimates against climate uncertainty, where the diurnal occupied period is more sensitive to the alteration of window opening behaviours than the nocturnal one. Indeed, the magnitude of the resultant values is rather comparable between the mean and the upper interval during the daytime within each home; it is the nighttime values that show a drastic drop of impact by the ventilation during sleep hours. Particularly in the living room and the kitchen, the robustness of thermal comfort for the mid-terraced house is clearly worse than that for the top-floor flat under TM59 and ADO-day rulesets, possibly owing to additional heat transfer uncertainty through the ground floor. Comparatively, their estimates appear to be rather similar under the ADO assumption. This indicates that nighttime ventilation not only enhances the heat resilience against climate uncertainty, but may possess certain 'universal' effectiveness across the housing stock of heterogeneous building characteristics.

Discussion

The primary goal of this study is to elucidate the impact of refined window opening assumptions in ADO on overheating assessment and compliance outcomes for English dwellings. The results presented in the preceding section revealed a statistically significant disparity between different rulesets regarding both the effectiveness and the robustness of summertime thermal comfort with climate uncertainty considered.

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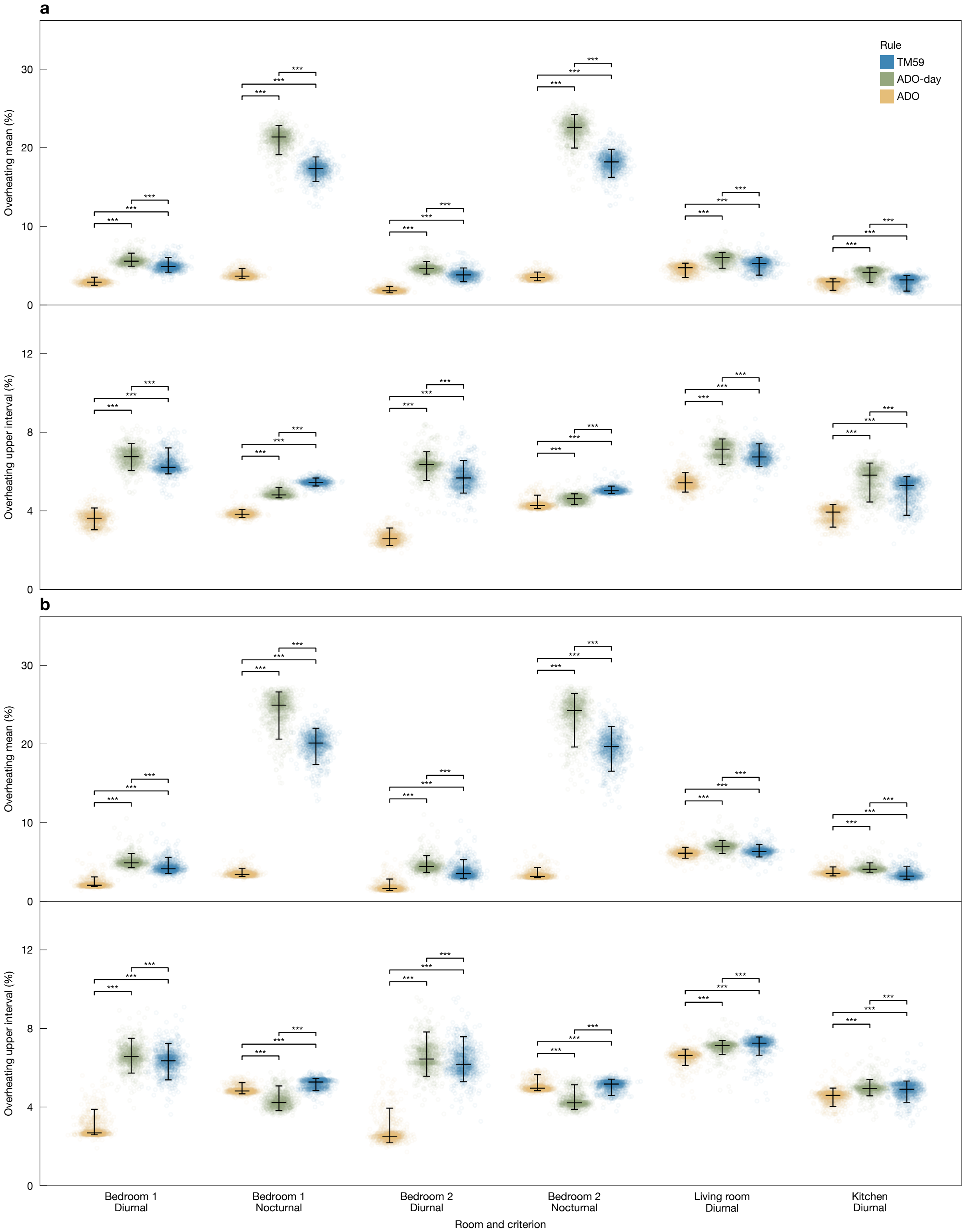

*Figure 4: Comparison of expected overheating risk and its variability. The mean and the upper interval of the bootstrapped overheating rates in different sampled building characteristics of the mid-terraced house (**a**) and of the high-rise top-floor flat (**b**) under the 2050s A1B climate scenario.*

This disparity was particularly pronounced in bedrooms, especially during sleep hours, whilst marginal in the living room and the kitchen of high-rise top-floor flats.

The research design employed in this study provided a unique perspective to explore the role of adaptive ventilation at nights in the pressing need to curb overheating and ensure the heat resilience of future homes.

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ADO imposes limits on the standardised occupant behaviours of window control for both diurnal and nocturnal occupied periods, each with varying implications. The nighttime window opening is triggered by a simple logic based on occupants' perception of warmth. Although the perceived warmth may not necessarily equate to 23 °C in reality, it is arguably more realistic than the proportional control of the window opening ratio with respect to indoor temperature as stipulated by the daytime limits. Conversely, except for nocturnal bedrooms, the individual impact of the daytime rulesets was shown to be limited in terms of both the expected overheating risk and its variability. On the other hand, the provision of 'semi-adaptive' ventilation at nights demonstrated its great potential for enhancing heat resilience, particularly its implied ability to flatten not only the heterogeneity of building characteristics within the same dwelling archetypes but that of thermal profiles between different archetypes. This is also an indication of adaptive ventilation being more paramount than some other variables commonly associated with increased indoor overheating, such as thermal insulation.

Naturally, other factors such as security and noise must be considered when opening windows during sleep, as emphasised in ADO and discussed by numerous studies (e.g. Bhadra et al., 2023; Lomas and Li, 2023; Toledo et al., 2025). One particular aspect pertains to the possibility of excessively expelled heat during summer-winter transition periods exhibited by Figure 2. Discussions on this 'overcooling' issue in summers can be found in previous studies, in the presence of air conditioning in warm and hot climates (e.g. Alnuaimi et al., 2022; Ford et al., 2022), or mechanical night ventilation in temperate regions (e.g. Pellegrini et al., 2012; Landsman and Brager, 2016). One report (Orme and Palmer, 2003) from the literature qualitatively discussed the possibility of overcooling by natural ventilation through facade openings in the UK, which is exhibited even in the mid-century in this study; this is likely a result of certain combinations of external temperature and wind direction that lead to an excessive amount of cold air inlet. Future work is warranted to generate more evidence to investigate whether this will be a genuine concern in the warming climate, especially in the housing of the vulnerable. Strategies should also be devised to enable better informed control of windows for occupants, such as by internal and external thermometers, as exemplified by Orme and Palmer (2003).

Conclusion

This paper analysed the differences in overheating assessment results between varying window opening rulesets implemented in TM59 and ADO, revealing that the heat resilience is most sensitive to the modifications to the occupant behaviours for the nocturnal period. The comparison also highlighted the significant role of adaptive ventilation in mitigating indoor overheating and enhancing thermal comfort robustness of future homes considering climate uncertainty. An overcooling possibility due to excessive heat purging at night was also identified for the winter-summer transition periods, suggesting the need for future investigation into its potential hindrance to encouraging occupants to avoid overheating during sleep by window opening. A key limitation of the present study concerns the small number of building characteristics involved, wherein other important overheating-related variables such as the glazing type and the window-to-wall ratio were not included in the analysis. Future work is expected to capture a more comprehensive spectrum of the heterogeneity of the housing stock.

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